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Hybridization challenges in energy-economy integrated models and representation of the low carbon transition: An application to the Brazilian case

Julien Lefevre

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Par

Mr Julien LEFEVRE

Hybridization challenges in energy-economy integrated models and
representation of the low carbon transition
An application to the Brazilian case

Thèse présentée et soutenue à Nogent-sur-Marne, le 14 octobre 2016 :

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Introduction

The Paris climate agreement adopted in December 2015 seems to embody a real wind of change in climate negotiations. The first universal agreement on climate change sets the objective to hold “*the increase in the global average temperature to well below 2°C above pre-industrial levels*” (FCCC-UN, 2015a). In addition, the text includes for the first time the operational translation of the objective in terms of GHG emissions in the long run: to reach zero net emissions during the second half of the century with a peak of emissions as soon as possible. However, the credibility of the agreement is based on the capacity of countries to trigger the appropriate change in the medium run. Yet, current national commitments released by countries for the 2025-2030 horizon once summed, lead us as such to an increase of more than 3°C above pre-industrial levels.

Strengthening the political paradigm shift of negotiations may help to accelerate action. That is the “*shift towards building a low-carbon society that offers substantial opportunities and ensures continued high growth and sustainable development*” (UN, 2011, paragraph 10 of the UNFCCC Cancun Agreements). It means switching from a “climate first” perspective to a “development first” approach, in which climate change mitigation goals are part of the broader project to ensure sustainable development. For developing countries, the question is how the obstacles to development can be overcome in synergy with a low carbon pathway (Shukla and Dhar, 2011). For western countries in the adverse context of the economic crisis, the question is of the synergies between economic recovery and a low carbon energy transition. “*Green growth*” (OECD, 2011) or “*green economy*” (UNEP, 2011) concepts echo this will to align environment and mitigation goals with economic development objectives. As for climate negotiations, the idea of a *bottom-up* framework based on the aggregation of regional initiatives and a loose coordination of goals has been established. In practice since the Cancun framework, each country party has been individually encouraged to adopt mitigation objectives consistent with its own developmental goals within the NAMA’s (Nationally Appropriate Mitigation Actions)¹ (Bodansky and Day, 2014).

¹These NAMAs are especially integrated in the national contributions, the Intended Nationally De-

Redirecting climate policies in the context of development goals seems determinant to favor the political acceptability of low carbon pathways and accelerate action. All the more so as most of the policies that drive emission pathways are not actually motivated by climate goals in the first place, but by other policy objectives such as energy security, local pollution or urban planning. In this view, the resulting emissions abatement can even be perceived as a co-benefit of these “non-climate” policies. That’s why the appropriate design of action plans rests on the articulation between climate and non-climate policies in the search for synergies between decarbonization and desired development pathways.

Historically, the scientific discussion about mitigation issues has been first “climate-centric” and has focused on the technological and economic issues to abate emissions in the long run. At the global level the question has been that of the three flexibilities (Manne and Richels, 1997): (i) *when* flexibility - the timing of action, (ii) *where* flexibility - the regional breakdown of action and (iii) *what* flexibility - articulation between different mitigation options and different GHGs. The core analysis has been based on the results of numerical models which have else provided quantitative assessments of mitigation costs and technological dynamics. However, the new “conversation”, which the current policy context calls for, seems much wider and includes at least the two key following dimensions: (i) the issue of the margins of maneuver to meet simultaneous climate and larger economic and development goals and of the related policy packages and (ii) the issue of the conditions of the transition in the medium run and the possible operational plans robust to uncertainty to trigger that transition.

Furthermore, just as most recent IPCC assessment reports, it seems state-of-the-art research and quantitative scenarios have not provided satisfying answers to these questions yet. Worse, latest IPCC report (Edenhofer et al., 2014, AR5 - WGIII) seems to reflect a marginalization of the quantitative analysis of key topics such as competitiveness, fiscal reforms, finance or even development patterns. In practice in AR5, specific chapters are devoted to qualitative explanations about economic and sustainable development concepts with little linkages to the core chapter about the quantitative assessment of transformation pathways. This gap between qualitative developments and quantitative scenarios finally questions the insights provided by quantitative scenarios about economic, policy tools and transition issues. Therefore a central question arises: to what extent can state-of-the-art quantitative tools and models already provide robust insights to current policy debates? At the background of this interrogation is the question of the areas of competence of state-of-the-art numerical models themselves

terminated Contributions (INDCs), which have been recently released by countries.

and the way they are used to address policy issues. This questioning is the starting point of the present thesis.

Since the early 70's, the fast increase of computer capacities and the expansion of data bases have enabled an exponential development of modeling tools. It has made it possible to turn theoretical frameworks such as general equilibrium (Arrow and Debreu, 1954), activity analysis (Koopmans, 1951) or else system dynamics (Forrester, 1968) into operational tools to study real world empirical issues. A numerical model has to be thought of as a simplified representation of a complex real system and constitutes a laboratory of studies of future paths of that system that can not be analytically or mentally assessed. In the climate-energy-economy field, numerical models fit into a forward-looking - or *prospective* - approach which especially aims to explore plausible futures, identify risks and opportunities, and assess levers of action to foster present policy-making. In practice, the forward-looking analysis rests on building scenarios which are internally consistent, and plausible descriptions of future pathways (McCarthy, 2001). Since the SRES scenarios exercise (Nakićenović and Swart, 2000, Special Report on Emissions Scenarios), the generation of scenarios for climate policy assessment has been standardized and follows a "story and simulation" approach: contrasted qualitative visions of the future - in terms of technology, socio-economic and policy context, etc - are further translated into model simulations to span plausible futures.

The surge of deciders demand for climate and energy policy assessment in the last fifteen years, has caused the burst of the number of research teams, modeling tools and scenarios globally produced² and the provision of much sharper diagnoses. However, one adverse side effect of these developments is the apparent higher complexity of the landscape of models despite the standardization of practice in scenario generation. This tends to decrease the clarity about the relative relevance of models to address a given issue, which depends on models internal vision of the energy-economy system. Earlier, through the bottom-up - top-down debate between engineers and economists, modeling tools could more easily be classified in a few identified paradigms (Crassous et al., 2006) - similar for global and regional analysis - with a clearer control of their areas of competence. Recently, the increased complexity of the incorporated mechanisms and the hybridization of historical approaches have resulted in a more blurry picture, which is reflected by the usage of generic labels such as *integrated* (Fischedick et al., 2011) or *hybrid* models (Hourcade et al., 2006).

²As for global assessments, the database of the contribution of working group III to AR5 (IPCC, 2014b) includes almost 1200 global scenarios generated by more than 30 different models, whereas the IPCC Second Assessment Report (IPCC, 1995) contained "only" 200 scenarios.

Considering the urgency to provide robust assessments to support policy-making, there is a key issue to improve the diagnostics about (i) the policy questions covered by the state-of-the-art integrated studies with regard to the new challenges and about (ii) the landscape of models and the methods to provide forward-looking analysis. In this regard, for some time now, the CIRED has been exploring methodological issues about Energy-Economy-Environment (E3) models to support decision making. Building on this background, the thesis defended by Frédéric Gherzi (2003), Renaud Crassous (2008), Olivier Sassi (2008), Céline Guivarch (2010), Henri Waisman (2012) and Emmanuel Combet (2013) among others have made it possible to build innovative modeling tools to contribute to the policy debate on climate change mitigation.

This thesis seeks to pursue these efforts at two levels: (i) first with a methodological contribution based on an analysis of the state-of-the-art modeling toolbox and the provision of new model guides, in the context of integrated and energy-economy hybrid models; (ii) second with a contribution to the current policy debate about the low carbon transition in Brazil based on the construction of a new modeling tool which benefits from previous methodological effort.

The document includes two parts.

Part I (chapters 1 to 4) performs a methodological assessment of integrated models at two different levels: (i) a global analysis based on models integrated conception of the low carbon transition and (ii) a specific assessment of the energy-economy hybridization challenges in multi-sector CGE models.

Chapter 1 provides a general diagnosis of global integrated studies based on the IPCC AR5 transformation pathways scenarios. From a careful examination of modeling exercises, two types of limitations are highlighted: (i) key remaining gaps between the policy insights provided by studies and the framing of the low carbon transition question and (ii) a lack of uncertainty management linked to models alternative structure and conception. We also show that historical model taxonomies are not sufficient to inform the diversity of recent integrated and hybrid models conceptions.

Chapter 2 builds on chapter 1 diagnosis and introduces a guide of integrated models based on their internal vision of energy-economy transformations and their integrated conception of the low carbon transition. Our guide characterizes models along three dimensions: (i) the pattern of “interdependence” as the “snapshot” of the system modeled, (ii) the type of transformation drivers and (iii) the type of transition dynamics.

Chapter 3 and 4 narrow the methodological analysis on the specific issue to hybridize energy - economy representations in CGE models. Chapter 3 provides a synthesis of the existing options to couple bottom-up and top-down representations of

technical systems in multi-sector CGE models. Chapter 4 underlies the need for hybrid databases as a prerequisite for bottom-up and top-down hybridization. In addition it enhances the crucial role of energy-economy initial conditions for CGE assessment and proposes an innovative method to build hybrid accounting systems and better control CGE models initial conditions.

Furthermore, Part II (chapters 5 to 8) develops an application of the methodological concepts of PART I to the construction of a new model for climate policy assessment in Brazil. The scenarios produced explore key issues of the articulation between decarbonization, energy policy and economic development in Brazil.

Chapter 5 introduces the Brazilian context on energy, climate and economic topics and highlights a set of key policy questions and challenges at time horizon 2030. These questions are especially relevant in the context of Brazilian INDCs.

Chapter 6 introduces the *IMACLIM-BR* model specially designed to assess climate and energy policies in Brazil. It details the modeling choices and characterizes the model in light of the methodological considerations of Part I.

Eventually chapters 7 and 8 translate chapter 5 highlights into new scenarios produced with *IMACLIM-BR* at time horizon 2030. These scenarios have a double goal: to demonstrate *IMACLIM-BR* potential of analysis and to provide preliminary insights for policy debates. Chapter 7 explores the macroeconomic and distributive implications of carbon tax policies in Brazil until 2030 and the interplay between policy options and the economic structure to reach simultaneous policy objectives. Chapter 8 studies the possible articulation between climate policy and the development of the oil sector.

This thesis has benefited from several fruitful collaborations beyond the work with our PhD advisor Jean-Charles Hourcade. Chapters 2 and 3 build on a joint effort carried out with Ruben Bibas, whose PhD thesis has been defended in July 2015. Chapter 4 is based on a joint work with Emmanuel Combet, Frédéric Gherzi and Gaelle Letreut. In addition, the *IMACLIM-BR* adventure fits into a close collaboration with the COPPE of the University of Rio de Janeiro and the team of Prof. Emilio La Rovere. The already old collaboration has stepped up with the work of the partnership I have constituted with William Wills, which has resulted in the construction of the *IMACLIM-BR* model. More largely, *IMACLIM-BR* has been designed as part of the development of the *Imaclim* team at CIRED and the project to develop regional policy assessments.

Part I

Methodological assessment of integrated models: hybridization challenges and representation of the low carbon transition

Chapter 1

Integrated modeling at energy-economy-climate change mitigation interface : where do we stand?

1.1 Introduction

The IPCC Working Group III reports gather the state-of-the art scientific knowledge about climate change mitigation at global scale. Looking at IPCC Fifth Assessment Report (AR5) (IPCC, 2013), it seems the scientific community has taken stock of the recent shift of the policy framing of mitigation issues. WG III contribution to the AR5 (IPCC et al., 2015) actually updates perspectives - compared to AR4 - towards reinforcing the objective to study mitigation issues in the broader context of sustainable development: *“sustainable development provides a framework for the evaluation of climate policies”*. Such perspectives enforce that climate policies and mitigation should not be studied on their own - any more - but as part of broader development objectives. The report details further the idea: *“a key message of [AR5] is that designing a successful climate policy may require going beyond a narrow focus on mitigation and adaptation, beyond the analysis of a few co-benefits of climate policy, and may instead require ‘mainstreaming’ climate issues into the design of comprehensive sustainable development strategies, including at local and regional levels.[...] In the broadest, boldest perspective, the choice of the development path is at stake.”*

In addition, key IPCC Working Group III insights rest on global integrated scenarios

generated by Energy-Economy and Integrated Assessment Models (IAMs). These models and scenarios provide insights about the required transformation pathways in a multi-regional and cross-sectoral perspective, to reach desirable climate targets. The number of models and scenarios has boomed since the late 90's and, just like IPCC AR5 integrated scenarios, studies have become more and more detailed regarding the policy regimes and the technological issues explored. In addition, to take benefit from the diversity of available models, model inter-comparison exercises or cross-model studies have become customary to generate scenarios, which are consistent across given sets of integrated models (Kriegler et al., 2015c; Weyant and Kriegler, 2014).

Nevertheless, the result of these important research efforts remains ambivalent if the objective is to provide robust policy insights to design “*successful climate policy*” and “*comprehensive sustainable development strategies*”. On the one hand, they certainly reflect an improvement of our knowledge about climate change mitigation issues. On the other, it seems recent scenarios have not really taken into account some of the implicit recommendations and caveats made in AR4¹. If scenarios have been refined towards non-idealized policy regimes and delayed action, the least-cost approach in perfect economic environment remains central with the emphasis on average carbon prices and aggregated mitigation costs. The questions of why action is delayed and of the economic constraints to the transition towards low carbon pathways seem to be forgotten. Questions about fiscal reforms, competitiveness or second-best issues - some of which had been key aspects of former IPCC reports - are not mainstreamed in the numerical information provided in AR5. In addition, the discussion focuses on technological responses like CCS, nuclear, etc., which eclipses the wider discussion that should happen about the “material” content of development pathways in order to design comprehensive sustainable development strategies. Finally, emphasis is given to model comparisons and questions arise about the management of uncertainty in multi-model studies.

Starting from the example of the global integrated studies reported in AR5, this first chapter attempts a critical synthesis of state-of-the art integrated modeling of low carbon transformation pathways. After providing a short synthesis about IPCC AR5 assessment of transformation pathways - including improvements done since AR4, we highlight in section 1.2 that limitations remain upon two lines: (i) the scope of scenarios and the research questions studied and (ii) the management of uncertainty in model intercomparison studies. Finally the status of integrated models is at stake.

¹“Most models use a global least cost approach to mitigation portfolios and with universal emissions trading, assuming transparent markets, no transaction cost, and thus perfect implementation of mitigation measures throughout the 21st century.”(Metz et al., 2007)

Therefore the chapter ends with detailing the landscape of state-of-the art models as it is described in the literature. We show that existing taxonomies are limited to inform the conceptual and structural diversity of models which form a “jungle” of integrated models. We conclude that new model guides would be useful as a prerequisite to both better assess existing models and further improve the model toolbox.

1.2 Insights from IPCC AR5 assessment of global transformation pathways

In this first section, we draw a short synthesis of the study of global transformation pathways in the context of climate change mitigation, which is detailed in the chapter 6 of WG III contribution to AR5 (IPCC et al., 2015). That chapter of WG III AR5, as well as the model inter-comparison studies themselves on which the chapter builds, are representative of the policy questions explored and the methods used in state-of-the-art integrated studies. Our own synthesis is based on a careful examination of these studies and of the chapter 6 of WG III AR5².

The general framework for assessing transformation pathways is introduced as follows in (Edenhofer et al., 2014, Chapter 6): *“First, what are the near-term and future choices that define transformation pathways including, for example, the goal itself, the emissions pathway to the goal, the technologies used for and sectors contributing to mitigation, the nature of international coordination, and mitigation policies? Second, what are the key decision making outcomes of different transformation pathways, including the magnitude and international distribution of economic costs and the implications for other policy objectives such as those associated with sustainable development? Third, how will actions taken today influence the options that might be available in the future?”* These questions reflect the general blueprint to explore transformation pathways in their detailed technical, economic, regional and dynamic dimensions and the articulation of climate policies with other sustainable development objectives.

1.2.1 The method of cross-model scenarios

The exploration of these issues is mainly based on the production of scenarios by large scale integrated models: AR5 includes 1,184 new scenarios, which have been produced since AR4 by 31 models. The bulk of scenarios have been provided by

² For the studies, we only retained published papers on cross-model comparisons, excluding the papers with results provided by a single model.

Table 1.1: AR5 scenario table [adapted from (IPCC, 2014b, AR5 scenario database)]

Model Intercomparison Exercise	Year Completed	Number of models	Number of Scenarios	Areas of Harmonization
ADAM (Adaptation and Mitigation Strategies—Supporting European Climate Policy)	2009	5	15	Technology availability Mitigation policy
AME (Asian Modeling Exercise)	2012	16	83	Mitigation policy
AMPERE (Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates)	2013	11	378	Technology availability mitigation policy GDP population
EMF 22 (Energy Modeling Forum 22)	2009	7	70	Technology availability mitigation policy
EMF 27 (Energy Modeling Forum 27)	2013	16	362	Technology availability mitigation policy
LIMITS (Low Climate Impact Scenarios and the Implications of required tight emissions control strategies)	2014	7	84	Mitigation policies
POeM (Policy Options to engage Emerging Asian economies in a post-Kyoto regime)	2012	1	4	Mitigation policies
RECIPE (Report on Energy and Climate Policy in Europe)	2009	3	18	Mitigation policies
RoSE (Roadmaps towards Sustainable Energy futures)	2013	3	105	Mitigation policy GDP growth population growth fossil fuel availability

model intercomparison or cross-model studies. Table 1.1 lists the different model intercomparison studies involved in AR5.

Two types of integrated studies exist in the literature: (i) studies based on one single model and (ii) studies based on cross comparisons with multiple models. In the context of single model studies, contrasted scenarios are generated by contrasted sets of parameters and input assumptions. Such studies make it also possible to perform sensitivity analyses to identify the sensible determinants of future low carbon pathways. For instance, Webster et al. (2008) performs a sensitivity analysis of carbon prices and macroeconomic costs of stabilization to the uncertainty of key parameters - elasticities of substitutions, autonomous energy efficiency improvement, etc - with the

EPPA model. Nevertheless such studies basically lack the richness of the comparison of alternative modeling frameworks. As a contrast, studies involving several models actually may yield richer insights stemming from alternative modeling choices. As put by [Kriegler et al. \(2015c\)](#) in the introduction of the AMPERE study: *“the purpose of involving a wide range of models with different structures and assumptions was to improve the robustness of findings by identifying and diagnosing differences in model results. To this end, modeling work on mitigation pathways for the 21st century can be seen as a mapping exercise exploring consequences of different courses of action in a range of plausible environments.[...] The multiplicity of results and assumptions in model comparison exercises thus provides a more comprehensive picture and can warn users against too much confidence in a single number or action.”* [Riahi et al. \(2015\)](#) adds that *“the diversity of approaches is an important asset, since it helps us to better understand structural uncertainties, and to focus on findings that are robust across a wide range of methodologies.”* In a word, involving a wide range of models makes it possible to introduce the issue of **uncertainty about model structure and conception** beyond pure parametric uncertainty. This is a crucial epistemic aspect of modeling studies ([Oreskes and Belitz, 2001](#)).

Furthermore, the scenario design of cross-model studies is based on the classical comparison of **“policy” scenarios against counterfactual baselines**. This protocol has been customary since the 90’s and was developed to address the question of mitigation costs ([Jaccard et al., 2003](#)). In short, a baseline scenario is first generated and is supposed to represent a future path where no specific action targeting emissions abatement is implemented. Then the policy scenario is built by adding one given mitigation policy over the baseline context. Most of the time, climate or mitigation policy means either carbon prices or emissions constraints. This protocol makes it possible to assess the techno-economic implications of the specific mitigation policy studied compared to the baseline situation where it is not implemented. In this sense one given policy scenario is inseparable from its related baseline. In up-to-date cross-model studies the scenario design keeps these basics but is generally expanded in two directions: (i) different exogenous contexts are explored (contrasted availability of technologies, of natural resources potential, etc.) and give as many contrasted baselines and (ii) for one given context, different policy cases are studied (550 ppm or 450 ppm global targets, fragmented policy, staged accession scenarios, etc.). It results in a scenario design that can be represented with a double entry table like for the EMF27 study ([Kriegler et al., 2014](#), Table 1).

Then the scenarios assumptions are implemented in the set of models chosen. Doing so requires a certain level of **harmonization across models** in order to manage the global uncertainty of the exercise. In practice the baselines are harmonized across

models so that they yield similar pathways in terms of emissions, GDP growth or energy intensity. Moreover, the input assumptions about costs, technology portfolios, etc., can be harmonized as much as possible across models in policy simulations. In this case, the range of results across models for one given scenario reflects the heterogeneity of model structure beyond discrepancies about input and parametric assumptions. Harmonization across models is a difficult balance between sufficient convergence of key outputs and contrasted outcomes due to model structural differences.

1.2.2 Central issues addressed in AR5 cross-model studies

AR5 integrated scenarios fit into the continuity of former mitigation scenarios but show a net improvement in the sharpness of the analysis and the diagnostics provided.

First of all, these scenarios remain in the tradition of **cost-efficient mitigation scenarios** and generally seek to assess the **least-cost pathways** consistent with given emissions pathways or stabilization targets. Accordingly, cost assessment does not include climate change damages and the potential benefits of mitigation in terms of avoided climate change³. The consequences of transformation pathways in terms of radiative forcing and temperature are usually explored separately. In addition, the general discussion about cost-effective transformation pathways revolves around the customary issue of the “three flexibilities”: (i) the *where* flexibility or the breakdown of mitigation efforts between regions, (ii) the *when* flexibility or the time frame of efforts, and (iii) the *what* flexibility and the breakdown of abatement between the different types of GHG and the different sectors (fossil fuels emissions vs land-use changes, etc).

Furthermore, scenarios have been greatly expanded since AR4 towards at least two directions: (i) **the role of key technologies** (mainly CDM - carbon dioxide removal - and energy supply and conversion technologies) and (ii) **the implications of non-idealized policy implementation regimes** in terms of “delayed participation” and “fragmented action”(Edenhofer et al., 2014).

Just as AMPERE and EMF27 studies, which provide for almost 2/3 of the scenarios, cross-model studies first explore the role of key technologies and energy carriers such as CCS (Carbon Capture and Storage), renewable energy (solar and wind power, etc.) and bioenergy, nuclear power, etc. For instance, EMF27 study is more specifically devoted to the question of technologies (Kriegler et al., 2014). The study analyses among others, the implications for reaching the 450 ppm and 550 ppm stabilization

³By contrast, cost-benefit analysis deals with the trade-off between mitigation costs and climate change damages.

targets of the availability of the CCS technology, of nuclear phasing-out objectives and of a limitation of global primary bioenergy resources. Individual papers analyze the specific role of these different technologies: renewable energy (Luderer et al., 2014), CCS (Koelbl et al., 2014), bioenergy (Rose et al., 2014), etc. As detailed in Riahi et al. (2015), AMPERE scenarios also analyze the sensitivity of the feasibility of given climate targets to different energy supply portfolios and possible individual technology constraints. To a lesser extent studies integrate land-use and carbon cycle dimensions in the analysis.

In addition, the exploration of non-idealized policy implementation scenarios is a core focus of recent studies. It should be linked to the evolution of climate negotiations, as framed in the introduction of the thesis, and the new paradigm of fragmented action with country-specific pledges, as opposed to a global Kyoto market. In this context, there is a need to understand to what extent given sets of country pledges and intended national contributions in the medium run, are consistent with global stabilization goals in the long run and what can be the regional economic impacts of possible accession scenarios. Moreover, the insufficient global action, which we are currently experiencing, incites the research community to study the possible implications of delayed action. The AMPERE study thus specifically focuses on staged accession scenarios and discusses, for instance, the economic implications for Europe or China of these scenarios (Kriegler et al., 2015b). The EMF27 study also includes fragmented policy analysis. Another AMPERE paper (Riahi et al., 2015) besides studies the implications of current mitigation pledges on the feasibility of long term targets and the mitigation costs involved.

In fact, these two main directions of study - the role of technologies and non-idealized policy implementation scenarios - are taken up in an integrated manner, because they are intrinsically related. The time frame and magnitude of technology penetration depends on the emissions trajectories contemplated by the different countries. Conversely, the feasibility of long term targets in case of delayed action and the regional breakdown of mitigation costs, strongly depend on the availability and costs of the key technologies. In a word, we can say that studies typically explore the articulation between different possible abatement trajectories including the regional breakdown of effort, and the technological structure and constraints of energy supply and carbon removal. The implications of this articulation in terms of aggregated mitigation costs is also emphasized.

Furthermore, the results about transformation pathways are expressed by means of general systematic indicators or more specific ones depending on the focus of studies. The set of indicators discussed is usually limited and includes:

- Emissions pathways and warming
- Kaya's variables: energy intensity of GDP and carbon intensity of energy
- Primary energy mix
- Power generation technology mix
- Sometimes the fuel mix of final energy demand and the sectoral breakdown of emissions
- Aggregated discounted mitigation costs (per region) and carbon prices

Eventually the key new insights of most recent cross-model studies can be very shortly summed up with two quotes from the executive summary of [Edenhofer et al. \(2014\)](#):

"Emissions through 2030 will have strong implications for the challenges of, and options for, bringing concentrations to about 450 to about 500 ppm CO₂eq by the end of the twenty-first century".

"The availability of key technologies and improvements in the cost and performance of these technologies will have important implications for the challenge of achieving concentration goals".

1.2.3 Transformation pathways in a second best world and co-benefits of mitigation in AR5

Many models used for AR5 scenarios represent *"an idealized implementation environment with perfectly functioning economic markets devoid of market failures, institutional constraints, and pre-existing tax distortions"* ([Edenhofer et al., 2014](#)). This is the reason why the analysis of **existing distortions and barriers - in the largest sense - and their implications for transformation pathways** is not mainstreamed in cross-model studies. Complementary works tackle the issue in AR5 and discuss to what extent these existing market failures can be treated in synergy with emission abatement on the one hand - reducing drastically the mitigation costs in some cases - or are worsened by mitigation action in the other. There actually exists a whole literature about how the implementation of complementary policies - beyond pure climate policy - like larger fiscal reforms or policies targeting labor markets, transportation infrastructures, etc. can greatly alter the usual cost profile (including the temporal profile) of emissions reductions. Some studies even show net negative costs for mitigation action in cases where the **economic co-benefits** of action are maximal. Eventually, the existence

of market failures and others barriers (institutional, organizational, behavioral, etc), opens the room for possible synergistic effects between emissions reductions and other economic or development objectives related to employment, urban planning, energy security, etc.

In addition, the **multi-objective approach** beyond pure mitigation concerns has been greatly expanded in AR5 compared to AR4. In accordance with the general objective to mainstream the study of climate issues into the broader sustainable development topic, WG III AR5 chapter 6 explores the global implications of transformation pathways for others objectives linked to sustainable development. The goal is to identify what can be the **co-benefits or adverse side-effects of mitigation** in terms of various others objectives such as air pollution and health, energy security, energy access, employment, biodiversity conservation, water use, etc. In general the study of co-benefits has been carried out outside the cross-model studies referred in table 1.1. It typically involves specific models, which can take the characteristics of transformation pathways derived from integrated models as inputs, to derive the implications of these pathways in terms of others objectives: air pollution, biodiversity, etc. However specific cross-model studies tackle the issue of co-benefits like the LIMITS study, which includes an assessment of energy security issues for major countries in the context of long term mitigation scenarios (Jewell et al., 2013). Eventually, others recent studies have carried out integrated analyses of multiple objectives which is a new trend in integrated research. For instance McCollum et al. (2013), as part of the Global Energy Assessment (GEA) carried out by IIASA, uses a cost-effectiveness approach to assess the interactions at global scale between climate mitigation, air pollution and energy security policies. Bollen et al. (2010) addresses similar issues but uses a single encompassing tool to perform a global cost-benefit analysis of the three concomitant classes of objectives. In both studies, the conclusions converge towards the idea that climate change mitigation offers a synergistic basis to meet air quality and energy security objectives.

1.3 Some limitations of state-of-the-art integrated studies

Recent cross-model studies and their insights synthesized in chapter 6 of WG III contribution of AR5, represent an important progress in our understanding of transformation pathways and climate change mitigation issues. A large endeavor has been carried out to provide much finer analysis, with a focus on (i) the regional breakdown of action, (ii) the timing of action and (iii) the role of key technologies. Each dimension has been analyzed in greater details to improve policy relevance: *Stage accession* or *frag-*

mented action scenarios reflect more realistic future regional articulation; *delayed action* scenarios sheds light on the practical objectives to be reached in the medium run; and alternative technology scenarios provide details about the technological strategies to implement. In addition multi-model studies have made it possible to take benefit from the richness of the model tool box to yield more robust insights.

However, one can identify scope for further improvements by noting specific limitations of existing integrated studies at two levels:

- Crucial issues about transformation pathways especially important for policy-making are still insufficiently addressed. It is especially required to widen the cost-efficient paradigm and the three flexibilities issue in order to mainstream mitigation issues in the design of sustainable development and low carbon transition strategies.
- From a methodological viewpoint, despite important recent progress, it is still needed to improve uncertainty management regarding the diversity of models internal structure.

The reminder of the section details these two types of limitations.

1.3.1 A set of insufficiently addressed issues

Central AR5 studies of transformation pathways represent a very useful set of **benchmark cost-efficient mitigation scenarios** in perfect economic environment with alternative timing and breakdown of action and a focus on energy technologies, carbon dioxide removal solutions or else land-use implications. However they can not on their own provide sufficient insights to help designing sustainable development and low carbon transition strategies for the real sub-optimal world. That's why in AR5, central transformation scenarios are completed with analysis about market failures and pre-existing distortions, societal change, co-benefits and the interaction with other sustainable development objectives. However, these topics can not be studied on the side only, and should be somehow mainstreamed in transformation pathways scenarios to improve the policy relevance of integrated assessments. To take just two examples, taking into account structural market failures such as labor market rigidities (Guivarch et al., 2011) or the opportunity of complementary policies beyond carbon prices (Waisman et al., 2012), changes drastically the estimations and profiles of mitigation costs and provides more useful insights for real world policy-making. In addition, the nature of the future development pathways in terms of "material" content is the first driver of emissions and energy demand. Therefore, beyond analyzing pure carbon price-based

mitigation pathways at the margin of BAU economic development frontiers, there is an issue to mainstream alternative assumptions about development patterns in transformation pathways scenarios, in order to design consistent sustainable low carbon strategies (Shukla et al., 2008).

We can further structure our diagnosis about state-of-the art scenarios limitations along three dimensions:

- The drivers of final energy demand and the “material” content of economic development
- The interaction between technical systems and macroeconomic mechanisms and the transition in a second-best world
- The articulation of policy levers beyond carbon prices to reach simultaneous climate and non-climate objectives

1.3.1.1 The drivers of final energy demand and the “material” content of economic development

The cost-efficient approach of mitigation scenarios in perfect economic environment leads to focus on technological strategies to decarbonize energy carriers to the detriment of the detailed analysis of final energy demand drivers and the energy intensity of GDP. However, there is in practice important market-based potential of decoupling energy consumption and GDP along multiple underlying pathways. This potential should be more deeply analyzed beyond aggregated energy efficiency and energy intensity considerations. In addition, the energy content of GDP is an aggregated result of the “material” content of the economic development path, which is further an indication of its sustainability. Exploring the details of energy demand drivers is required to identify the synergies between mitigation and sustainable development pathways.

At the highest level, mitigation pathways can be described as the articulation between the decarbonization of energy supply, the increase share of low-carbon energy carriers in end-use sectors and the decrease of final energy use. These complementary drivers of mitigation are usually illustrated through Kaya’s equation. One important issue in mitigation studies is to assess the relative role of these drivers in magnitude and across time. AR5 studies provide aggregated results about the trade-off between reduction in carbon intensity of energy and reduction of energy intensity of GDP (Krey et al., 2014). In addition, studies acknowledge the crucial role of energy intensity in global mitigation: *“Finally, an important finding illustrated by our results is the paramount importance of energy efficiency and behavioral and other measures to limit energy demand.*

These measures not only reduce the cost of the transformation, but can also hedge against the risk that low stabilization targets might become unattainable when following a high emission pathway to 2030 in the near term.” (Riahi et al., 2015).

However in practice there is a much higher emphasis on technological issues of energy decarbonization to the detriment of the drivers of final energy demand. Just looking at scenarios designs confirms this idea: scenarios contemplate detailed alternative conditions about power generation technologies and energy resource availability but very few alternatives about energy intensity of GDP⁴. The evolution of end-use sectors and demands is actually not the subject of extensive analysis. Neither demand patterns nor energy technologies at the level of end-use sectors are usually addressed. The standard treatment of this issue is through an aggregated energy efficiency coefficient. One study linked to EMF27 explores energy efficiency issues with a focus on rebound effects sorted in three types: direct, indirect and macroeconomic (Sugiyama et al., 2014). Nevertheless, the lens of rebound effects as such is too limited for a detailed assessment of energy demand drivers. The authors also mention that most models can not track specific energy services. In addition, models implement contrasted strategies to yield energy intensity decline: *“Decomposition of the transportation sector down to a service level for a subset of models reveals that to achieve energy efficiency, a general equilibrium model tends to reduce service demands while partial equilibrium models favor technical substitution.”* Finally no robust conclusions arise and the dynamics of aggregated energy intensity seem a “blind spot” of models.

On the other hand, energy supply, and power generation especially, are more understood and assessed subjects. Technical and economic issues are simpler because often reduced to a least-cost problem under technical constraints. Conversely, energy demand and its relation to GDP is a much wider and uncertain subject and refers to broader technical, economic and social considerations across multiple sectors. One important adverse-effect could be that mitigation studies may overemphasize strategies pertaining to the decarbonization of energy (like CCS and biomass penetration) instead of energy intensity decline, whereas the latter may have underestimated cost-efficient potential⁵.

Eventually, reducing energy intensity issue to aggregated coefficients can lock in the reasoning on mitigation pathways along a BAU economic development frontier. In order to open the box of alternative material content of development and improve

⁴For instance EMF27 study (Kriegler et al., 2014) considers at least five alternative energy technologies an resources scenarios and only one low energy intensity scenario.

⁵It may not be by chance that most multi-sector CGE models consider more potential of energy intensity decline - through structural changes of final demand for instance, whereas single output models only rely on aggregated energy efficiency.

the analysis of energy demand drivers, it is required to discuss minimum mechanisms underlying aggregated energy intensity of GDP. It could include consumption patterns, structural changes, dematerialization⁶, inter-industry matrix, space planning, resulting demand for energy services and finally technologies and infrastructures to supply for these energy services. Mainstreaming alternative assumptions about development patterns in transformation pathways scenarios finally requires to have the appropriate variables in modeling tools.

1.3.1.2 Transition in a second-best world

Most models among the integrated models used for the AR5 assess the transformation of the E3 system in perfect economic environment. This means that markets, mechanisms, policies assume a perfect implementation, deployment and effects. On the contrary, the issue of the transition, understood as the impact of temporary disequilibriums and second best settings, must be studied to understand the possible inefficiency and barriers to the climate policies as defined in those models.

Such barriers include market inefficiencies (e.g., the no-regret options potential, the energy efficiency gap), market disequilibriums, in particular under-employment of factors and resources. In addition, the interaction with other policy (such as measures targeting economic growth, to cite but one) may need to find a form of compromise between climate and other objectives. The imperfect expectations in the real world may lead to inefficient technological, economic and development choices that would negatively impact the performance of climate policies.

However, in those studies, these mechanisms are often absent (e.g., intertemporally optimizing models with perfect expectations). This has been underlined in the AR4 already (Metz et al., 2007, Summary for Policymakers): *“Most models use a global least cost approach to mitigation portfolios and with universal emissions trading, assuming transparent markets, no transaction cost, and thus perfect implementation of mitigation measures throughout the 21st century.”*

1.3.1.3 The articulation of policy levers to reach multiple objectives

In most integrated models exercises, climate policies are reduced to the implementation of either an emission target or a carbon price. Climate policy can be accompanied by technology specific policies targeting given levels of penetration or phasing-out implemented under the form of technical constraints.

⁶GDP content in basic materials for instance

In a perfect economic environment, emission targets and carbon prices are equivalent and trigger the least-cost mitigation pathways. Therefore there is theoretically no need to look for alternative or complementary policies if the objective is to assess the least-cost trajectory. As soon as one departs from this first best setting, there is an issue to explore further policy packages because the sole carbon price may not yield the least-cost pathway any more. Such an approach is finally required when one wants to depart from benchmark scenarios in first best setting to explore real world situations.

For instance, implementing a carbon price in fact implies economic transfers between economic agents whether explicit or not. In pure optimizing models, the question makes no sense because the carbon price corresponds to the shadow price of the emission constraint. However in multi-sector recursive dynamic CGE models considering initial tax distortions, these economic transfers play a crucial role. The way carbon tax payments are recycled in the economy has a key impact on GDP costs of mitigation. However this issue is not really mainstreamed in transformation pathways.

In addition, complementary policies beyond carbon prices may help to decrease mitigation costs in case of the existence of market failures pertaining to the investment in infrastructures for instance or imperfect labor markets.

More largely, there is a need to mainstream climate policy in general development policies.

1.3.2 What management of uncertainty in cross-model studies?

One critical epistemological aspect with integrated modeling rests with the **management of uncertainty**. State-of-the-art mitigation scenarios indeed “*involve a wide range of technological, socioeconomic, and institutional trajectories*” (IPCC, 2014a, Summary for policymakers, Working Group III), even to reach similar GHG concentration targets in the long run, which indicates a high level of uncertainty about future pathways. For instance, “*estimates of the aggregate economic costs of mitigation vary widely and are highly sensitive to model design and assumptions as well as the specification of scenarios, including the characterization of technologies and the timing of mitigation. [...] Mitigation scenarios that reach atmospheric concentrations of about 450 ppm CO₂eq by 2100 entail losses in global consumption [...] of 1 % to 4 % (median: 1.7 %) in 2030, 2 % to 6 % (median: 3.4 %) in 2050, and 3 % to 11 % (median: 4.8 %) in 2100 relative to consumption in baseline scenarios that grows anywhere from 300 % to more than 900 % over the century.*”.

In a modeling context, one can distinguish several epistemological components of uncertainty. The first one is uncertainty about a “*model’s quantities*” (Boulanger and Bréchet, 2005) or “*parameters*” (Oreskes and Belitz, 2001), which are the numerical

parameters and initial conditions also described as input assumptions. Values of elasticities or technological costs fall in this category. The second one is uncertainty about model “conception” (Oreskes and Belitz, 2001). Within this category, Boulanger and Bréchet (2005) further distinguishes “model’s pertinence” and “model’s structure”. *Pertinence* refers to the scales and boundaries of the model: spatial and time scale, level of aggregation (i.e., granularity), the selection of the key variables to be included⁷. *Structure* refers to the type of representation of the mechanisms at play. It concerns the relationships between variables, in particular the functional forms used and causal chains represented.

In addition, managing uncertainty generally includes two complementary aspects often mixed up in practice (Saltelli et al., 2008): *sensitivity analysis* and *uncertainty analysis* itself. However the difference is actually clear: uncertainty analysis aims to quantify directly the state of uncertainty about model features (inputs and conception) and thus on model results - in order to reduce the uncertainty *per se*, whereas sensitivity analysis only seeks to relate uncertainty about model outputs to the uncertainty about upstream model features and input assumptions. Therefore sensitivity analysis does not help to *decrease* uncertainty *per se* but it is very useful to control the propagation of uncertainty within models and better understand model behaviors.

Developing the sensitivity analysis of scenarios outcomes to both input assumptions and model conception is a crucial endeavor to improve modeling insights. In practice though, sensitivity analysis mainly deals with model parameters and input assumptions. There exists advanced statistical methods to deal with parametric uncertainty to perform a sensitivity analysis⁸. These customary methods are crucial parts of the “menu” for a serious evaluation of single models and are widely performed (Webster et al., 2008; Stern, 2007). However, dealing with sensitivity analysis on the model’s structure and/or pertinence is at the same time much more difficult and much less explored in the existing literature (Schwanitz, 2013). The uncertainties targeted, point at the choice of variable and interdependence represented in the model as well as the form to model specific mechanisms. They relate to the conceptual vision of the system embodied in the model whereas input assumptions deals with the model quantification of it. Sensitivity analysis on model structure is thus hard to perform with a single model and requires model comparison exercises, with contrasted models internal structures. However it requires both a cross comparison of detailed model

⁷For instance the uncertainty around the relevant level of technological detail has been at the core of the bottom-up - top-down controversy of energy-economy models.

⁸Variance-based approaches for instance, often combined with Monte Carlo sampling of the multi-dimensional input space (Sobol, 2001).

structures and to harmonize enough input assumptions across models which may be tricky in practice. Meta-analysis (Fischer and Morgenstern, 2006; Barker et al., 2006) and recent cross-model studies seek to go in this direction.

In addition reducing uncertainty *per se* may not be the relevant goal for long term E3 scenarios. Anyway, as Kydes et al. (1995) puts it, in no case running a model makes it possible to decrease uncertainty : “Applying formal modeling techniques, which are heavily influenced by exogenous assumptions about costs and rates of technical progress or efficiency improvement, provides conditional projections that help illustrate the implications of assumptions without reducing the underlying uncertainty *per se*”. In fact the only way to reduce uncertainty *per se* - about the right parameters and model features - may be “to improve our scientific knowledge” (Boulangier and Bréchet, 2005)⁹. However long term modeling and “prospective” analysis is another topic. Because the future of the E3 system is intrinsically unknowable and uncertainty is at some point irreducible (Oreskes and Belitz, 2001). All the more so as the E3 system is open and part of it concerns human behaviors and decision making which are largely “Terra Incognita” (Schwanitz, 2013). Finally, model validation in the strictest sense - that is assessing the capacity of a model to *forecast* E3 pathways - may not be relevant for integrated models evaluation.

Rather, model evaluation and uncertainty analysis should be adapted to the overall goal behind scenarios building. In the perspective of a stakeholders process for policy-making, the hierarchy of model features and assumptions should be guided by the perception of the plausibility of the “story” carried out by the model. In practice Jasanoff (2010) describes the exercise as a “three-body-problem” involving “scientists, scientific knowledge, and committees translating science into policy relevant forms”. In an other context, model conceptual relevance will be assessed by its ability to reproduce stylized facts about the system represented or part of it (Wilson et al., 2013). It can also be a mix of different objectives. In any case, model evaluation and uncertainty analysis are continuous, progressive and dynamic efforts.

Furthermore, what general diagnostic can one make about uncertainty management in cross-model studies? First of all, relying on a large panel of models with contrasted structure provides favorable conditions to explore uncertainty about model conception. In addition, the diversity in model structure and input assumptions and the scenario design based on expert judgments should provide a good order of magnitude of general uncertainty about future pathways. However, efforts are still to be

⁹In economics the advancement of scientific knowledge is based on the critical analysis of existing theories leading to the validation or refutation of these theories and the formulation of more advanced or new theories.

made to improve knowledge about the sensitivity of results to input assumption and modeling choices.

Just as AMPERE and EMF27 framing papers (Kriegler et al., 2015b, 2014), model intercomparisons target policy analysis in the first place to the detriment of uncertainty analysis as such. As previously explained, studies are based on designing scenarios crossing policy, technological and economic conditions, which are further implemented in the range of models. Only key socio-economic assumptions like GDP and population are usually harmonized across models in baselines. Then studies seek to enhance robust policy insights across the range of model results. The underlying assumption is that the range of results reflects a reasonable range of model input and structural assumptions. However limited efforts are made to relate input and structural assumptions to results. Anyways, input assumptions about costs, elasticities, etc. are loosely harmonized across models so that it is difficult to isolate the differences in model structure. Therefore these studies are not capable as such to relate, for instance, the level of mitigation costs to given costs assumptions or structural model features. Yet, this type of analysis is essential for a robust scientific process. Finally very few elements concern the uncertainty about the scope of models. Typically carbon revenues recycling has a paramount influence on mitigation costs and a comparative assessment should be performed between models which can or can not represent this key policy feature.

In addition, two types of companion analysis exist that expand uncertainty analysis. First, studies relying on a smaller number of models like Luderer et al. (2012) or focusing on a specific topic like energy efficiency (Sugiyama et al., 2014). Luderer et al. (2012) provides a sharper diagnostic of the link between model features and respective cost profiles. In Sugiyama et al. (2014), results about energy intensity of GDP are related to alternative representation of rebound effects in models. Second, model top-down diagnostics studies like Kriegler et al. (2015a). The objective is to characterize general models behaviors through their response to standardized policy set-ups - like a given path of carbon price - along key aggregated indicators such as the level of abatement, mitigation costs, the level of structural change in the energy system and the relative reliance on decarbonization of energy and energy intensity reduction. Such diagnostics can provide indications to sort models according to their general response and are certainly useful to improve the management of the model toolbox. But it can only provide a weak answer to the key question of *“why results differ between models”*.

Eventually, we can conclude that important improvement have been made in the uncertainty management in cross-model studies. However focusing on top-down

model diagnostics to complement policy analysis as suggested by [Kriegler et al. \(2015a\)](#), may impede the necessary efforts to improve uncertainty management, especially in terms of sensitivity analysis about model structure and scope. To do so it is first required to endeavor towards separating parametric from structural sensitivity exercises. In addition it means to expand the bottom-up approach and come back to the diversity of internal visions of models.

1.3.3 The status of integrated models

We have attempted in this section to point at some limitations of state-of-the-art integrated studies upon two dimensions: the scope of analysis and the management of uncertainty in a multi-model context.

As far as the limitations of the scope of study are concerned, we have identified three key directions insufficiently explored. First of all, studies insufficiently assess the interplay between low carbon pathways and the “material” content of a sustainable development pattern. However it seems a prerequisite to understand how climate policies can be mainstreamed in sustainable development strategies. Elements such as the type of consumption patterns, structural changes, dematerialization, urban planning, infrastructure, etc. are key components of alternative development pathways as well as the deep drivers of final energy demand. However in integrated studies, the discussion is mostly reduced to the aggregated energy intensity of GDP. Finally, most scenarios concern mitigation pathways at the margin of given development pathways and emphasize the issue of the decarbonization of energy supply and the penetration of low-carbon energy carriers to the detriment of energy demand issues. Second, central scenarios do not discuss the real-world economic, institutional, behavioral barriers and distortions which however have important impacts on policy cost assessment. Furthermore scenarios do not explore the possible economic co-benefits of climate policies and complementary policies such as policies targeting labor markets or efficient infrastructure. Third and consequently, cross-model studies do not assess the articulation of policy levers to reach climate and non-climate targets because in perfect economic environment carbon prices deliver least-cost pathways.

We do not mean here that existing integrated studies have limited value because of the insufficiently addressed issues highlighted above. We rather mean that the topics mentioned about development patterns, second-best or transition issues should take a larger space in integrated assessments and forms of articulation have to be found with more technology-oriented scenarios in perfect economic environment.

Aside from issues of scope, uncertainty management in cross-model studies raises

questions. The usual positioning is to consider that the range of alternative model structures and input assumptions available provide a reasonable basis to derive robust policy insights from simulations. Then these policy insights are based on *ex post* statistical analysis of model outcomes around aggregated indicators such as Kaya's variables, energy mix, actualized costs and carbon prices. Nevertheless no careful analysis is carried out about the links between model outcomes and both model features and input assumptions. However cross-model studies should somehow be the place for robust model's structure and pertinence sensitivity and uncertainty analysis. To give just one example of potential biases involved, one might ask: What tells that the diagnosis on low carbon technology issue for global mitigation is robust to uncertainties on consumption patterns or else on transport infrastructures if models do not represent these elements? Finally top-down model diagnostics can provide indications to sort models according to general response but can only provide a weak answer to the key question of "*why results differ between models*".

On the whole, our diagnostic finally sets the question of the status of modeling tools themselves in relation to their conception and internal structure which ultimately condition their domains of competence. Because one can first wonder to what extent some issues remain insufficiently addressed because of models limited conception - through missing variables and mechanisms - before biases due to scenario design. In addition, standard top-down diagnostics may provide information about general model response but actually hide the conceptual diversity of models. Finally there is a need to assess the structural diversity of models in order to diagnose the domain of competence of the toolbox regarding the limitations of existing studies and as a prerequisite for more robust uncertainty analysis, especially linked to alternative model conception and structure.

1.4 Existing taxonomies of models: incomplete user guides?

Historically, different types of models from different scientific communities have co-existed to answer to different types of questions. Nowadays, energy-economy and integrated assessment models (IAMs) result from the integration and hybridization of traditional modeling approaches and are used to answer a common set of questions about technical, environmental, economic and social aspects of transformation pathways. However, model conception can still be very different from one integrated model to the other, so that models are not equally relevant to address the different aspects of transformation pathways. In addition, one can question the race towards more integration within models and the wishful thinking to address all issues in an

integrated manner with a satisfying uncertainty management of modeled pathways.

In this last section of the chapter we thus get into the detail of modeling practices in order to synthesize the state-of-the-art taxonomies of energy-economy integrated models. The main question we want to address is to what extent existing taxonomies already represent satisfying user-guides to manage the structural and conceptual diversity of integrated models.

1.4.1 From the *bottom-up* and *top-down* “tribes” ...

The development of historical modeling paradigms has resulted from the progress of computer performance: general equilibrium models based upon [Arrow and Debreu \(1954\)](#), activity analysis relying on [Koopmans \(1951\)](#) or system dynamics in the line of [Forrester \(1961, 1968\)](#). The IPCC Second Assessment Report (SAR) ([IPCC, 1995](#)) reports in the early 90’s the existence of various modeling tribes. Compact growth models dedicated to more theoretical considerations, while two complementary strands of models were designed for the study of empirical issues: *top-down* and *bottom-up* models. The opposition between top-down and bottom-up models has structured the controversy on mitigation costs in the 1990s ([IPCC, 1996](#), Chapters 8 and 9). This dichotomy has shaped the discussions until very recently. The properties of these historical paradigms are well known and succinctly recalled below.

First, the upholders of the **bottom-up** approach focus on the competition between energy technologies for both energy supply and end-use demand. Bottom-up models are usually formulated in a partial equilibrium setting around energy markets and accounts for energy flows, technological constraints and production capacities with physical metrics. In practice, they embark exogenous macroeconomic scenarios driving demand for energy services (value-added, household’s income, etc). Then, these models compute the reaction of energy systems to exogenous shocks (carbon tax, technology-specific capacity constraints like nuclear phase out, etc) in terms of technological changes (substitutions between existing technologies and technological progress) and demand for investments. Therefore bottom-up models build mitigation scenarios that are articulated around low carbon and energy efficient technology portfolios. Within bottom-up models, two subgroups are usually distinguished. In the tradition of MARKAL ([Fishbone and Abilock, 1981](#); [Fishbone et al., 1983](#)), the models of *energy system optimization* compute the least intertemporal costs energy systems under the constraint to meet exogenous energy service demands. Conversely, *energy system simulation* models compute the dynamics of energy markets resulting from myopic sequential behaviors for supply and demand. Like in optimization models, energy

system simulation models are fed with exogenous demands for energy services. The Edmonds-Reilly model (Edmonds and Reilly, 1983) has been a pioneer in this second category.

On the contrary, the **top-down** approach focuses on economy-wide implications of energy and climate policies. Therefore, top-down models seek to represent the economy as a whole and thus have been alternatively termed as “full-economy” or “total analysis”. Historically, different sub-categories of top-down models have emerged. First, *compact* models were developed to assess intertemporally optimal strategies to address climate change challenges. These models build on the initial work of W. Nordhaus who further developed the DICE model (Nordhaus, 1993a) which is the emblematic model of this category. Such models are based on a *compact general equilibrium optimal growth* framework (one single composite sector) including emissions or energy as production factors in a very stylized fashion. These models are used to perform global cost-benefit analysis (compute optimal intertemporal welfare through the trade-off between growth, mitigation and climate change damages) and study optimal climate policies along optimal economic paths. Alternatively, more detailed models including several economic sectors were developed to assess the implications of climate policies in terms of structural change, competitiveness or employment. These *multi-sector models* have followed at least two contrasted routes. *Macroeconometric* models represent the economy in disequilibrium highlighting Keynesian effects of the short run especially. Producers and consumer behaviors are based on econometric relationships estimated on past trends. On the other hand, *computable general equilibrium models* (CGE) are rooted in Arrow-Debreu general equilibrium theory applied to macro-economic accounting data. In neo-classical CGE models, the behaviors of producers and consumers are micro-founded¹⁰ and are generally calibrated on a given year benchmark database¹¹. The GREEN model (Burniaux et al., 1991) developed by OECD is the “father” of many multi-sector CGE models used to assess climate policies. Thus, compact and multi-sector top-down models are identical in their scope: both cover the overall economy. The fundamental difference between compact and multi-sector top-down models lies in the inter-sectoral relationships: they are implicit in compact models and represented by means of an input-output framework in multi-sector top-down models. Furthermore mono and multi sector top-down models usually differ in the formulation of foresight and economic choices. In compact mod-

¹⁰ The *micro-foundations* of CGE models refer to the theoretical corpus of microeconomics analyzing consumer and producer behaviors in theoretical “idealized” settings. Therefore, the term of micro-foundations does not recover the same empirical reality that a bottom-up model may exhibit.

¹¹ More complex econometric techniques have alternatively been applied to estimate producer’s and consumer’s behaviors (Jorgenson and Wilcoxon, 1993).

	Historical families	Archetype	Examples
BU	Energy system simulation	Edmonds-Reilly	MiniCAM, AIM-enduse, ASF, IMAGE, TIMER, MEDEE, MEDPRO, Petro, Poles
	Energy system optimization	Markal	Times, DNE21+, MESSAGE, TIAM-World, TIAM-ECM
TD	Monosector GE optimal growth	Rice	Dice, MIND, Response
	Multisector CGE optimal growth	Goulder	PET, WIAGEM, EDGE, GEM-E3, G-CUBED
	Multisector CGE simulation	GREEN	GEMINI-E3, GTAP-E, World-Scan, ENV-LINKAGES
	Macroeconometrics	CMDM	LBS World Model, Inforum national models, Mesange

Table 1.2: Historical families and top-down - bottom-up dichotomy

els, an omniscient agent optimizes welfare intertemporally under perfect foresight. In contrast, multi-sectoral models generally include agents with myopic or limited foresight and models are formulated in a recursive dynamic fashion. We find the same kind of *optimization - simulation* dichotomy as for bottom-up models which has been in practice a source of misunderstanding. We come back to this point later on. Finally, a few models combine the multi-sector CGE approach with an intertemporally optimizing framework (Goulder and Schneider, 1999).

Table 1.2 summarizes the historical families of models through the bottom-up - top-down dichotomy. The sub-categories explained above are included. For each category, related emblematic models are provided, as well as other examples of models formerly or currently in use.

The **limits of traditional bottom-up and top-down models** have been identified since the 1990s. Part of the criticism towards the bottom-up approach targets the realism of micro-economic behaviors of economic agents in choosing and adopting technologies. For instance Zhang and Folmer (1998) highlights that traditional bottom-up models underestimate transaction costs and market or behavioral failures in technology adoption. However, the main drawback of these models is the absence of interactions of energy pathways with the rest of the economy that would affect the structure, direction and rate of economic growth through different channels. We can mention among others: the impact of energy prices and technical change on energy service demand (rebound effect), on structural change and the general growth engine; the impact of energy trade; the impact of energy investments which may crowd

out investments in non energy sectors, etc. Conversely, top-down models have been first criticized for their lack of technological explicitness (Grubb et al., 2002). Production and consumption trade-offs are represented by means of aggregated production and demand functions which embed stylized substitution possibilities between macro economic production factors such as capital, labor, energy and other intermediary inputs. Furthermore, top-down models struggle to embark specific technical information and to assess technology specific policies beyond economy-wide price policies such as carbon taxes. Beyond technological explicitness, top-down models lack flexibility beyond current production and consumption patterns. Whether it be through econometric functions (macroeconometrics) or production functions calibrated on one given year cost-shares (neo-classical CGE), top-down models struggle to represent unprecedented¹² technical routes as well as induced technological change. Finally, they are limited in the exploration of unprecedented deep decarbonization pathways characterized by deep induced technological and structural changes.

The bottom-up - top-down classification is somehow rooted in the controversy of the early 90s regarding the estimation of mitigation costs (Hourcade et al., 1996a). The debates have concerned at least the need for a “full economy analysis” to capture economy-wide effects, the nature and metric of economic costs and the existence of “no regret” options. The latter has originated the idea of the optimism of bottom-up models against the pessimism of top-down models regarding mitigation costs. The analysis of mitigation costs from a strict technological viewpoint has actually enhanced the existence of such “no regret” options which are mitigation options with negative costs¹³. The response of economists has been that if such “low hanging fruits” existed, market forces would automatically make agents to pick them (Sutherland, 2000). Economists have alternatively assumed the existence of “hidden” costs or market failures: transaction costs, constraints to access to capital, etc. The controversy is better known as the “efficiency gap” (Jaffe and Stavins, 1994a).

Beyond such debates, as soon as the SAR, the modeling community has acknowledged that the frontier had been less and less clear between the two classes with grow-

¹² Indeed, the standard use of CES production functions in neo-classical CGE modeling requires to calibrate the CES function with exogenous constant elasticity of substitution and initial cost shares, based on the assumption of optimizing behavior. In this sense, the elasticity of substitution cannot vary with the conditions of the economic system or the changes in behavioral patterns. As such, all the possible technical pathways are contained within the calibration (which can lead to unprecedented shares of capital, labor and energy for instance. However, this substitution has to follow the smooth CES substitutability conditions. Since the CES elasticity is supposed to be calibrated on past data, the technical substitutability derives from past behavior. Therefore, the representation of “unprecedented” behavior may be difficult with this modeling specification.

¹³ No regret options occur when additional investment costs are more than compensated by the energy bill decrease.

ing attempts of **hybridization** between bottom-up and top-down approaches (IPCC, 1996, Chapter 8). Already in the late 1970s, Manne and Richels with the ETA-MACRO had included a feedback loop between the energy system and the macroeconomy (Manne, 1977; Manne and Richels, 1990) thus creating a “full economy model” detailing the energy system. The ETA-MACRO model is the precursor of an important class of integrated models as we will see later. The Third Assessment Report reaffirms the limits of the BU - TD dichotomy for three reasons (IPCC et al., 2001, Chapter 7): “While useful, this taxonomy has its limits. First, differences in parameter values among the models within a given category may be more significant than the differences in model structure across categories. Second, many differences emerge between the theory underlying a particular model group and the actual models. Third, most models are hybrid constructions linked to provide greater detail on the structure of the economy and the energy sector.” (Hourcade et al., 1998). The report also gives some clues about the hybridization issue but without dealing with it in depth: “A hybrid approach sheds light on both the economic and technological aspects of reducing energy-related CO₂ emissions, but it does have its drawbacks. Consistent results require that a hybrid approach remove all the inconsistencies across the linked models. This process is often cumbersome and time consuming.” After being at the core of discussions, the hybridization debate seems to have been relegated to the background in the Fourth Assessment Report (AR4). First the report uses the BU - TD classification to sort mitigation costs estimations without referring to hybrid models. Second, the hybridization debate is eclipsed and outdated by the parallel debate on endogenous technological change (ETC) (Barker et al., 2007).

Endogenous technological change (ETC) acknowledges that technological change can not be reduced to an exogenous phenomenon but is partly endogenous to the economic and political context (Grubb et al., 1995). Therefore, models have started to endogenize part of technological change and have made it dependent upon socio-economic variables such as prices, R&D investments or cumulative production (learning by doing)¹⁴. On the whole, AR4 and others studies (Löschel, 2002) have highlighted the significant effects of representing ETC on mitigation costs for both bottom-up and top-down models.¹⁵

Interestingly, despite intense debates, the landscape of models has not changed

¹⁴The types of ETC features generally differ between TD and BU models. ETC in TD models has usually been inspired by the theories of endogenous growth (Lucas, 1988; Romer, 1990) and is represented in compact models as a biased technological change towards better energy efficiency of GDP resulting from R&D investments (Jaffe et al., 2003). In contrast, BU models have usually included learning-by-doing mechanisms at the technology level but R&D mechanisms are also possible.

¹⁵including learning effects show much lower mitigation costs compared to exogenous representations. The results with R&D mechanisms are less unequivocal because of opportunity costs of R&D investments and crowding-out effects.

much in 15 years. One just has to compare the taxonomy of the SAR or the one provided by Kydes et al. (1995) in the mid 1990s with that of Edenhofer et al. (2006) to note the repetitive mention of the 5 families highlighted in table 1.1: *energy system simulation models*, *energy system optimization models*, *optimal growth models*, *multi-sector CGE models* and *macroeconomic models* (or other top-down simulation models). The problem is that such “boxes” had become less and less relevant to characterize hybrid models. For example putting a model like IMACLIM-R, which is a hybrid model by construction, inside the CGE box (Edenhofer et al., 2006) - because it is actually based on a multi-sector CGE framework - runs the risk to eclipse the decisive modeling choices carried out to give up the standard top-down toolbox and the endeavors of the modelers to represent energy sectors as in energy system models. In addition, choosing a box for models of the ETA-MACRO family like MARKAL-MACRO or MESSAGE-MACRO is clearly irrelevant because these models are precisely a combination of a bottom-up energy system optimization model and a top-down optimal growth model. In this case the BU - TD dichotomy is irrelevant and even confusing. This way the MESSAGE-MACRO modeling framework has been alternatively labelled bottom-up (Edenhofer et al., 2006) or top-down (van Vuuren et al., 2009) depending on the authors. Such limits of the traditional taxonomies led the modeling community to advocate the abandon of the bottom-up - top-down terminology to qualify models (Fischedick et al., 2011).¹⁶ Eventually the terminology is absent of the Fifth Assessment Report and all models used to generate scenarios fall under the generic category of “large scale **integrated models**” (Edenhofer et al., 2014).

¹⁶ Fischedick et al. (2011) wrote a box on the topic in the IPCC special report on Renewable Energy sources: “Box 10.1 - Moving beyond top-down versus bottom-up? In previous IPCC reports (e.g., Herzog et al., 2005; Barker et al., 2007), quantitative scenario modelling approaches were broadly separated into two groups: top-down and bottom-up. Although this classification may have made sense in the past, recent developments make it decreasingly appropriate. Most importantly, (i) the transition between the two categories is continuous, and (ii) many models, although rooted in one of the two traditions (e.g., macro-economic or energy-engineering models), incorporate important aspects of the other approach and thus belong to the class of so-called hybrid models (Hourcade et al., 2006; van Vuuren et al., 2009).

In addition, the terms top-down and bottom-up can be misleading, because they are context dependent and used differently in different scientific communities. For example, in previous IPCC assessments, all integrated modelling approaches were classified as top-down models regardless of whether they included significant technology information (van Vuuren et al., 2009). In the energy-economic modelling community, macro-economic approaches are traditionally classified as top-down models and energy-engineering models as bottom-up. However, in engineering sciences, even the more detailed energy-engineering models that represent individual technologies such as power plants, but essentially treat them as ‘black boxes’, are characterized as top-down models because they do not assume a component-based view, which would be considered bottom-up. For these reasons, the modelling tools used to generate scenarios in this review are simply referred to as large-scale, **integrated models**.”

1.4.2 ... to the “jungle” of integrated models

The AR5 thus enforces the idea that we have passed from a few well identified modeling *tribes* to a *jungle* of integrated models. The maintenance of distinct model families was formerly associated with the idea that each model family was designed to answer to specific questions. For instance, energy system optimization models were developed to design economically optimal energy systems in given exogenous contexts (macroeconomic contexts in particular). Multi-sector CGE models aimed at assessing the economy-wide impacts of price-based climate or energy policies. Therefore, have we managed to design the “missing models” called for by Grubb (1993)?

To add to the confusion energy-economy models are merged with Integrated Assessment Models (IAMs) under the umbrella of “large scale integrated models”. Integrated Assessment Modeling (Weyant et al., 1996) originally refers to the broader modeling concept of linking human systems (energy system, economy, etc.) with other systems involved in climate change: ecosystems and land-use, atmosphere and ocean, etc. In practice IAMs include the representation of land-use, the carbon cycle and the climate response and impacts beyond energy-economy interactions. However in mitigation studies, the climate impacts of IAMs are usually not included in the analysis and some energy-economy models have been developed towards representing land-use issues. Finally the frontier between IAMs and energy-economy models is not really clear in mitigation studies, thus the generic label of *integrated models*.

In this new context of integrated models, an implicit change of paradigm has occurred because **all models are supposed to address a common issue: the transformation pathways in the context of climate change mitigation**. This change of paradigm forces to classify the diversity of existing integrated models with a common set of criteria. The AR5 proposes the following criteria:

- Economic coverage and interactions and especially the opposition between “full” and “partial economy” models
- Foresight and the opposition between “perfect-foresight” and “recursive-dynamic” models
- Representation of trade regarding the substitutability of goods
- Model flexibility, i.e the easiness to change course and to transform the energy-environment-economy system
- Sectoral, regional, technology and GHG detail

- Representation of technological change and exogenous vs. endogenous technological change

Individual authors like [Krey \(2014\)](#) adopt similar criteria enlarging economic coverage to *system boundaries*, talking about *heterogeneities* for all kind of details and *solution concepts* for foresights and partial vs general equilibrium issues.

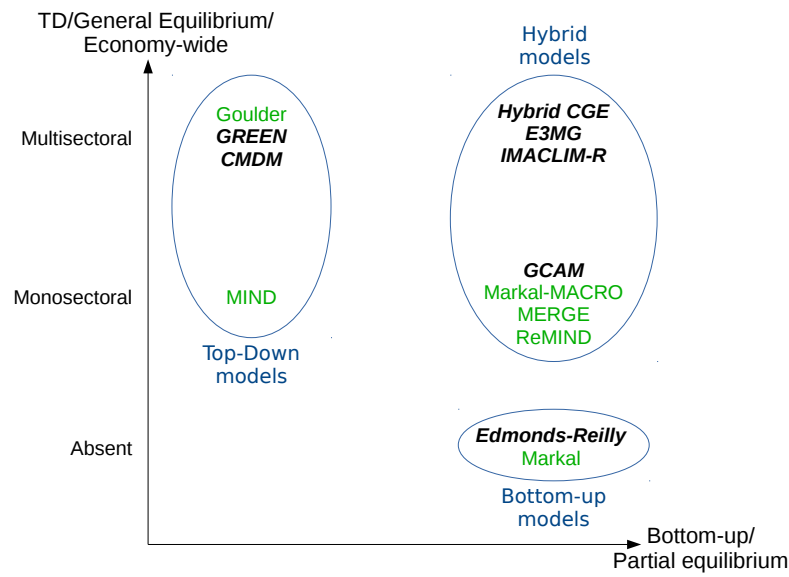
Without surprise, we first find again something close to the two historical axes of opposition: full vs. partial economy¹⁷ (part of the bottom-up - top-down dichotomy) and optimization vs. simulation. Moreover, the full vs. partial economy criterion is often identified with general vs. partial equilibrium (GE vs. PE) criteria, although they refer to different criteria. Macroeconometric models are full economy models but not equilibrium models for instance. Beyond the issues of trade and technological change, the remaining criteria are reduced to the questions of heterogeneity and flexibility. The heterogeneity concerns the level of detail of the picture painted in terms of technologies, sectors, regions and the flexibility assesses the easiness to induce changes to the picture. However, such criteria do not target the *nature* of the modeled inter-dependencies between the elements of the picture - technologies, economic sectors and agents, goods and factor markets, etc - and the resulting conditions of transformation of the picture. In fact, these criteria refer more to a top-down¹⁸ assessment of models consistent with recent model diagnostics ([Kriegler et al., 2015a](#)). The flexibility of models is assessed with respect to global Kaya variables and energy system structural changes but it gives no clue about the nature of the *deep mechanisms*¹⁹ that cause different level of flexibility.

In practice though, it is true that very few models are designed as hybrid constructs from the start. Indeed, most integrated models result from the combination of existing models so that integrated models can be characterized in relation to the “parents” models. It enables to draw a more precise state-of-the art taxonomy of integrated models - more or less explicit in the literature - which we have attempted to reproduce in figure 1.1. In this figure, models are classified along three dimensions including the two historical axis. First models vary in the degree to which they include bottom-up features (along the horizontal axis, in abscissa), top-down features (along the vertical axis, in ordinate). Within top-down we distinguish between monosectoral and multisectoral

¹⁷ However, integrated models are supposed to incorporate a minimal level of feedback between energy systems and economic growth. Incidentally, arises the issue of appraising the extent of such feedbacks in the case of partial economy models.

¹⁸ In this sentence, the term of phrase “top-down” refers to the approach of model assessment and not to a type of model.

¹⁹ We use the term “deep mechanisms” to refer to the mechanisms at play rather than just on the evolution of Kaya aggregate values. Thus, for instance, we want to characterize the modalities of technology substitution to understand energy system structural changes.



Legend

Intertemporal optimization model / Perfect foresight
 Simulation model / Recursive dynamic / Myopic

Figure 1.1: A taxonomy of integrated models

models as explained earlier. Also, models vary in the way they are expressed and resolved. This is referred to as solution concept or mathematical formulation. Most commonly, it is either intertemporal optimization with perfect foresight (in green), or recursive dynamic models (in black and italic), which can be called simulation models with myopic expectations (mostly applied to bottom-up models) or recursive dynamic with myopic foresight.

It is easy to locate the historical families in this figure. Traditional bottom-up models (*MARKAL* and *Edmonds-Reilly*) are situated in the lower right quadrant with the distinction of their mathematical formulation. Conversely, traditional top-down models are on the top left quadrant with the distinction between optimal growth models (mono-sectoral and intertemporal optimization - *MIND*), multi-sector CGE models recursive-dynamic (*GREEN*) or in intertemporal optimization (*Goulder*) and multi-sector macroeconometric models (*CMDM*).

Integrated models are situated in the top-right quadrant of the figure because they combine a minimum of bottom-up and top-down features. It is then possible to identify at least three sub-families of integrated models as resulting from the evolution from a particular historical model or based on the combination of two historical models:

- **The models of the ETA-MACRO family** - MARKAL-MACRO, MESSAGE-MACRO, MERGE, REMIND, etc - which combine a monosector optimal growth model including energy as a macroeconomic production factor with an energy system optimizing model. These models are classified as full economy and general equilibrium.
- **Models of energy system simulation augmented with some feedback loops with macroeconomy** (GDP essentially). The GCAM model for instance falls in this category. These models are classified as partial equilibrium and partial economy even if it can be debatable for the latter criteria because GDP - as full economy indicator - is endogenous in the model - even if all markets are not solved: capital, labor, composite good, etc.
- **Multi-sector recursive-dynamic full economy models with improved representation of technical systems.** This last family is further divided between macroeconometric and CGE models.

Such a general taxonomy certainly gives a first idea of the landscape of integrated models. Nevertheless it says very little about the deep linkages between technical systems and the structure, direction and pathway of economic growth embodied by models. Understanding such deep mechanisms and to what extent they differ between models is however a prerequisite to be able to relate the span of model outcomes to the diversity of model structures and underlying visions of the E3 system. Technically, the former is furthermore a prerequisite for the management of structural uncertainty. More largely, it is crucial for the policy value of model-based assessments (O'Neill and Nakicenovic, 2008; Hedenus et al., 2013). A top-down methodology to class models according to their aggregated responses makes it possible to draw a synthetic diagnosis and is certainly a pragmatic option when time and resources are constrained. Nonetheless, it is undoubtedly the sign of some renouncement vis-à-vis the comparative assessment of deep structures of models. However, a bottom-up approach that looks deeper inside models - around hybridization issues especially - is required in the end, even if the task is hard and requires to "*know all models in detail*". Besides, we are firmly of the opinion that such a bottom-up approach is crucial to improve our common knowledge about integrated modeling, assess the relative relevancy of models regarding specific questions and be able to create innovative modeling tools. That's why the remainder of this chapter and the next two chapters attempt to make a step in this direction. Last subsection explores the issue of *hybrid* modeling and enhances the fuzziness of the concept.

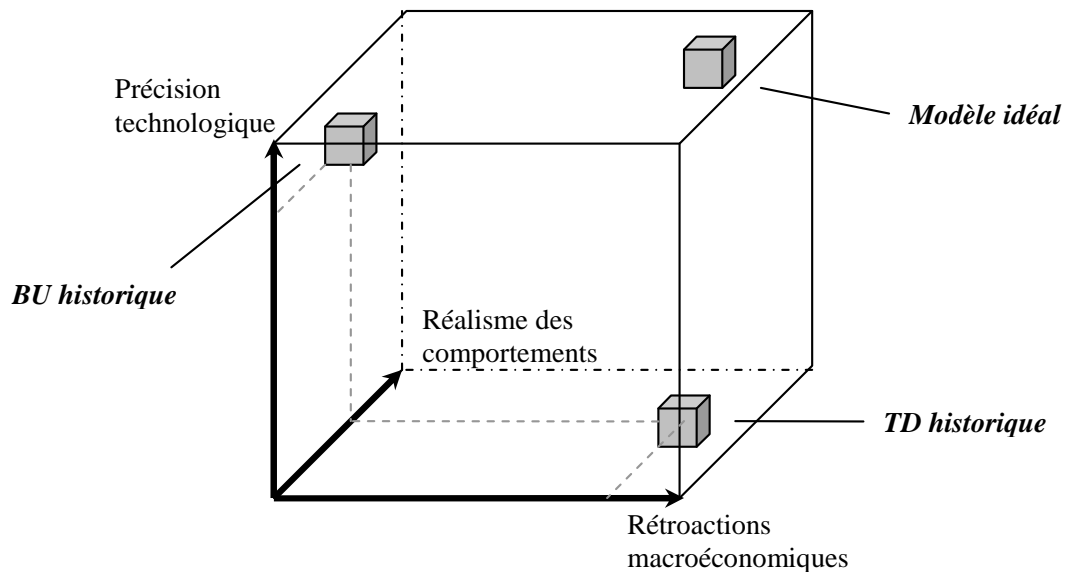


Figure 1.2: Expansion on historical model taxonomy (adapted from Jaccard et al. (2003); Hourcade et al. (2006); Crassous (2008))

1.4.3 The fuzzy class of emerging hybrid models

At the core of integrated models characterization is the concept of bottom-up - top-down hybridization. If the issue dates back to the IPCC SAR at least, few studies have tackled it in depth.

M. Jaccard proposed a three-axis framework to assess the efforts towards the combination of bottom-up and top-down features within models (Jaccard et al., 2003). In this perspective, an E3 model should perform well along the three following dimensions: (i) *technology explicitness*, (ii) *preference incorporation* and (iii) *equilibrium feedback*. Similar schematics have been retained in Hourcade et al. (2006) and Crassous (2008) with slight differences. We reproduce in fig. 1.2 the schematic of Crassous (2008) which distinguishes: (i) *technology explicitness*, (ii) *behavioral realism* and (iii) *macroeconomic feedbacks*.

Conventional bottom-up models perform well in technology explicitness but generally includes low behavioral realism and no macroeconomic feedback. Behavioral realism is higher in models from Edmonds-Reilly family though because they include real behavioral functions compared to the intertemporal optimizing program of an omniscient planner in MARKAL-type models.

Conversely, conventional top-down models include full macroeconomic feedbacks

but are not technology-explicit and include insufficient behavioral realism. The richness of macroeconomic feedbacks differs a lot between compact growth models and multi-sector models though. In addition, in most historical top-down models, behaviors are aggregated, stylized and have a weak empirical basis. For instance, although they are micro-founded, behaviors in neoclassical CGE models are those of optimizing representative agents with polar expectations (either myopic or perfect).

Furthermore, the schematic allows to build a large definition of hybrid models (Hourcade et al., 2006): *“We define hybrid models, therefore, as those BU or TD energy-environment models that have made at least one modification that shifts them substantially away from their conventional placement in the cube of [fig. 1.2]. Some hybrids originated as BU models, some as TD models, but all hybrids have characteristics that differentiate them significantly from conventional TD and BU models.”* The ideal hybrid model would be placed in the very top right corner of the cube and would be technology-explicit, includes realist behaviors and full macroeconomic feedbacks.

Jaccard’s approach thus provides a mental map which makes it possible to assess integrated models. This approach also suggests directions to improve the modeling toolbox towards an hypothetical “ideal” model. While doing so, it is important to keep in mind to avoid the pitfall of trying to build a model in a 1:1 scale, where everything is represented. In addition, the chosen criteria (the three axes), although close at first sight to those of the AR5 or fig. 1.1, are actually different in nature. The criteria in fig. 1.1 targeted technical features whereas Jaccard’s criteria target the nature of the resulting representation. Moreover, beyond the “quality” of bottom-up - top-down integration, the approach adds the dimension of behavioral realism which has been a common challenge for bottom-up and top-down approaches both. The development of the CIMS model (Bataille et al., 2006) for instance, illustrates the endeavors to include behavioral realism in a bottom-up model.

Besides, we have so far considered models as stand-alone tools, but hybrid modeling architectures can also be based on the coupling of several - in general two - existing models. Böhringer and Rutherford (2008) actually distinguishes the two cases: the *soft-link* approach which links two existing models on the one hand, and single models that integrate both bottom-up and top-down features on the other hand. *Soft-links* are already mentioned by Kydes et al. (1995). We will come back to the issue of soft-links in chapter 3. Most hybrid models - usually defined as individual models - fall under the second category.

Beyond Hourcade et al. (2006), few authors have tried to characterize the degree and quality of bottom-up and top-down integration within integrated models. For example, Böhringer and Rutherford (2008) distinguishes two degrees of integration:

- A *weak* integration where one type of model - bottom-up or top-down - is completed with "*reduced form*" representations of the other. Models of the ETA-MACRO family fall in this category. The MACRO model is in this case considered a reduced form of a top-down model.
- A *strong* integration to "*capture both technological details and economic richness in a single mathematical format*". Market equilibrium formulated as mixed complementarity problems (MCP) (Böhringer, 1998) and the SGM model fall in this category. This category is sometimes referred to as *hard-link*.

Crassous (2008) makes the same kind of distinction splitting between "*pseudo-hybrid*" and "*hard-links*". For Crassous (2008), "*hard-link*" also includes very different models such as E3MG, IMACLIM-R and CIMS .

In the end, the concept of *hybrid model* remains a fuzzy one. The last paragraph provides a global mental map and the distinction of two degrees of possible hybridization. But this should be only a starting point since the criteria used for model assessment need to be expanded to be able to compare existing modeling approaches precisely and continue improving the model toolbox. Moreover, the hybrid concept and the consideration of different degrees of hybridization should be extended with caution and in precisely bounded cases not to be misleading. We attempt to clarify further the hybridization issues in the context of multi-sector CGE models in chapter 3.

Eventually, the debates around bottom-up - top-down dichotomy - and hybrid models - and the debates on technological change (whether exogenous or endogenous) have somehow **eclipsed the more crucial conversation that should happen about the growth engine of models based on the interplay between macroeconomic dynamics, the detailed economic structure and underlying technical systems** (see for instance Chapter 11: The dark matter of economic growth in Grubb (2013)). In a word this refers to the question of modeling the *material content of economic growth*. That's why in this thesis and in chapter 2 especially, we attempt to make a step in this direction by developing a guide of integrated models based on this more encompassing conversation. This will make it possible (ii) to explore back the usual controversies - bottom-up - top-down hybridization, technological change - from a new and sharper angle and (ii) to develop crucial issues usually overlooked in the literature around mid-term dynamics especially.

1.5 Conclusion

This chapter attempts a critical synthesis of state-of-the art integrated studies and of technical assessments of integrated models and enhances several conclusions:

- Since AR4, the production of scenarios about global transformation pathways has boomed and cross-model studies involving numerous teams and models have become a new standard for scenario generation. Such a research effort has provided key new insights in AR5 to support policy making. In particular, scenarios provide a sharp assessment of the role of key technologies such as CCS, renewables and bioenergy to meet climate targets. In addition, studies explore realistic and detailed staged accession scenarios, the regional breakdown of costs and analyze at length the consequences of delayed action. On the methodological side, the multi-model framework enables more robust uncertainty analysis. Eventually, with the view to mainstream climate policies in broader sustainable development strategies, AR5 includes an assessment of the co-benefits of mitigation for others sustainable development objectives.
- However it seems we are only in midstream in terms of the issues addressed. Benchmark least-cost mitigation scenarios in perfect economic environment should actually be supplemented with further research efforts in at least three complementary directions. First, with studying the interplay between mitigation and sustainable development patterns around the drivers of final energy demand especially. Second, key market, institutional, behavioral barriers, distortions and frictions should be mainstreamed in the analysis in order to highlight the possible economic co-benefits - beyond non-economic co-benefits - of mitigation and study the conditions of the transition towards low carbon societies. Third and consequently, scenarios should include broader policy-packages beyond carbon prices to reach simultaneous climate and non-climate objectives.
- In addition, multi-model studies under exploit the potential for more robust uncertainty analysis about model conception. Most studies focus on the policy insights that are robust to the range of models used but do not really analyze why results differ across models. Moreover, top-down diagnostics of models do not really help to clarify the links between results and models alternative internal structure, which is however a prerequisite for robust uncertainty analysis.
- Finally, the status of the models themselves is at stake, vis a vis their conception and internal structure. However, usual taxonomies struggle to reflect the diver-

sity of model conception and the deep mechanisms involved beyond a top-down classification based on a few - sometimes misleading - criteria. Beyond, the concept of hybrid modeling provides an important mental map to assess integrated models but remain insufficient as such to reveal the deep energy-economy interactions within models. Eventually, more advanced guides seem to be needed to both better assess the potential of existing models and be able to improve the toolbox.

Chapter 2

Energy-economy transformation pathways: a three-dimension guide of integrated models

2.1 Introduction

“Already, they can greatly improve our understanding of the nature of the climate change problem in all its complexity. Developing such models further, and subjecting them to the kind of rigorous critique and discussions now faced by the climate models themselves, should be a high priority.” Grubb (1993)

The previous chapter has shown how existing taxonomies of integrated models may not be sufficient tools to characterize the structural diversity of state-of-the-art models and their embodied vision of the energy-economic system. This task is becoming even more complex as the hybridization of historical paradigms is today the norm within so-called *hybrid* models. However, managing models internal vision seems a prerequisite to rightly assess their areas of competence - and identify the remaining gaps vis a vis new key questions to be explored.

Historical criteria of classification are actually not sufficient any more to assess integrated models as they are most of the time hybrid constructions - incorporating bottom-up and top-down features - and often capturing economy wide interactions. Beyond, a too general discussion about models *heterogeneity* (Krey, 2014), *details* or *flexibility* is insufficient to reveal models specific vision of energy-environment-economy (E3) dynamic interactions. For instance, it is required to further characterize the *type* of details and interdependence modeled. In addition, it needs clarifications about

how model flexibility results from a specific pattern of interactions between economic behaviors, technical constraints and market forces.

The present chapter aims to contribute to the common understanding of the integrated models “ecosystem”. The idea is to build a cross-cutting model guide that enables to scrutinize, then structure and compare their internal vision based on their precise technical features¹. This guide of existing models also aims to provide a “mental map” to develop new models or to improve the existing ones in specific directions. In addition, models internal vision is analyzed under the angle of the nature of the economic trajectories represented and their underlying “material content”. Said differently it amounts to the encompassing question of the representation of transformation pathways about the carbon-energy content of economic growth, which is a key cross-cutting question of energy-economy integrated modeling.

Previous taxonomies (Jaccard et al., 2003; Hourcade et al., 2006; Crassous, 2008) have enhanced the historical filiation to class models in a small number of families. Instead, we open the box of integrated models just as they are technically described in model documentations. In practice, behind the apparent complexity and variety of models, one can find constitutive commonalities and components or “building-blocks” constitutive of all integrated models (such as growth engine, markets of goods, energy conversion sectors and technologies, end-use energy sectors, etc.). Furthermore, models differ in the type of representation for each block as well as the nature of the linkages between blocks. Some of them represent given components explicitly with a great amount of details, some of them in a very compact or even implicit manner. Eventually, one given model’s internal vision can be derived from the specific assembly of given building blocks.

The model guide we develop in this chapter derives from the preliminary painstaking study of a sample of global models which complete list is shown in table 2.1. This preliminary work, reported in appendix A, has consisted in (i) building a table to collect, organize and interpret the detailed technical features of models by breaking them down into identified building-blocks and (ii) in performing the technical analysis for a sample of representative models. Building a detailed analysis grid to capture and compare models detailed structure and inform this analysis grid for key state-of-the-art models, are relevant research output *per se*. This especially provides key material to perform further multi-model analysis. However, as the the devil is often in the details, we derive from this preliminary analysis a more compact and conceptual guide which makes it possible to capture the key aspects about a model’s vision. For clarity

¹As a complement to an approach based on models general behavior like in Kriegler et al. (2015a) or as a prerequisite for further model diagnostics.

Model	Up-to-date documentation	Other documentation
AIM/CGE	Fujimori et al. (2012)	Fujimori et al. (2014)
AIM/END-USE	Kainuma et al. (2003)	
BET	Yamamoto et al. (2014)	
CIMS	Tu et al. (2007)	Nyboer et al. (2000)
CMDM	Barker et al. (1980)	
DICE	Nordhaus (1993a)	
DNE21+	Akimoto et al. (2010)	
EC-IAM	Zhu and Ghosh (2014)	
Ecofys	Deng et al. (2012)	
Edmonds-Reilly	Edmonds and Reilly (1983)	
E3MG	Barker et al. (2014)	
EPPA	Paltsev et al. (2005) Older version: Babiker et al. (2001)	Technical change: Jacoby et al. (2006) Forward-looking version: Babiker et al. (2009, 2008)
ENV-LINKAGES	Chateau et al. (2014)	
ETA	Manne (1976)	
ETA-MACRO	Manne (1977)	
FARM	Sands et al. (2014a)	Sands et al. (2014b)
GCAM	Edmonds et al. (2010)	Wise and Calvin (2011)
G-CUBED	McKibbin and Wilcoxon (1999)	
GEM-E3	E3MLAB (2010)	
GEMINI-E3	Bernard and Vielle (2008)	Older version: Bernard and Vielle (1998)
GRAPE	Kurosawa (2006)	
GREEN	Van der Mensbrugge (1994)	Burniaux et al. (1991)
GTAP-E	Nijkamp et al. (2005) ; Truong et al. (2007)	Burniaux and Truong (2002) ; McDougall and Golub (2007)
GTEM	Pant (2007)	
KEI-LINKAGES	Lim and Kim (2012)	
IEEJ	Matsuo et al. (2011)	
IMACLIM-R	Bibas et al. (2015)	French version: Bibas (2013)
IMAGE	Stehfest et al. (2014)	
INFORUM	http://inforumweb.umd.edu/Models.html	
LBS	Mabey et al. (1997)	
MARKAL	Loulou et al. (2004)	Fishbone and Abilock (1981) ; Fishbone et al. (1983) ; Seebregts et al. (2002)
MARKAL-MACRO	Manne and Wene (1992) ; Hamilton et al. (1992)	Kypreos (1996)
MARIA23	Mori (2012)	Mori (2000)
MERGE	Manne and Richels (2005) ; Manne et al. (1995)	(Kypreos and Bahn, 2003, MERGE-ETL)
MESSAGE	Messner and Strubegger (1995)	
MESSAGE-MACRO	Messner and Schrattenholzer (2000)	
MIND	Edenhofer et al. (2005)	
MINICAM	Brenkert et al. (2003)	
PET	Dalton et al. (2008)	Dalton and Goulder (2001)
PHOENIX	Sue Wing et al. (2011)	
POLES	LEPII-EPE and ENERDATA s.a.s. (2009)	
PRIMES	Capros et al. (1999)	
R&DICE	Nordhaus (2002)	
REMIND	Luderer et al. (2013)	Equations: Bauer et al. (2011) Older versions: Luderer et al. (2011, 2010)
RICE	Nordhaus and Yang (1996)	
SGM	Brenkert et al. (2004)	Edmonds et al. (2004)
TIMES	Loulou et al. (2005)	TIAM: Loulou and Labriet (2008) TIMES-VTT: Koljonen and Lehtilä (2012)
TIMER	De Vries et al. (2001)	
WEM	IEA (2013)	
WIAGEM	Kemfert (2002)	Kemfert (2005)
WITCH	Bosetti et al. (2009, 2007)	
WorldScan	Lejour et al. (2006)	

Table 2.1: Models references

reasons, we only detail the final model guide in the core of the text². The reminder of the chapter is built as follows: section 2.2 introduces the model guide; section 2.3 to 2.5 detail the axes of analysis and section 7.5 concludes.

2.2 A three-dimension guide of integrated models

Our guide is oriented by the encompassing question about how models represent the carbon and energy content of future economic growth. This *parti pris* is aligned with state-of-the-art studies which assess transformation pathways through the lens of energy and low carbon technologies, Kaya's decomposition of emissions and macroeconomic costs (GDP or consumption costs) of climate policies. Even if some models were not originally built to answer to this global question, they end-up contributing to answer it. It is also important to understand for what part of the question the different models are really legitimate. The question of the carbon-energy and material content of future economic development is also crucial to assess the conditions of the transition towards low carbon sustainable development pathways.

We propose to characterize integrated models along three complementary dimensions or axes which make it possible to synthesize the nature of the techno-economic pathways generated:

- (1) the pattern of **interdependence**
- (2) the **transformation drivers**
- (3) the type of **transition dynamics**

The articulation between these three axes in shaping energy-emissions-economy pathways can be schematically represented in the emissions/output plan (fig. 2.1).

²We will refer to appendix A for technical details whenever necessary. The interested reader can also refer to appendix A for more technical details and models specific assessments.

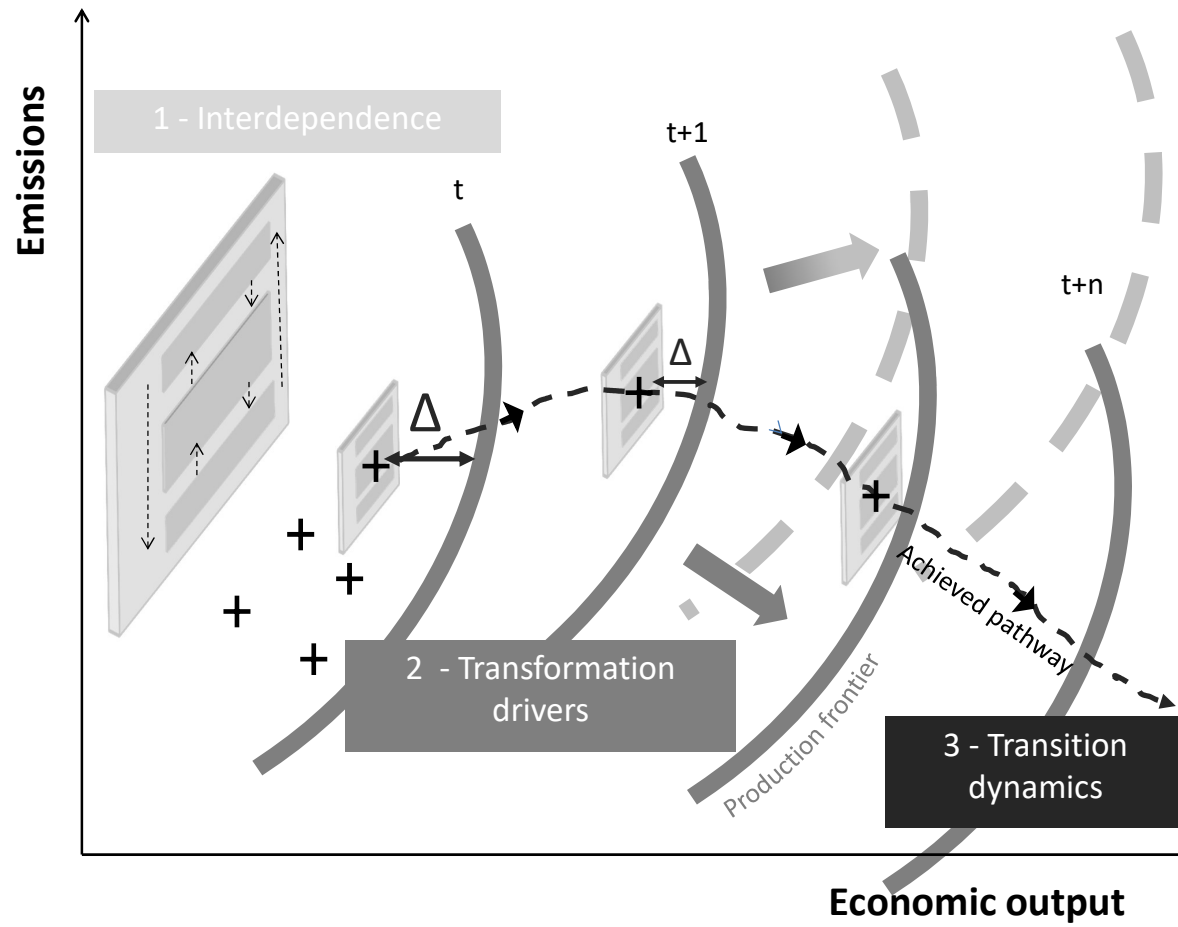


Figure 2.1: A three axes decomposition of energy-emissions-economy pathways

The pattern of *interdependence* first refers to the “snapshot” of the system modeled at each point in time, especially characterized by the inter-linkages between and within the energy system and the broader economy. It underlies each state of the economy (represented by a single point in the emissions/output plan). Second, the *transformation drivers* determine the trend evolution of the system through the drivers of evolution of the “production frontier” across time. The instantaneous production frontier corresponds to the curve at time t of “potential” - maximum - economic output depending on the target of current emissions level. It embodies the level and direction of potential economic growth. Eventually, the *transition dynamics* yield the achieved techno-economic pathways through both the effective inter-temporal determination of the production frontier and the dynamic “gap” between the achieved state of the economy and the current production frontier (see Δ in fig. 2.1). The nature of the techno-economic pathways depicted by models results from the dynamic interplay between these three components.

The pattern of interdependence not only includes the issues of system boundaries and the level of detail: it further refers to the *type* of linkages between the components of the system and the feedback loops contemplated. One key issue with integrated modeling has been to capture the linkages between the energy system and economic growth. Hybrid models have brought solutions to bridge the bottom-up - top-down gap but via pretty contrasted levels of inclusion of energy systems within the broader economy, resulting in contrasted pictures. Thus the interdependence axis includes the linkages between energy and economic growth but goes beyond to characterize the nature of technical systems representations on the one hand - technological explicitness, etc., the representation of the global economy in terms of economic sectors, production factors and economic operations on the other, and the cross-cutting articulation between the energy system, end-use energy sectors and the global economy. In a word it corresponds to the complete **accounting framework** contemplated in terms of physical and economic flows and stocks and their interdependence.

The transformation drivers are the forces of change of the production frontier and mainly allude to the **growth engine**, the **technical change** and the drivers of broader **structural changes**. Briefly speaking, through the evolution of factors endowment (demography, capital accumulation, resources, etc.) and total factor productivity, the general growth engine moves the production frontier to the right in the emissions/output plan and determines the *level* of potential growth. Then technical change biases towards higher energy efficiency (in the most general sense), more efficient low carbon technologies or else broader structural changes determine the *direction* of the production frontier along the Y-axis and pull the production frontier to the bottom-right corner

of the figure. Figure 2.1 illustrates two possible directions for the production frontier: (i) the dashed direction corresponds to a carbon intensive pathway where little energy technical change and structural changes happen and may refer to a kind of BAU direction; (ii) conversely, the solid direction embodies significant changes towards more energy and low carbon efficient production and consumption patterns. Capital inertia further constrains the speed of technical change and of the vertical shift of the production frontier. In practice, most large scale energy-economy models growth engine is based on Solow's approach of exogenous growth. In addition, specific attention has been given to the issue of technical change in energy sectors. However, if many models claim to include **induced technical change** mechanisms beyond exogenous energy productivity gains, it in fact refers to a wide range of contrasted mechanisms in practice, from learning or R&D effects about specific technologies to attempts to endogenize the growth engine itself. Eventually, the evolution of consumers "preferences" and possible contrasted patterns of sector productivity gains are the ultimate drivers of structural changes and the "direction" of economic growth and represent key characteristics of the development pathway.

Finally, transition dynamics ultimately determine the achieved economic pathways. Achieved pathways results schematically from the inter-temporal determination of the production frontier combined with the dynamic gap between the achieved state of the economy and the current production frontier (see fig. 2.1). The inter-temporal determination of the production frontier first results from the interplay between the transformation drivers and the inter-temporal economic behaviors of economic agents. The type of **expectations** or **foresight** plays a key role in shaping inter-temporal dynamics. In addition, the intra-period gap to the production frontier has no tangible reality but represents a convenient manner to characterize the second-best nature of the realized states of the economy compared to the reference first-best production frontier. It further enables to assess the ultimate socio-economic implications to change direction towards low carbon economy. In practice, the nature of the gap to the production frontier results from the interplay between *economic behaviors* in the short run (type of expectations, optimizing behaviors or not, etc.) and *market forces* (perfect or imperfect markets, etc.) under current *technical constraints* (capital malleability, available technologies, etc.). However, these questions have been largely overlooked in integrated modeling and the gap to the production frontier is almost null for most models. This comes from the fact that these models stick to the paradigms of instantaneous first-best equilibrium and growth models of the long run. In particular, Solow's growth model supposes that the economy is in a state of instantaneous macroeconomic optimum along the "transition" towards balanced growth pathways. Following this paradigm,

most integrated models represent technical transitions at economic optimum and the economy remains on the production frontier along the achieved pathway.

The remainder of the chapter develops further the three axes of model assessment.

2.3 Axis 1: Interdependence, heterogeneity and accounting framework

As shown in section 1.4, economy-wide integrated models essentially follow three paradigms: (i) **models of energy system simulation augmented with some feedback loops with macroeconomy**, (ii) **aggregate optimal growth model coupled with a detailed energy system model** and (iii) **SAM based multi-sector models with improved representation of technical systems**. However the structure of interdependence between the energy system and the wider economy and the trade-off between technology details and macroeconomic comprehensiveness can vary a lot even within each model family. Therefore we propose here a cross-cutting analysis grid of the type of interdependence and heterogeneity captured based on several progressive criteria : (i) the feedback of the energy system on economic growth, (ii) the accounting framework of the model which captures the details of energy-economy interactions, (iii) the representation of energy end-use sectors and (iv) the technology explicitness for energy supply, conversion and end-use demand.

2.3.1 Feedback of energy on economic growth

The first issue tackled by the integration of models is the feedback loop linking energy to growth. Historical bottom-up models use as exogenous data for energy demand drivers (usually GDP) while top-down models usually disaggregate energy as a sector or factor contributing whose demand derives from the growth of all sectors. As previously mentioned, the issue is thus the feedback loop linking energy to growth, as the feedback linking growth to energy is present in most modeling approaches. In the context of integrated models, we can distinguish three levels of feedback of energy to growth: *no feedback*, *partial feedback*, *full feedback*.

In the **no feedback** case, economic growth is independent from technical systems: this is the typical situation of historical bottom-up models. Models from MARKAL family or historical Edmonds-Reilly family fall in this category. Economic growth is generated from an external model and the GDP pathway is used to derive energy services demand which are input of one or several energy system models. Energy models further describe the technical features and investments needs of the energy

system to satisfy the given levels of demand for energy services. These models, which reason with exogenous economic growth, can not assess the impacts of technical systems evolution on the whole economy. Some integrated models still rely on this paradigm: models from MARKAL family - TIMES, TIAM-WORLD, DNE21 - or in the tradition of Edmonds-Reilly - AIM/END-USE.

Conversely, in the **full feedback** case, economic growth depends on technical systems and technical systems are fully integrated into the economic system. Energy in the form of secondary or final energy, is a set of economic sectors or more simply a production factor as capital and labor. At the macro level, economic growth is generated by the endogenous combination of energy and other production factors and growth is thus sensitive to energy prices, energy volumes and productivity. A key feedback passes through energy sector costs (including labor and capital costs) which are accounted for in the macroeconomic balance. All integrated models that are "economically closed"³ fall in this category including models based on a general equilibrium framework in the broadest sense (REMIND, MARKAL-MACRO, MERGE, WITCH, EPPA, IMACLIM-R. . .) or not (E3MG). Furthermore, such models can capture key energy-economy effects such as the impacts of technical progress in energy sectors on economic growth or else the crowding-out effect of investments in energy sectors on the rest of the economy, etc.

In between, the **partial feedback** case includes any attempt with partial feedback. The emblematic case is the GCAM model in which energy sectors are driven by an exogenous GDP, which can be modified with an elasticity to energy prices. Several issues arise from this description: first, economic growth rests on energy and the description of the dependence of growth to energy is more complex than an elasticity (if such growth can be completely independent from energy patterns). Second, several physical flows are missing, that represent the link between energy and economy. In particular, investment in capacities and energy production requires inputs that are not accounted for. Eventually, it results in a very stylized representation of energy-growth relationships.

³ A closed model can refer to two notions. The first one is an "economically closed" where all inflows and outflows are accounted for (eventually as going in and out of the system towards other regions. The second one is a closed economy model as opposed to an open economy model, where closed means that there is no trade with the rest of world. In this document, we used the term closed as synonymous to "economically closed", therefore following the first definition.

2.3.2 Accounting frameworks and economic sectors

The level of feedback of energy to economic growth is the first layer to understand how models represent the energy and carbon content of economic growth. However it is required to explore further the more precise pattern of inter-linkages between energy sectors, non-energy sectors and the wider economic structure. It actually corresponds to the general **accounting framework** of the model and the interdependence structure of physical and economic flows.

Just as the three main models types recalled in introduction, integrated models generally follow three routes. In partial equilibrium settings focused on energy markets, the accounting system is directly inspired from an energy balance which can be interpreted as an **Input-Output framework limited to energy sectors**. In this view, the accounting framework details the interdependence between energy sectors, i.e. the energy transformation processes, and the pattern of final energy consumption. However, the system is only balanced for energy flows - and sometimes agricultural commodities like in G_{CAM} - (in physical and economic units) but not balanced for non-energy goods, production factors (labor and capital) and macroeconomic income flows. This framework includes the representation of capital and labor content of both detailed energy supply (biofuels, fossil fuels, power sector, etc.) and end-use sectors (transport, industry, buildings, etc.). Eventually the whole energy system is driven by GDP which determines end-use sectors activity levels. This category includes models such as G_{CAM}, C_{IMS} or T21. Some models in this category evolved from the bottom-up paradigm, and are in the process of integrating more of the economic sphere (such as G_{CAM}) or focus on technology with detailed and empirical dynamics (such as C_{IMS}). System dynamics models (such as T21) aim at integrating many interactions between different spheres, however the economic sphere remains reduced compared to models based on SAMs.

Passing from partial to full economy models (including both GE or macroeconomic models), there is a **fundamental distinction between models based on a single macroeconomic composite good and models based on a multisectoral framework** with inter-industry relationships and a detailed Social Accounting Matrix (SAM). Models such as REMIND, MARKAL-MACRO, MERGE, WITCH fall in the former category whereas multi-sector CGE models like EPPA, IMACLIM-R or the E3MG macroeconomic model fall in the latter category.

Within single macroeconomic sector models, the global economy rests on the production of a single composite good which can be either consumed or invested. At the macro level, the accounting framework is that of a collapsed SAM with a unique

economic sector and an implicit representative economic agent which simultaneously produces, consumes and invests that good. Moreover, the composition of the economy can be somehow detailed through the production scheme of the macroeconomic good which usually relies on a nested-CES production function, combining general capital, labor and global energy at the upper level⁴. Furthermore the energy factor in the larger sense is singled out and broken down in different energy services or energy carriers and ultimately linked to a detail energy sub-module. Conversely, multi-sector models are based on an expanded SAM including explicit energy and non-energy sectors, the inter-industrial relationships via an I-O table of intermediary consumption, sector specific generation of value added as well as the structure of final demand of goods and services. In addition, these models usually detail the income distribution between several representative economic agents.

Consequently **single and multi-sector models embody intrinsically different visions of the economic system**. On the one hand, single-output models embody an aggregated and abstract growth phenomenon with a GDP composition based on *juxtaposed* contributions of macroeconomic factors and “sub-sectors” indistinctly, with a specific focus on energy sectors. In this view, the economic system is the simple combination of *independent* “sub-sectors” and macroeconomic factors, the former being weighted for by their value-added without referring to any explicit economic markets or operations of production-consumption. Therefore, the information about intermediary consumption is lost and the inputs to production are the primary factors only⁵. In this setting, value added coincides with the level of output and the difference between production, value added and income is blurred⁶. On the other hand, multi-sector models embody the vision of an economic system based on inter-industrial relationships and the interaction of economic agents and sectors. Furthermore they include explicit markets of goods (energy and non-energy) and factors with explicit production-consumption operations. In addition they reflect real-world accounting at sector level with the distinction between intermediary consumption and value-added. Therefore, the separation between the consumption of goods (even immaterial goods)

⁴The macroeconomic formulation of such models can be summed up with the two following equations:
 $Y = C + I + EC$ and $Y = f(K, L, E)$

⁵Formally the macroeconomic balance should be written as $GDP + IC = C + I + IC$, where IC is all the intermediate consumption (and production). The sum of the products sold in an economy is $GDP + IC$: when I buy a tomato, I pay the cost of the energy, water and transportation to produce it and not only the wage and profits of the peasant and of the merchants. Then IC can be cut from both sides of the equation only insofar as all the intermediate products can be aggregated in purely monetary terms, and thus tends to provide a somewhat incorporeal vision of the growth engine in which certain physical flows (such as materials) throughout the economic system tend to become invisible.

⁶ $Y = GDP$

and the rental of production factors (chiefly labor, capital and scarce resources) is clear. Eventually, these models yield a desegregated representation of the two sides of GDP: value-added and final consumption.

In fact compact growth models have been originally developed for specific aggregated analysis. The combination of a compact growth model with an energy optimization model through the energy factor has been the first means to link a detailed energy system to economic growth. The framework has originally been justified for its convenience (Manne and Wene, 1992): *“The linkage between MARKAL and MACRO is based upon one key idea – the concept of an economy-wide production function. Just as with any other attempt at understanding the complexities of an economic system, there are pros and cons in adopting this particular abstraction. The principal advantage is that this enables us to make a direct link between a physical process analysis and a standard long-term macroeconomic growth model.”* The question is furthermore to what extent this abstract vision of economic growth is reasonable if models are being expanded to capture finer economic structure and sector breakdown. Because as Manne and Wene (1992) adds, this framework can not capture sectors interplay and key propagation effects: *“The principal disadvantage is that we cannot make a direct connection with the interindustry composition of demands.”* Besides, there is no convenient way to implement given market specifics because the value-added contribution of sectors within the CES, refers to both production and consumption operations without representing the two aspects independently.

In practice though, single sector models do not detail the value-added contribution of non-energy sectors like basic industry, manufacture, agriculture or services but at best detail a set of energy services broken down to key end-uses (transport, industry, building, etc.) like in MARKAL-MACRO. In any case, **everything remains as if the energy system was “hung” to global economic growth whose direction and content (in terms of non-energy sectors) is not represented.** Because the bulk of value-added remains not distributed in different sectors and concentrated in macroeconomic labor and capital primary factors. *A fortiori*, these models do not capture explicit patterns of final demand for goods between households consumption, capital formation and trade. Eventually single sector models do not represent patterns of income distribution between heterogeneous institutional sectors (households, government, etc.)⁷.

In a word one key drawback of the single sector approach is the general difficulty to represent the ultimate drivers of the demand for energy services and the links to economic growth. It actually corresponds to the characteristics of development patterns such as structural changes (non-energy sectors breakdown of GDP), dematerialization

⁷They could use Gini assumptions but it would have no feedback on the economic system.

(structural changes towards less material intensive economic activities), consumption patterns (diets, articulation mobility - housing, etc), income distribution, trade patterns, etc. Conversely multi-sector models are based on accounting frameworks that facilitate the capture of these issues. The multi-sector representation of energy and non-energy sectors, the inter-industry relationships, the detail basket of households consumption make it possible to represent the “direction” of economic growth. Nevertheless the main advantage of the compact growth approach is to facilitate the expansion of the energy system representation through detailed energy carriers and technological processes. The multi-sector approach generally comes with more limited desegregation of energy sectors and technology explicitness (see section 2.3.4).

2.3.3 End-use energy sectors

One key issue across integrated models is the representation of end-use energy sectors. We have especially highlighted in section 1.3.1 the importance of end-use sectors dynamics for the assessment of low carbon pathways and the actual insufficiency of state-of-the-art studies on this aspect. The end-use sectors are the economic sectors which consume final energy to provide energy services or useful energy which further contribute to generate value-added. In energy studies, three main end-use sectors are usually distinguished: transport, industry and buildings. These end-use sectors are the drivers of energy demand and the energy intensity of GDP.

The diagnostic about energy end-use sectors representation in **traditional bottom-up and top-down models** is clear. Bottom-up models focused on energy supply, first take final energy demand as exogenous so that end-use sectors are not represented. In bottom-up models detailing energy demand, the representation of end-use sectors is based on **activity variables** which embody levels of demand for energy services broken down in different uses (transport, industry, buildings). This activity variables are expressed in physical units (e.g *pkm* for transport, *tons* for industry products, *m2* for buildings, etc.) and are derived “offline” based on GDP projections. Then the bottom-up model computes the technology portfolio, technology specific capital and infrastructures and the final energy demand needed to supply for the energy services. Therefore by definition bottom-up models of energy demand include a comprehensive representation of end-use demand sectors. On the other end of the spectrum, traditional top-down models (CGE, CDM) can single out individual end-use sectors (transport, industry) in the multi-sector matrix. For each individual sector, the activity level corresponds to the level of output of the sector expressed in \$ (pseudo-

quantity), implicitly related to a level of energy service⁸. In top-down tradition, final energy demand is finally derived from sector output by means of aggregated “KLEM” production functions combining final energy with others goods, labor and capital. Eventually, the dynamics of activity levels is comprehensively captured by general equilibrium mechanisms.

Passing to the case of integrated models, **the picture is more blurry and diversified and thus need to be clarified**. In partial equilibrium models loosely linked to GDP like GCAM, the representation of end-use sectors follows the traditional bottom-up approach and a comprehensive representation of end-use sectors. However, the dynamics of activity levels is exogenously prescribed from GDP projections and is not endogenous to general equilibrium mechanisms. **For SAM-based multi-sector models** the general structure of top-down tradition applies, however the representation of end-use sectors has been expanded towards a better representation of activity levels, infrastructures and technologies. In particular, activity levels are broken down in finer individual uses and may be expressed with physical units. This break-down can be implemented by means of further sector desegregation or advanced production function within one given economic sector detailing the combination of different specific end-uses. For instance a transport sector can be described with an advanced production function breaking down different transport modes. In practice, in CGE (EPPA) and macroeconometric (E3MG) models, energy services are still expressed in pseudo-quantities as in the historical CGE models. The CGE model IMACLIM-R, following in the footsteps of SGM, opted for a different approach, the expression of sectoral quantities in physical units, with technologies expressed in coupled bottom-up models.

The question is **more complex for single sector models** and the nature of end-use sectors representation is almost each case unique and in any case unclear and unresolved. This stems from **the ambiguity surrounding the energy factor within the macroeconomic production function**. The minimum ingredients to single out one given end-use sector or energy service is to represent an activity level and the specific combination of capital, labor and final energy to supply that energy service. In addition, the single sector nested-CES framework is a continuum of netputs and an input in one given nest is the output of a lower nest. The issue with end-use sectors is to capture end-use activity levels and the operations of final energy demands within such a nested-CES framework.

One can actually distinguish **two polar representations in single-sector general equilibrium models**:

⁸with the underlying assumption of a fixed output - energy service ratio.

- The energy factor can stand for *final energy* which is further combined with capital and labor to produce the macroeconomic composite good. In this view, the process of final energy consumption is embedded in the macroeconomic production so that no end-use sector is singled out. Furthermore it is not possible to capture end-use demand patterns with such framework.
- The energy factor can stand for *useful energy* or *energy services* broken down in different uses which correspond to explicit activity variables. Then end-use sectors processes can be detailed through lower CES nests or the coupling with an energy supply and demand sub-model. MARKAL-MACRO for instance breaks down useful energy in the macro CES function and expand the representation of end-use demand within the detailed energy system model. In particular such a framework makes it possible to capture end-use and technology specific investments flows regarding transport infrastructure or light vehicles types for instance.

In practice modeling choices stand in between these two polar views and result in ambiguous representations regarding end-use energy demand. The MERGE model for instance breaks final energy factor down between electric and non-electric energy. This trade-off between two classes of energy carriers certainly stands for a final energy demand arbitrage but is a very weak representation of end-use demand without explicit energy services. The WITCH model expands this framework by adding an intermediary aggregated energy service whose final energy intensity can vary according to R&D investments. This average energy service across the whole economy, does not refer to any tangible reality about energy end-use consumption. Eventually REMIND breaks down final energy between stationary and transport energy. In this way, final energy levels are in fact *proxies* of activity levels about transport and non-transport energy services but not explicit variables expressed in pkm or tons. Furthermore an ambiguity persists about the meaning of these proxies and the possibility to embark explicit information about technologies, infrastructures and investments flows about end-use sectors.

It is possible to synthesize the issues about interdependence and end-use sectors by constructing different types of schematic macro accounting frameworks. Figure 2.2 presents the four accounting frameworks which can be distinguished. The left column presents the accounting framework in SAM format. SAMs aim at encompassing all economic flows in an economy, and therefore capture all the economic flows corresponding to energy (or other needed spheres) as well. As a corollary, the initial picture in any E3 model can be described through a SAM, even an incomplete one

(where all flows are not reported). Furthermore, the SAM framework accommodates the representation of interactions between all agents in the economy. The right column corresponds to the layout of those flows and the interrelations (in a very symbolic formulation). The objective is not to provide a comprehensive overview of relations but rather to point out the form in which the sectors and agents from the SAM are interacting.

The first framework corresponds to the traditional top-down KLEM aggregate growth model. The second scheme refers to partial equilibrium models where the growth model is outside the energy system model and where energy is loosely linked to GDP through energy prices. The third scheme refers to single-sector GE models where the macro energy factor E is taken as *final energy* and is further broken down in different energy carriers E_i with details about the energy supply system. The fourth framework also corresponds to single-sector GE models but where energy factor E refers to *energy services* further broken down in different uses S_i with the detail representation of energy supply *and* demand system.

2.3.4 Technological explicitness

One last key aspect about the “heterogeneity” of integrated models is the level and nature of **technology explicitness about energy supply, conversion and end-use sectors**. Capturing technology explicitness in full-economy analysis has been a key endeavor in the bottom-up - top-down hybridization perspective. The main underlying objective is to improve the dialog between engineers and economists and increase the credibility about the technical aspect of the analysis. In practice, integrated models differ greatly in the way they represent technologies. It is worth noting that the concept of “technology” is taken here in the *engineering* sense and refers to an explicit technological process defined by the proportions of inputs and factors needed to produce one unit of output. It is possible to distinguish at least three degrees of technology explicitness: *no explicitness*, *semi explicitness* and *full explicitness*. Each degree correspond to a precise *nature* of technology representation beyond the simple consideration of a level of “details” about technology, which is however the usual blurry criteria.

The **full explicitness** refers to the traditional bottom-up representation of technologies. Our precise definition of a bottom-up representation is detailed in xx should include three aspects: (i) the accounting of energy flows in physical units, (ii) the accounting of technology specific engineering costs, (iii) the representation of mechanisms at the level of technologies and (ii) the accounting of technology specific productive capacities and the representation of capital under the form of “machine” capital.

Traditional bottom-up energy system simulation or optimization models embody full technology explicitness.

Conversely, the **no explicitness** case refer to the abstract vision of production based on traditional top-down productions functions. In this case, production or consumption trades-off are based on macroeconomic cost-shares and do not include engineering-based information. For one given economic sector the production process is based on the trade-off between inputs and factors including energy possibly broken down into different energy carriers but without referring to a basket of *discrete* technologies. The top-down production function embody the envelop of average production process resulting from the implicit underlying combination of individual technologies⁹. Furthermore it is not possible to relate production or consumption choices to any identified technology portfolio. Eventually, such a formulation is based on homogeneous mobile capital in contrast to technology embodied capital. Capital vintaging makes it possible to limit capital malleability but refers to top-down production structure embodiment instead of explicit technology embodiment. Alternatively macroeconometric models like E3MG partly use econometric relationships with aggregated variables without any technical information.

In between there is a space for **semi explicitness** which mostly derives from an expansion of the standard production function towards the inclusion of technology specific *engineering costs*. For instance, the combination of Leontief functions in a nested CES production function makes it possible to inform the substitution between identified technologies. In this framework, each Leontief function corresponds to one given technology and Leontief technical coefficients are calibrated on engineering costs (capital costs, fuel costs and O&M costs). Others technology agregators than the CES can be used such as a *logit* function. However in these framework the technology explicitness remain partial because the capital, although technology specific, remains in a top-down form different from discrete capacities which can operate with flexible level of utilization. Furthermore elasticities of substitution are still and abstract manner to represent technology substitutions.

To conclude, we can find these different degrees of technology explicitness across integrated models. Energy system simulation models like Gcam embody full technology explicitness for both energy supply and demand as they directly derived from bottom-up paradigm. In multi-sector CGE models technology explicitness can take any of the three forms. We come back to this issue in next chapter. To sum it up, most

⁹It is worth noting that in the *micro-economic* sense, "technology" refers to a set of production possibilities that might be accessed at different relative prices, that is the top-down production function. This top-down definition of technology is thus different from the bottom-up definition of a single technology.

models include semi explicitness at least for energy supply and power generation especially. It makes it possible to relate the decarbonization of power generation to the dynamics of identified technologies and embark engineering-based information about these technologies. A few models have included semi explicitness for end-use sectors distinguishing transport infrastructures and stocks of different types of vehicles¹⁰. However top-down formulation without technology explicitness remains common for end-use sectors in CGE models. Specific models like IMACLIM or using an MCP format (Mixed Complementarity Problem) include full explicitness for energy supply and part of end-use demand (transportation mainly). Eventually the strength of single-sector general equilibrium models is to expand full technology explicitness for energy supply sectors and power generation especially with possibly a large basket of individual technologies. However, some models in this category still rely on semi explicitness for energy supply (WITCH) and these models mostly include no explicitness for end-use sectors or semi explicitness at best.

2.4 Axis 2: Transformation drivers

Axis 1 assessed the structure of the interplay between the energy system and the broader economy as a *static* vision of internal interdependence captured by models. Axis 2 targets the drivers of *change* of this picture across time, which set the inter temporal evolution of the techno-economic frontier of the economy. These drivers are mainly constituted by the **growth engine**, **technical change**, the broader **structural changes** and the constraints linked to **capital inertia**. In practice, the type of transformation drivers is closely related to the interdependence structure of models and special attention will be devoted to these relationships.

2.4.1 Growth engine

The growth engine is the most important driver of the transformation of the initial static picture of the economy. The gist of the growth engine in all integrated models consists in the evolution of **production factors endowment** combined with the evolution of **factor productivity**. The ubiquitous solution to that in most models (including those using exogenous GDP) relies on the idea of Solow's exogenous growth model. It includes the prescription of exogenous trends of factor endowment (population - labor, natural resources, etc.), the endogenous accumulation of capital through investment and exogenous trends of factor augmenting productivity with substitutable production

¹⁰the EPPA model for instance.

factors along a single macroeconomic or several sector specific production functions. This base growth engine may be inserted in an intertemporal optimization framework to yield a Ramsey-type growth engine. Single-sector models are generally based on a Ramsey type growth model with a single CES macroeconomic production function. Multi-sector models are usually recursive dynamic (with exogenous saving rate) as initial Solow's model but the macroeconomic production function is broken down into sector specific production functions generally similar to Solow's macroeconomic function but with more desegregated production factors.

Therefore almost all energy-economy integrated model are based on the internal vision that general technical progress - as the principal source of economic growth beyond demography - is an exogenous and autonomous process, "*a manna from heaven*"¹¹ only depending on time¹². This persisting vision even in most advanced models is all the more surprising so as the assumption about the inducement of general technical change has been introduced for a long time in economic theory with the work of Hicks for instance (Hicks, 1932): "*A change in the relative prices of the factors is itself a spur to invention and to inventions of a particular kind – directed at economizing the use of a factor which has become relatively expensive.*" One of the reason is the success of Solow's model in growth theory and the convenience of its translation in empirical models. Nevertheless, Solow himself has warned that the specification about exogenous technical change has been chosen in the precise purpose to provide an alternative to the Harrod-Domar model and that this assumption should be considered with caution outside this context. However, Solow's model has been mainstreamed in macroeconomics, so that in the absence of a robust and convenient alternative, most applied energy-economy models have inherited its structure. In addition, prescribing general technical progress in energy-economy models and mitigation studies may be a reasonable assumption. Indeed, according to the "elephant and rabbit stew" metaphor formulated by Hogan and Manne (1977), since the energy sector only represents a few percents of economic activity, any change, even drastic, in this sector would not change the general economic growth engine. Subsequently, it is possible to specify a general growth engine based on exogenous general technical change on the one hand, to better

¹¹"This formulation is a very simplistic representation of technical progress. It seems to be void of theoretical content. It implies that technical progress happens exogenously ("*manna from heaven*" in economic jargon), independent of production inputs ("*disembodied*"), and smoothly over time. In reality, however, technical progress responds to economic variables, as well as to other influences, it changes the nature of production inputs (is "*embodied*"), and is inherently dynamic in nature (Peters, 1997)."

¹²In (Grubb, 2013, chapter 11), authors talk about the "*dark matter of economic growth*" to qualify this share of economic growth neither explained by increased labor and capital nor by the effect of capital accumulation on labor productivity. This "Solow's residual" represent around half of economic growth in many measurements.

focus on the specific technical progress happening in energy sectors on the other. Most integrated models are based on this assumption, especially single sector models which “hang” the energy system to the macroeconomic growth engine.

Nonetheless a few models at energy-economy-climate interface include an **endogenous** vision of economic growth and general technical change. Most of these models are inspired from the “new growth” theories developed in the 80-90’s like the Mankiw-Rome-Weil model (see appendix) (Mankiw et al., 1992). In these models, knowledge or human capital is a production factor whose stock grows through specific investment and is a substitute to others factors so that resulting factor productivity increases when knowledge stock grows. The level of investment in knowledge is furthermore a variable of control of total factor productivity and economic growth in the long run. Several applied models have been inspired by this approach like the model in Goulder and Schneider (1999). The model precisely includes a stock of knowledge which is substitutable to others factors to increase total factor productivity. However this type of models are not used to assess the energy-economy details of transformation pathways but display more theoretical ambitions (and usually are only top-down models). Let’s mention that in macroeconometric models like E3MG, economic growth is represented through correlations estimated based on econometry and thus factor productivity is endogenous to economic dynamics. However, these models do not describe the detailed mechanisms underlying growth dynamics.

The bulk of energy-economy models are thus based on an exogenous growth engine, and important distinctions can further be made within this paradigm. First of all, models differ in the **direction of exogenous technical change**, mainly between Hicks and Harrod neutral technical change. Hicks neutral technical change assumes that technical change affects uniformly all production factors through total factor productivity gains. One also talk about non-biased technical change. Conversely, Harrod’s neutral technical change assumes that technical change affects the sole labor factor which gets all productivity gains. In practice, models like REMIND and WITCH fall in the first category whereas MARKAL-MACRO, MERGE, EPPA, and IMACLIM-R models belong to the second case. The choice to allocate technical change to the labor factor historically comes from the skepticism about the capacity to justify the breakdown of technical change to others production factors, capital especially. Thus technical change is allocated to labor because labor to output ratios are easily measurable. The two types of technical change were not differentiated in Solow’s model due to the simple Cobb-Douglas production function. Nevertheless, with more complex production functions, the type of bias in technical progress is not neutral and has *a priori* important consequences on the level of growth and the share of value-added between factors.

However this question is generally not addressed in existing integrated studies.

Eventually there is a key difference in the *nature* of the growth engine between single and multi-sector models even with similar neutrality of exogenous technical change, due to the distinction of several individual production sectors. In multi-sector models like CGE models, the multi-sector structure implies that the apparent average macroeconomic productivity of a given factor results from the endogenous sector composition of GDP based on demand-supply dynamics as much as the exogenous productivity gains at sector level. In this sense, the **CGE growth engine is “mechanistic”**, because it represents the underlying mechanisms of macroeconomic growth and average factor productivity based on the dynamics of economic sectors. In contrast, **single sector models describe a more “phenomenological” growth**, where the growth dynamics is not made explicit, but rather subsumed with the aggregate production function. The word phenomenological here alludes to the fact that growth is described through a kinetic description with implicit causes. However, in both cases, the limit of explaining the evolution of factor productivity at macro or sector level remains untreated.

2.4.2 Energy technical change

Beyond general technical change, one key issue for energy-economy models is the specific technical change targeting energy sectors and the energy production factor. **Energy technical change** or simply technical change in energy-economy models, is about the penetration of new and more carbon and energy efficient production and consumption processes. It is in practice represented at different levels of aggregation. At technology level, technical change means new available technologies with increased energy efficiency or similar technologies with decreasing costs, whereas at the macroeconomic level it refers to the increase of the energy factor productivity. Technical change is a key driver of the ultimate decoupling between carbon, energy and economic growth through the shift of direction of the production frontier. Furthermore, a crucial question has been to what extent energy technical change could be an **endogenous process** and how it could be **induced** by specific policies. This question is especially important to assess climate and energy policies implications compared to a no-policy baseline and has made it possible to revise mitigation cost assessment. Since AR4, most integrated models have been including endogenous and induced technical change features. However, beyond the induced nature of technical change *per se*, a key issue usually overlooked in model assessment is the level at which technical change is represented and the objects to which it applies in relation to the pattern of

interdependence of the models: technologies, sectors, macroeconomy, etc.

First of all, technical change should be in theory differentiated from the **substitution** between existing technologies or already available production and consumption processes, even if the distinction is not always clearly made in practice. For instance, standard production functions whether macroeconomic or sectoral, are supposed to embody the ensemble of available combinations between inputs and factors to produce one unit of output at time t ¹³. Therefore the endogenous substitutions between energy carriers or between energy and others production factors triggered by relative prices change are not considered technical change *per se*. Similarly, changes between available technologies in bottom-up models is technological substitution and not technological change which is concerned with the introduction of new technologies.

This difference being clarified, energy technical change has been first introduced in models as **exogenous** and **autonomous** by means of autonomous energy efficiency improvement (AEEI) coefficients. Such coefficients are nothing but the translation of exogenous technical progress of Solow's model to the energy factor specifically. Historically such a coefficient has been used at the macroeconomic level in top-down models to mimic the observed decrease of energy intensity of GDP across time that could not be explained by the change of relative factor prices and energy prices evolution. Therefore the decrease of energy intensity of production could not be captured by production functions and elasticities of substitution so that modelers have implemented factor augmenting coefficients specific to the energy factor. This specification has been criticized in the literature for the numerical uncertainty about AEEI projections and the crucial impact they have on baseline emissions and subsequently on policy diagnostics (Azar and Dowlatabadi, 1999).

In integrated models one can find three types of AEEI implementation: (i) AEEI applied to *energy services* in the macroeconomic production function (MARKAL-MACRO), (ii) AEEI applied to *final energy* in the macroeconomic production function (MERGE) and (iii) sector specific AEEI in multi-sector models (EPPA). This perfectly illustrates both the **linkages between technical change representation and the accounting structure of models and the ambiguity of the AEEI formulation**. On the one hand AEEI can have a certain technical interpretation in multi-sector models and can represent sector specific energy efficiency gains due to autonomous trends or the introduction of technical standards for instance (vehicle efficiency in transport, industrial norms, etc.). Conversely AEEI applied to energy services in a macro-economic production function refers to a global decoupling between energy services and GDP. It thus does not refer

¹³Nevertheless others interpretations of an aggregate formulation of production processes can be made such as with the concept of innovation possibility curve (see xx).

to specific technical efficiency any more but encompasses structural changes towards the production-consumption of less energy intensive goods (increase of the share of services and manufacturing in GDP for instance). Eventually AEEI applied to final energy in same macroeconomic production function embodies both technical energy efficiency and structural changes but can not be related to specific sectors and technical content. Finally, AEEI is a convenient tool to prescribe general energy intensity of GDP but does not enable to describe the mechanisms driving energy efficiency in relation to given sector or technical content (in single sector models especially) which is an obvious drawback for the study of transformation pathways. Beyond AEEI, most integrated models include exogenous technical change features at the technology level. This technological change corresponds to the deployment of “back-stop” technologies and exogenous changes of technology costs. Most integrated models include such features for energy supply technologies (bioenergy, ccs, etc) even multi-sector models with medium technology explicitness (cf. section 2.3.4).

In order to overcome the weaknesses of exogenous representations of energy technical change, models have been improved towards **induced technical change** in order to capture the possible effects of policies and other economic variables on innovation and energy technical change. Key efforts have been made at technology level first of all, although certain advanced models like GCAM still do not include endogenous mechanisms of technology evolution. The first mechanism developed is the “learning-by-doing” implemented by means of learning curves for advanced technologies which relate decreasing technology costs to the level of capacities implemented. Most integrated models include technology specific learning curves. Less developed is the mechanism of “learning-by-searching” at technology level which relates technology efficiency or costs to a level of R&D investment. The WITCH model for instance includes “learning-by-searching” mechanisms for power generation technologies. Furthermore, developments have been carried out to represent induced technical change and efficiency gains for end-use energy consumption. The modeling approach is inspired by endogenous growth models but the key difference is that productivity gains only apply to the energy factor. It assumes that investments in a given stock of knowledge makes it possible to increase energy efficiency of production. This mechanism is usually linked to a diffusion mechanism of more efficient processes between regions to capture “spillover” effects. However, such mechanisms are implemented at very different levels of aggregation according to model interdependence detail, ranging from a global disembodied vision of induced technical change to technology or sector specific mechanisms. In the WITCH model for instance, the aggregate of total final energy consumption is combined with a global energy R&D capital to “produce” the aggregate of

total energy services within the macroeconomic production function. The endogenous accumulation of energy R&D capital makes it possible to decrease the final energy - energy services ratio. Such a model feature certainly captures global inducement of energy efficiency but remains at a very abstract level. Furthermore its calibration is a tricky issue as the mechanism can not be related to a clear technical reality nor any identified energy end-use sector. Conversely a model like IMACLIM-R , which details specific energy end-uses, includes R&D mechanisms with energy efficiency gains at sector level and can relate energy technical change to a more precise techno-economic reality.

As a conclusion, we have seen that energy technical change representation has been greatly developed in integrated models with the expansion of energy technical change inducement especially. However, setting apart technological change in energy supply sectors, **models differ especially on the level of abstraction of the representation of energy efficiency gains** regarding energy end-use especially. These contrasts can actually be related to the difference of accounting frameworks enhanced though axis 1. Furthermore, a too aggregated representation of energy technical change prevents to distinguish energy efficiency from wider structural changes.

2.4.3 Capital inertia

One key constraint to the *speed* of technical change and the shift of the production frontier towards more carbon and energy efficient processes is imposed by capital inertia. The techniques in use are embedded in the existing capital and the substitution towards different processes and the effective introduction of new techniques happens either with the installation of new capital (investment) or with the reallocation of already installed capital. The constraints imposed by capital inertia on technical substitution and technical change finally depend on the lifespan of installed capital and its malleability vis a vis the possibilities of retrofit or the reallocation in the economy.

The representation of capital inertia and the type of technical embodiment varies significantly between models and within models depending on the scale of representation. In partial equilibrium models of energy markets (GCAM, WEM), the full technology explicitness of both final energy supply and end-use demand, makes it possible to embed technologies in specific capital singled out as production capacities. In single-sector general equilibrium models, the diagnostic is similar for the bottom-up energy module when there is one (MARKAL-MACRO, REMIND, MERGE). Such modules include full technology explicitness and activity analysis. In both cases, the installed capital is attached to a specific technology and lifespan with no further malleability

beyond specific retrofitting and learning effects. This framework makes it thus possible to represent explicit technological inertia through capital embodiment along the technical transition. However in these cases, capital inertia only applies to energy sectors and not at the level of the growth engine and the macroeconomic production frontier.

At the macroeconomic level, the diagnostic about capital inertia is less obvious when technical substitutions and technical change are captured by means of production functions. In Solow's original growth model, capital is *perfectly malleable* at each time step and total capital stock at time t (including already existing capital) can be freely combined with labor via the macroeconomic production function. Consequently, the short run elasticity of substitution matches the long run elasticity and the model does not capture any technical inertia. This formulation of perfect capital malleability, which may be acceptable for aggregated and theoretical purposes, has been however applied to the macroeconomic CES production function of most single-sector energy-economy GE models (MARKAL-MACRO, REMIND). Subsequently, technical choices about final energy demand, driven by the nested-CES function and aggregated energy efficiency gains, are actually *disembodied* and no technical inertia is accounted for through capital partial malleability. Finally, beyond the weak technology explicitness of final energy demand and the weak - if not absent - representation of energy end-uses, such modeling frameworks **ignore the technical inertia of end-use energy sectors and final energy consumption**. In clear, such models can not *a priori* capture the inertia of transport infrastructures or building stocks for instance. It eventually results in a weak representation of the technical transition about final energy consumption.

One key improvement to overcome these pitfalls has been the inclusion of *partial capital malleability* in standard production functions. In practice, part of the capital installed in one given year remains non-malleable in the following year and remains attached to the production structure chosen at that year through the production function. Furthermore the malleable part of the capital stock plus the new invested capital are freely malleable and mobile in the economy. Schematically these features make it possible to track a set of capital vintages, each one attached with a specific Leontief production structure (Jacoby and Sue Wing, 1999). Within this paradigm alternative formulations are possible. With the *putty-clay* option, total installed capital remains non-malleable and the sole new invested capital is malleable and mobile across economic sector. With the putty - semi-putty formulation, part of installed capital remains malleable and enables to capture retro-fitting and early-scraping effects. In practice few single sector models include partial macroeconomic capital malleability (MERGE). Conversely, these modeling features have been largely adopted in multi-sector CGE

models at sector level (EPPA, IMACLIM-R). It makes it possible to capture technical inertia and to differentiate short run and long run elasticities of substitution. It eventually provides a certain realism of technical transitions although technical inertia is generally not captured at technology level - contrary to a bottom-up formulation - but at the level of an average production structure of the sector even with medium technology explicitness.

2.4.4 Towards the induction of structural change

The discussion about energy technical change generally mixes the transformation of the technology portfolio - towards low carbon technologies and more energy efficient processes - with the question of structural changes. However these two issues refer to different realities in nature and scale. Structural changes ultimately explain the decoupling between income growth and energy services demand which results from intertwined mechanisms which are important to disentangle. Schematically, structural changes result from the interplay between the structure of final demand, of the inter-industry matrix and the productivity gains realized in the different economic sectors. In addition it is probable that along deep decarbonization pathways a dynamic interaction between these components may happen, partly through a sort of **co-induction between technical change and wider structural changes**. For instance drastic technical change in one given sector may have key implications on the production structure of others economic sectors. To take a single example, massive building renovation combined with the construction of new low-energy buildings may trigger technical and structural changes in economic sectors producing the building materials with the need for new and physically different materials. In addition, technological changes may determine part of the transformation of final demand and consumption patterns. The capacity to build low-energy housing in suburbs coupled to the development of more efficient vehicles will be a key driver of changes about demand for mobility.

Surprisingly the question of structural change has been so far largely overlooked by integrated models. Partial equilibrium energy market models like GCAM include a very simple treatment of structural change through exogenous projections of end-use sectors structure between transport, industry and buildings. Whether it be through exogenous specifications (AEEI) or macroeconomic R&D based inducement (in the WITCH model), single sector models capture the effect of structural changes on the decoupling between economic growth and energy demand in the most abstract manner by means of simple coefficients relating energy demand to GDP¹⁴. Therefore such

¹⁴Let's recall that using AEEI coefficients to inform the evolution of the final energy intensity of GDP

features make it certainly possible to have a transparency about the energy content of GDP in scenarios but prevent to explore any precise aspect of structural changes and furthermore on the nature of future development patterns.

Multi-sector models provide by nature a more detailed treatment of endogenous structural changes through the relative prices and income effects of supply-demand interactions. However this treatment is usually limited by the fact that production and demand functions are mostly fixed once and for all along pathways. Yet it is probable that an important *bifurcation* towards very different technical systems and including drastic changes in transport, buildings sectors and industrial organization yields a change of production functions and elasticities of substitution¹⁵. In traditional CGE models, preferences are usually kept constant. However some integrated models include an update of the utility function across time to capture changes of consumption patterns in the long run. For instance, EPPA features an adjustment to consumption shares and elasticities. In IMACLIM-R, the preferences are a function of the revenue. In addition, the utility function features variable consumption ceilings and floors. Outside the CGE perimeter, T21 follows exogenous Engle's curves and E3MG resorts to econometric estimation of functional relationships.

2.5 Axis 3: Transition dynamics

Together with considerations about transformations and technical change in the long run, integrated models provide insights about the *temporal* details of transformation pathways. Special attention in recent integrated scenarios has been paid to the integration between long- and short-term perspectives and the question of how to get "from here to there" (Krey et al., 2014). As detailed in chapter 1, integrated scenarios have focused on the interplay between alternative emissions pathways with different timings of action and the compatible *technical and technological transitions* towards low-carbon energy-carriers and processes. The issue of the time-frame of transformation pathways brings us to the third and last axis of model analysis which concerns transition dynamics and the way models actually generate achieved pathways in their temporal, technical and economic dimensions. Owing to our conceptual framework (see fig. 2.1), achieved pathways can be schematically characterized in two steps: (i) first, the effective determination of the production frontier across time periods, considering the transformation drivers of axis 2, provides a pathway of reference points

maintains the confusion between technical energy efficiency and the decoupling between energy services and GDP.

¹⁵This aspect is explored in Ghersi and Hourcade (2006).

for each time period and (ii) second, the current achieved state of the economy within each time period is determined through the gap to the current production frontier.

First of all, the *inter-temporal* trajectory of the production frontier mainly results from the interplay between the transformation drivers and the inter-temporal economic choices. In this respect, models mainly differ in the type of *expectations* of economic agents about future inter-period economic conditions. The choice of inter-temporal economic behavior has a fundamental impact on techno-economic trajectories between baselines and policy pathways especially, in relation to contrasted visions about *path-dependency* and “*lock-in*” phenomena. In addition, whatever the type of inter-temporal arbitrage retained and the related path of the production frontier, in the bulk of integrated models, transformation pathways are studied in *perfect economic environment* for the short-run¹⁶ and most models generate pathways as successive *intra-period* first-best economic equilibria. In this case, at any time step, economic agents perfectly adjust to the current economic conditions through perfect markets. In clear, the gap to the production frontier is null, the economy is always on the production frontier, and transition assessment is reduced to the dynamics of the production frontier across time periods and of the economy along that frontier. Subsequently models capture technical transitions mechanisms but generally ignore the *economic processes* of the transition.

The usual argument made to justify such assumptions is that short run fluctuations do not affect long term trends. The underlying hypothesis is that any shock along pathways is quickly absorbed by appropriate market mechanisms. However the literature about the effects of shocks like oil prices variations show that short term effect may have substantive medium run economic implications (Jones and Leiby, 1996). Eventually in the real world, mitigation costs may be mainly concerned with transition costs between two pathways, which can be assessed with difficulty by most models. Finally, the possibility of more chronic disequilibrium sets the question of the second best aspects of transformation pathways and the possible economic co-benefits of low-carbon pathways. In this last section we attempt to enhance how integrated models capture transition dynamics, through the interplay between *technical constraints*, *economic behaviors* and *market forces*. It makes it especially possible to shed light on the implicit visions about transition dynamics attached to the alternative modeling choices.

¹⁶“The aggregate economic costs reported [...] have assumed [...] in many cases an idealized implementation environment with perfectly functioning economic markets devoid of market failures, institutional constraints, and pre-existing tax distortions.” (Edenhofer et al., 2014, Chapter 6, section 6.3.6.5)

2.5.1 Inter-temporal dynamics

Axis 2 described the *drivers* of the shift of the production frontier through time. The effective determination of the pathway of the production frontier depends on the interplay between these drivers and the inter-temporal economic choices of economic agents. The key aspect of inter-temporal choices is the degree of expectations about future economic signals from myopic expectations to perfect foresight including any degree of limited foresight. Connected to expectations are the type of behaviors of agents from optimization to specific behavioral routines. In practice, the bulk of integrated models include two polar views about expectations: either perfect or completely myopic expectations. In single sector optimization models, inter-temporal economic behaviors are reduced to the action of a single omniscient and benevolent social planner who optimizes inter-temporal welfare with perfect expectations. Conversely, most multi-sector recursive dynamic CGE models retain completely myopic behaviors of decentralized agents whose economic choices only concern intra-period operations considering current information only (price, income, etc.). Inter-period decisions are driven by exogenous saving rates.

In fact, these two polar views about expectations and inter-temporal economic choices are guided by the two original growth models from which they are derived: Solow's and Ramsey's growth models. However these models have been historically developed for precise theoretical purposes and the authors themselves have warned about the use of their theoretical frameworks outside the original context. In the case of aggregated optimization models, unless the perfect expectations paradigm of a central optimizing planner is only used for *normative* purposes - energy planning for instance, it is not really relevant for real world representation as claimed by Solow (1994)¹⁷. In addition the *perfect* foresight paradigm may be actually a misinterpretation of the theory of *rational* expectations (Muth, 1961) which only assumes that the *expected* gap of expectations is null, due to agents learning, but not that expectations are any time right¹⁸. On the other hand, the assumption of myopic behaviors included in recursive dynamic CGE models may not be as such more plausible and is also a

¹⁷"I cannot say the same about the use made of the intertemporally-optimizing representative agent. Maybe I reveal myself merely as old-fashioned, but I see no redeeming social value in using this construction, which Ramsey intended as a representation of the decision-making of an idealized policymaker, as if it were a descriptive model of an industrial capitalist economy. It adds little or nothing to the story anyway, while encumbering it with unnecessary implausibilities and complexities."

¹⁸"... the rational expectations approach need not and should not assume that men apply reason to "circumstances that are perfectly known." [...] The implication that economic agents or economists are omniscient cannot fairly be drawn from Muth's profound insights. It suggests rather that information is costly and that it will be used efficiently". (Kantor, 1979)

highly idealized representation of real world decision making¹⁹. A few integrated models have attempted more realistic decision behaviors with limited foresight. For instance the IMACLIM-R model represents investment decisions under imperfect foresight. At a given date, agents have limited information about the future and shape their expectations on the basis of past and current trends (adaptive expectations).

The type of foresight has crucial implications for the techno-economic pathway represented. First of all, the combination of capital inertia, increasing returns to scale and induced technical change creates as such a phenomenon of *path dependency* included in most models.²⁰ However, this path dependency has not the same implications about the conditions to bifurcate to a low carbon pathway depending on the type of expectations retained. In the case of inter-temporal optimization under perfect foresight, all the possible techno-economic routes are known in advance with all possible effects of scale and capital inertia, and the optimal pathway is selected. This has at least two consequences. First, as the baseline corresponds to the optimal techno-economic pathway without emission constraint, any alternative low carbon pathway incurs a net discounted cost compared to the baseline. Second the model does not really capture the bifurcation towards low carbon pathways but rather computes alternative low carbon techno-economic routes with often very limited costs. Taking into account induced technical change leads in some studies to highlight the existence of *multiple equilibria* between a carbon intensive and a low carbon future with similar GDP levels.

Introducing myopic or imperfect foresight in conjunction with capital inertia and induced technical change breaks the inter-temporal optimum of pathways and yields “lock-in” phenomenon in given techno-economic directions. Such features make it possible to shed light on possible inter-temporal sub-optimum sequences in baselines linked to carbon lock-in and to explore the conditions to bifurcate towards a low carbon pathway. In practice the effect of myopic foresight in dynamic recursive CGE models may be limited because of limited capital inertia, limited learning and induced technical change and smooth technical constraints. Specific models like IMACLIM-R emphasize the potential role of imperfect foresight in shaping low carbon pathway compared to a baseline. For instance, under limited foresight, redirecting investment towards low carbon processes may require high carbon price in the short run compared to perfect foresight where long-term prices are internalized in short term decisions which makes

¹⁹“Clairvoyance is an implausible assumption, but myopia seems even worse.” (Manne and Rutherford, 1994)

²⁰It implies in practice that the incremental shift of the production frontier from t to $t + 1$ depends on the state of the economy at time t in terms of installed capital and embedded technologies. The partial malleability of capital constrains incremental technical change and increasing returns to technology adoption (learning-by-doing for instance) favor all the more further technology adoption as the technology is already adopted.

high short-term prices unnecessary. In addition, limited foresight may lead to sub-optimum baselines with “bad surprises” at some point that can be avoided in low carbon pathways²¹.

2.5.2 Paradigm of economic transition at first-best equilibrium

From the inter-temporal evolution of the production frontier, the achieved techno-economic pathway can be ultimately characterized by the dynamic intra-period²² gap to that production frontier. This gap translates transitory or permanent (if the gap cancels out after a certain number of periods or not) under-optimum of the current state of the economy. It can be broken down into different underlying components from techno-economic efficiency gap to more macroeconomic distortions, market failures and adjustment constraints. In practice, the achieved state of the economy results from the interplay between intra-period *economic behaviors* and *market forces* under current *technical constraints* (capital malleability, available technologies and production/consumption processes, etc.). However, most integrated models capture such an interplay through the computation of a first-best general equilibrium (in the neoclassical sense) including flexible adjustments embedded in smooth production functions. Relying on this paradigm traps modelers into the narrow vision of an economic transition as successive first-best equilibria, which may not be a very convincing representation of transition dynamics.

Most integrated models based on general equilibrium computation, whether including a single or multiple economic sectors, fall in this category. As far as single-sector models are concerned (MARKAL-MACRO, MERGE, REMIND and WITCH) they are usually based on a twofold optimum following Ramsey’s growth model. These models actually combine inter-temporal optimization - as already discussed, with intra-period first-best conditions. Within each time period the marginal conditions of optimum are met via the usage of a standard CES macroeconomic production function calibrated at base year. Subsequently each production factor and energy sub-aggregate is implicitly paid at its marginal productivity just as in Solow’s original model. Everything happens as if the social planner was also coordinating intra-period markets to reach first-best (or perfect, or competitive) intra-period equilibrium - in the sense of Arrow-Debreu. And just as in Solow’s growth model, the markets of production factors are implicit and reflected by the marginal macroeconomic conditions. Such intra-period equilibria happen under the technical constraints imposed by the bottom-up energy

²¹For instance the earlier development of low carbon technologies and infrastructure may alleviate the negative impact of the peak oil insufficiently anticipated in the baseline.

²²In models the length of intra-period generally varies from 1 to 5 years.

sub-module when it is present (MARKAL-MACRO, MERGE, REMIND). Furthermore the energy module endogenizes the set of final energy carriers or energy services “endowments” - as macroeconomic production factors - and relates it to the constraint of energy system costs. However the energy module does not impact the optimal character of the macroeconomic equilibrium. Eventually these models represent economic transitions as successive perfect macroeconomic equilibria under the constraint of a detailed technological transition.

The multi-sector recursive dynamic CGE models that are neo-classical in spirit (EPPA, FARM, AIM/CGE, ENV-LINKAGES, etc.) suffer the same type of pitfalls regarding transition dynamics. We put in this class of models the bulk of multi-sector CGE models, which are based on a translation of the microeconomic theory of the Arrow-Debreu competitive equilibrium, which provides microfoundations to macroeconomic behaviors. As detailed in appendix A.1.4, following mainstream CGE practice, these models generally add two key assumptions to the historical general equilibrium framework beyond income and accounting balance: (i) market clearing for all goods and production factors and (ii) zero profit conditions. Furthermore, techno-economic choices at sector level are usually based on nested-CES production functions calibrated at base year. Compared to single-sector aggregate optimization models, these models are based on a detailed SAM which singles out different economic agents - producing sectors, one or several representative households and the government - which interact through markets and income transfers. In terms of economic behavior, each representative economic agent optimizes his intra-period surplus (profit or utility) based on current price signals. Economic agents interact on explicit markets of goods and production factors characterized by perfect competition (zero profit condition)²³. As detailed in former subsection, the inter-temporal dynamic of these models is usually completely myopic with exogenous saving rates and the allocation of resources is not inter-temporally optimized. However, within each period, economic agents make optimal investment and production choices and the anticipated prices are the realized equilibrium prices within the production functions. Therefore economic agents have *perfect short-term expectations* and realize short term optimal choices with full price flexibility to yield intra-period competitive equilibrium under given technical constraints. In particular

²³It is worth noting that in a first best setting, a decentralized equilibrium with multiple agents should be equivalent to a centralized equilibrium. Lipsey and Lancaster (1956) phrased it as follows: “It is well known that, under suitable assumptions on the preferences of consumers and the production possibilities of producers, the allocation of resources in a competitive equilibrium is optimal in the sense of Pareto (no redistribution of goods or productive resources can improve the position of one individual without making at least one other individual worse off), and conversely every Pareto-optimal allocation of resources can be realized by a competitive equilibrium (see for example Arrow (1951), Debreu (1951) and the references given there).”

including partial malleability of capital and capital vintages to capture technical inertia does not change the nature of the equilibrium and malleable capital is perfectly allocated among sectors and “technologies” within each time period. Eventually these models also represent economic transitions as successive first-best equilibrium (under specific technical constraints) and the economy coincides with the production frontier.

In fact these models are trapped in a simplistic vision of economic transitions because they stick to aggregate growth and general equilibrium theory with the assumption of short term competitive equilibrium and the use of calibrated CES production functions. However, growth models have been originally developed for specific purposes such as the study of balanced growth pathways in the long run. From the viewpoint of modeling economic transitions, aggregate optimization models and standard dynamic recursive CGE models reflect the initial vision of respectively Ramsey’s model and a combination between Solow’s growth model and the Arrow-Debreu model of competitive equilibrium. The empirical expansion of initial economic theory with multiple economic sectors, complex nested-CES production functions, capital vintages or else the coupling with energy optimization models, certainly improve techno-economic realism but does not challenge the nature of the economic transition embodied by original growth and general equilibrium theory.

Concretely, relying on Solow’s growth model and solving successive intra-period competitive equilibria with CES calibrated production functions strongly constrain the vision of economic behaviors and economic transitions. First of all, Solow himself has warned about the fact that his model ignored transitions between growth regimes²⁴. In addition, in Solow’s model, the transition towards the balanced growth regime happens with satisfying the marginal conditions of optimality at each time step through the macroeconomic production function. Solow’s model thus describes a pathways of continuous short-term implicit competitive equilibrium. This pattern is used as such in aggregate optimization model with a single CES production function, and could be conveniently combined with the static model of multi-sector competitive equilibrium in multi-sector integrated models to make the link between two pillars of neo-classical economics: Solow’s growth model and Arrow-Debreu competitive equilibrium. However the competitive equilibrium was originally purely static to perform comparative statics analysis. The resulting vision of an economic growth process and capital accumulation as successive static equilibria has been largely criticized (Robinson, 1974): “*We might suppose that we can take a number of still photographs of economies each in station-*

²⁴“a systematic way to talk about and to compare equilibrium paths for the economy. [...] In doing so, however, it failed to come to grips adequately with an equally important and interesting problem : the right way to deal with deviations from equilibrium growth”(Solow, 1988)

ary equilibrium ; [...] This is an allowable thought experiment. But it is not allowable to flip the stills through a projector to obtain a moving picture of a process of accumulation.”

The corner stone of this paradigm is the usage of calibrated CES production functions to solve intra-period competitive equilibrium. In practice these convenient functions are calibrated for each sector on one given year statistics based on Shepard lemma which requires that every agents optimize their intra-period surplus (profit or utility). The constant static returns else accommodate well with the zero-profit condition. Using these tools as such have several key implicit implications that modelers should keep in mind. Strictly speaking, it first assumes that behaviors are micro-founded even if this status can be debatable in applied models and one could argue that the calibrated production functions first pursue an objective of empirical realism. Second, calibrated production functions force the level of foresight of agents and the nature of behaviors towards short-run optimization under perfect foresight about intra-period relative prices. One thus clearly sees how this paradigm makes it difficult to explore alternative visions about economic behaviors within the wide spectrum of possible routine behaviors under limited foresight²⁵. Eventually it implies that the “malleable” portion of capital remains a kind of “jelly” with the same properties as others production factors regarding production choices. In this view, production possibilities as substitutions among factors according to their relative prices, are identical *ex ante* (before investment) and *ex post* (after the capital is installed)(Arrow et al., 1961). Subsequently, investment and production choices are simultaneous and perfectly adapted to intra-period demand as well as observed relative prices of production factors. Such a representation of capital and the simultaneity of considerations of return on capital and capital productivity has been at the core of the “Two Cambridge controversy” which has not eventually yielded changes of mainstream theories (Cohen and Harcourt, 2003).

2.5.3 Techno-economic transitions in a second best world

In the real world the gap to the production frontier is never null and the production frontier is itself a theoretic concept to organize thought. Understanding the main reasons for the existence of intra-period gaps to the production frontier through relevant modeling representations, makes it possible to enhance crucial economic aspects of the transition to low carbon economy ignored by first-best equilibrium approaches. The relevant second-best features to think about low carbon transition are multiple

²⁵ Akerlof (2007) for instance shows how social norms can explain some departure from pure optimizing behaviors.

and diverse. At the techno-economic scale, there are first all the considerations linked to the “efficiency gap” (Jaffe and Stavins, 1994b) which assumes the existence of sizeable energy efficiency and low carbon potential under exploited despite economically favorable. This refers to a wide range of market and behavioral failures, from individual behavior to institutional constraints and specific finance issue of low carbon and energy efficiency projects for instance. At the macroeconomic level, one can cite the issue of existing tax distortions, imperfect markets and market power, imperfect capital allocation, rigidities such as that linked to labor markets or general price adjustment (like keynesian short run price rigidity), non-market barriers, etc. Capturing such mechanisms in models makes it possible to renew the diagnostic about the costs to bifurcate towards a low carbon pathway compared to a given baseline.

Few integrated models have ventured exploring second best issues of the short to medium run and very few depart significantly from the first best paradigm. First, mono-sector optimization models based on Ramsey’s growth paradigm generally strictly adhere to the first-best assumption and ignore sub-optimum issues of the medium-run. Second, certain multi-sector CGE models, even neo-classical in spirit, capture some gaps between the economy and its production frontier. A first important element often taken into account relates to the existence of initial tax distortions. Furthermore implementing an appropriate carbon tax policy can make it possible to correct part of the existing distortions and provide an economic dividend beyond the environmental dividend. In addition, the core neo-classical approach is readily amenable to incorporate market failures such as information asymmetries or market power based on rigorous microeconomic theory. In practice in these models, market failures are generally reduced to the implementation of specific market imperfections for goods. For instance, the GEM-E3 model includes alternative market clearing conditions departing from competitive markets with implementing targeted oligopolistic markets²⁶. However, these models incorporate limited second-best features in practice, without challenging the core paradigm based on market clearing for all goods and production factors and rational optimizing behaviors under perfect intra-period foresight with no constraint in price adjustment.

In the integrated modeling landscape, one can find at least two routes that have been explored in mainstreaming key second-best mechanisms: (i) one based on a larger and empirically oriented vision of CGE modeling with the IMACLIM-R model and (ii) several simulation macro-econometric models based on post-keynesian theory like E3MG .

²⁶Market imperfections linked to rent generation can even be represented through roundabout means within a first-best equilibrium formulation, like using fixed factors under the zero profit condition.

First of all, the IMACLIM-R model is inspired by the *ex ante* / *ex post* decomposition of the production function proposed by Johansen (1972)²⁷. The IMACLIM-R framework comprises a yearly iteration of two phases: a dynamic step based on *ex ante* production choices, and static equilibrium involving *ex post* production and consumption choices. During the *ex ante* phase (dynamic evolution), agents takes stock of the economic signal – quantities, prices. . . – from the last equilibrium and form expectations in order to take decision on capacity investment in a bottom-up model – either in a full or reduced form. During the *ex post* phase (static evolution), the model computes a Walrasian equilibrium of goods – quantities, prices. . . – with fix production capacities – that is capital factor. Such a framework allows several innovations in representing second best mechanisms in the short run and dynamic gaps with the production frontier:

- the possibility of under employment of capital (production capacities)
- imperfect markets of goods and mark-up pricing
- possibility to implement alternative patterns of limited and adaptive expectations and routine non-optimizing behaviors²⁸

The static equilibrium also includes the possibility of involuntary unemployment and imperfect labor markets.

Macroeconometric post-keynesian models like E3MG represent an interesting alternative. Econometric functional relationships represent substitutability possibilities and market relationships. These function relationships allow for the evolution to be influenced by the empirical mechanisms of capacity investing separated from operations. This evolution is implicitly calibrated in the functional relationships. In addition these models usually include the representation of a gap between notional and effective economic choices to reflect existing constraints of adjustments in the short run (prices especially). However, for macroeconometric models, the difficulty to represent unprecedented trajectories poses problem. This refers to the critique of Lucas (1976): *“Given that the structure of an econometric model consists of optimal decision rules of economic agents, and that optimal decision rules vary systematically with changes in the structure of series relevant to the decision maker, it follows that any change in policy will systematically alter the structure of econometric models”*. Peters (1997) gives that argument to question the role of econometry for forward-looking analysis: *“Especially, econometric estimates can say nothing about the direction of causality. They fail to understand the mechanisms*

²⁷He exposes the difference between *ex ante* production function offering the whole spectrum of possibility between technological choice, while the *ex post* production function represents the production arbitrage after capital has been installed (see chapter xx).

²⁸like inefficient behaviors regarding energy efficiency for instance.

of technical progress. They give a picture of technical progress very abstract and completely disembodied. [. . .] They are therefore to be taken with extreme caution and any extrapolation on their basis is hazardous”.

2.6 Conclusion

This chapter develops a guide to scrutinize and synthesize the internal vision of integrated models in order to characterize the nature of the techno-economic pathways they generate. Doing so, it can serve both as a user-guide of existing models to better understand their areas of relevance and as a “mental map” to improve the toolbox and design new models. The characterization of energy-economy integrated models is based on three complementary axes: (i) the pattern of interdependence, (ii) the transformation drivers and (iii) the type of transition dynamics. In the emissions - output plan of the pathways generated, the pattern of interdependence corresponds schematically to the snapshot of the system modeled at time t , the transformation drivers are the inter-temporal drivers of the production frontier, and the transition dynamics determine the achieved techno-economic pathway through the dynamic gap to the production frontier.

Applying this analysis scheme to existing models provides some elements of diagnostic along the three axes of analysis.

First of all, state-of-the art energy-economy models greatly differ in the interdependence modeled. When the energy sector is fully integrated in growth dynamics, an important dichotomy exists between models based on a single sector vision of macroeconomic interdependence and models based on a multi-sector pattern. The former build on an aggregated vision of value added and GDP and ignore inter-sector relationships, whereas the latter break down value added between identified sectors and capture the structure of intermediary and final consumption. The key side-effect for single sector models is that they struggle to represent explicit end-use energy sectors (transport, industry, buildings) and their relationship to GDP. Nevertheless the more simplistic macroeconomic structure allows to integrate full technology explicitness for energy supply and conversion sectors in single sector models, whereas multi-sector models usually only rely on semi explicitness at best.

As for transformation drivers, models share one commonality: they generally overlook the source and direction of general technical change to focus on the specific technical change linked to energy sectors and final energy demand. In addition, both technical change explicitness and inducement greatly vary between models. Single sector models usually include advanced and technology specific inducement mecha-

nisms for energy conversion sectors but a rough aggregated vision of the decoupling between final energy demand and GDP. Conversely, multi-sector models struggle to incorporate induced technical change at technology level but do inform the sector break-down of general technical change. Likewise capital inertia varies across model and across sectors within models. Finally, the issue of the drivers of broader structural changes beyond pure technical change remain a blind-spot of energy-economy models.

Eventually, most energy-economy and integrated models reflect a simplistic vision of transition dynamics and represent technical and technology transitions at first best economic equilibrium. Single sector models add the inter-temporal optimum under perfect foresight to the intra-period optimum. Recursive dynamic multi-sector models allow inter-temporal imperfections through myopic expectations. However, limited capital inertia and smooth intra-period adjustments prevent to capture important path-dependency and “lock-in” effects. In addition, second-best mechanisms and market failures are sometimes captured by these models but remain marginal under a neo-classical approach grounded in “rigorous” microeconomic theory. Some integrated models have mainstreamed second-best mechanisms by giving up the neo-classical production function and its strict micro-foundations or by including some aspects of post-keynesian theories. Models venturing in this track can provide very different economic assessments of transformation pathways and contrasted estimations of mitigation costs compared to a baseline.

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Chapter 3

Reconciling bottom-up and top-down in CGE models: a synthesis of existing approaches

3.1 Introduction

The motivation to use multi-sector CGE models for climate and energy policy assessment has come from their comprehensive treatment of energy and non-energy sectors within a unified macroeconomic framework. [Robinson et al. \(1999\)](#) talks about “*a versatile empirical simulation laboratory*” to analyze the economy-wide impacts of the interactions of “*specific sectors*”. Thus, the multi-sector structure allows to connect the representation of energy supply, conversion and final demand as well as technical change at sector level with the representation of broader structural change (change in sectors shares in GDP) in relation to final demand behavior. Nevertheless, these strengths usually come with difficulties to embark engineering based information and structural assumptions about technical systems. The lack of technological explicitness of CGE models has been a recurrent debate of the bottom-up - top-down controversy ([Grubb et al., 2002](#)).

In addition, attempts at integrating engineering based representations of technical systems in a CGE model show that the nature of these representations strongly impacts climate and energy policy assessment. Thus, [Böhringer \(1998\)](#) and more recently [Lanz and Rausch \(2011\)](#) compare the impact of alternative formulations of the power generation sector within a larger CGE model: two standard constant elasticities of substitution (CES) production functions with KLEM inputs and one engineering

based formulation with discrete technologies. In both cases two conclusions arise. First, the differences between engineering based and aggregated production function representations are structural and have a large effect on policy assessment. Second, the engineering based representation shows a non-monotonic behavior that would be very difficult to capture through the use of conventional production functions. Furthermore, [Gheri and Hourcade \(2006\)](#) finds that integrating bottom-up information in a general equilibrium framework can significantly alter the economic and technical diagnosis, even at a macro scale. This means that different degrees and forms of bottom-up integration may thus impact energy and climate policy assessment differently.

Integrating engineering based representations of technology in a CGE model is also necessary to improve the dialog between engineers and economists and enhance the quality control and credibility of CGE model assessment of climate and energy policies. [Böhringer \(1998\)](#) summarizes this idea: *“the hybrid approach increases the credibility of CGE models in energy policy analysis because the possible substitution patterns in energy conversion can be based on ‘true’ technology rather than restrictive functional forms.”*

One problem is that the literature does not provide a precise technical typology of these attempts to hybridize bottom-up and top-down approaches in multi-sector CGE models. ([Hourcade et al., 2006](#)) fosters the broader concept of hybrid modeling and reviews the existing approaches in four categories: (i) top-down models renouncing some conventional macroeconomic tools (CES production function, and the autonomous energy efficiency index (AEEI)); (ii) top-down models that increase their disaggregation level and resort to Leontief fixed-input ratios to include a reduced-form bottom-up module of some part of the energy system ; (iii) bottom-up model expanding into macro-economic toolkits ; and (iv) hybrid models including structural characteristics of top-down and bottom-up models. Their conclusion is that the model must be adapted to meet the necessary level of description for the specific problem under study. If the study highlights the diversity of existing hybrid modeling efforts, it does not provide a precise technical comparison of modeling approaches. [Böhringer and Rutherford \(2008\)](#) makes a step in this direction and distinguishes three categories of hybridization efforts: (i) the coupling of two pre-existing bottom-up and top-down models through *“soft-linking”*, (ii) the integration of a reduced form of one model type into the other and (iii) completely integrated models. The two last categories are also referred to as *“hard-links”*. However the authors do not go further in the characterization of hybrid approaches and put forward algorithmic issues of model coupling.

This chapter seeks to fill this gap in the context of multi-sector CGE models and builds a renewed typology and a critical synthesis of the attempts to embark engi-

neering based representations of technical systems in CGE models. The question of bottom-up - top-down hybridization, often boils down to a question of trade-off about the level of details and aggregation: *"multisectors CGE models are designed to take account of the myriad interactions among sectors of an economy, and among countries through international trade, and thus they cannot, at the same time, incorporate detailed specifications of technologies and devices that underlie the sector level projections"* (Schafer and Jacoby, 2005). But in fact the objective of hybrid modeling should not to get at all costs an *"all-encompassing model with full technology detail incorporated within a multination, multi-sector general market equilibrium representation of the macroeconomy."* Rather, the question should be put differently: to what extent is it possible to incorporate descriptions of technical constraints at sector level in CGE models that mimic bottom-up information and mechanisms? Put this way, the problem is less a question of level of granularity and complexity of representations *per se* than to get a representation of production and consumption possibilities that reflects the main structural constraints informed by bottom-up models and makes it possible to secure a dialog between engineers and economists.

The present chapter is organized as follows. Section 3.2 starts from the standard paradigm of the top-down production function and introduces the typology of the approaches to integrate bottom-up representations in a CGE model. Sections 3.3, 3.4 and 3.5 detail each main type of approach and highlight the respective strengths and weaknesses. Section 3.6 underlies the role of data and section 3.7 concludes.

3.2 A typology based on the nature of bottom-up integration

In order to characterize the existing options to integrate engineering based mechanisms in CGE models, it is useful to recall the standard toolkit used to capture production constraints in traditional CGE models: the top-down production function. CGE modelers traditionally use aggregated production functions to represent the technical possibilities for each economic sector. This function embodies the space of possible efficient combinations of aggregated factors and inputs (capital, labor, energy and others inputs) at time t - to produce one unit of output: $Y = F_t(K, L, E, M)$. Such "KLEM" production functions originate from aggregated growth models (Solow, 1957) and have been applied to the sector level in CGE models. The CES (Constant Elasticity of Substitution) form is the most common among standard CGE models and can be nested to different levels of complexity. However, capital, labor, energy and other inputs are originally not desegregated at the technology level (in the engineering sense). The base production function, which embodies price responsive technical *substitutions* can

be completed with two features to lead “semi-endogenous” *technical change* (Löschel, 2002): autonomous energy efficiency improvement (AEEI) and capital vintaging. As a result, technical dynamics results from the interplay between factor substitutions triggered by relative prices change, autonomous energy technical change and capital inertia.

Production functions are customary calibrated on a given year Social Accounting Matrix (SAM)¹. Elasticities of substitution are exogenously prescribed and sometimes come from specific econometric studies. Relying on the assumption of instantaneous producer’s cost minimization (or consumer’s utility maximization), Shephard’s Lemma² is used to calibrate the coefficients. These coefficients exactly correspond to the cost-shares in the initial input-output matrix. These cost-shares form a cost structure, which defines production inputs in terms of intermediate consumption – including energy, capital rent, labor wages and taxes. The weakness of the technical content of the calibrated top-down production function is thus rather intuitive. The calibration process starts from rough assumptions about substitutions possibilities between factors (most of the time of the nested-CES form) and the prescription of elasticities values only loosely specific to the sector under study. Then the heroic assumption of instantaneous optimum for base year historical data and for any future time steps, makes it possible to infer from a single year cost shares the future substitution constraints of one given production sector. One understand clearly the tautological aspect of such a *modus operandi*. Serious doubts about the technical content of production functions have been actually formulated. Solow himself has warned that the macroeconomic cost-shares “‘*wrinkle*’ is acceptable only at an aggregate level (for specific purposes) and implies to be cautious about the interpretation of the macroeconomic production functions as referring to a specific technical content” (Solow, 1988). Furthermore, Frondel and Schmidt (2002) raise concerns on this methodology, since the estimates for capital-energy elasticities are already driven by the cost shares and may not represent technological substitution: “*inferences obtained from previous empirical analyses appear to be largely an artefact of cost shares and have little to do with statistical inference about technology relationship*”.

To overcome these difficulties, economists have naturally attempted to modify or

¹There exists an important literature about the econometric estimation of production functions over a long time series, such as the key contribution of Jorgenson and Wilcoxon (1993). However the use of long time series to estimate production functions has become scarce and most recent CGE models are calibrated on a single year database. McKittrick (1998) further details the debate calibration *versus* estimation of production functions.

²Shephard’s Lemma corresponds to the application of the envelope theorem to the cost minimization for the producer.

combine the top-down production function paradigm with “true” technical information stemming from engineering based bottom-up models. Since almost a decade, the usual classification of these attempts has been that taken from [Böhringer and Rutherford \(2008\)](#) already mentioned in introduction. This classification of hybrid models mainly relies on the coupling mode between top-down and bottom-up models from an algorithmic point of view into soft- and hard-links. [Böhringer and Rutherford \(2008\)](#) defines the concept of “soft-link” as the coupling of “*independently developed bottom-up and top-down models*”. This coupling takes place through an exchange of data and parameter values to build consistent top-down and bottom-up scenarios. Examples include a coupling in just one direction: MARKAL transmitting information to EPPA ([Schafer and Jacoby, 2005](#)), or a convergence criterion between the coupled models: in general, one part of the CGE is exogenously fixed by the output of the bottom-up model. He opposes to soft-links two categories: reduced form of one representation within the other, and completely integrated models. [Crassous \(2008\)](#) proposes three categories: soft links, pseudo-hybrids (analog to reduced forms in [Böhringer and Rutherford \(2008\)](#)), hard links for completely integrated models. In this system, hard-link refers to jointly developed top-down and bottom-up models, integrated from conception. [Riekkola et al. \(2013\)](#) labels bottom-up models with simplified macro-economic feedbacks in hard-links, thus emphasizing the integration, but not the level of adequacy of the description, which would be labeled reduced forms or pseudo-hybrid in the previous classifications.

This typology, described in table 3.1, therefore emphasizes both the algorithmic mode to solve hybrid models and the level of integration of top-down and bottom-up representations. However the mode of coupling - whether soft or hard - is a technical issue *per se* and what finally matters is rather the kind of integrated vision embodied by the model coupling. In addition, the distinction between reduced forms and full integration within hard-links is blurry as such and need to be further characterized. For instance in which category should be put the attempts to expand CES production functions with information about individual technologies?

In this chapter we start from this initial typology to propose a slightly different one which directly emphasizes the quality and consistency of the integration of engineering based representations in multi-sector CGE models. We first assume that the “pure” engineering based representation of technical systems corresponds to the *activity analysis* ([Koopmans, 1951](#)) of bottom-up models. It includes (i) to distinguish a basket of discrete technologies characterized by given input ratios, (ii) to account for energy flows in physical units, (iii) to account for technology specific productive capacities with possible varying rates of utilization and (iv) to take into account techni-

Scope	Methodology	Examples
Soft-link	Calibration of time-dependent CES production functions with BU models	Schafer and Jacoby (2005)
	Substitution of full BU model for production function	Drouet et al. (2005)
Pseudo-hybrid or reduced form (also called hard-link)	Bottom-up models with simplistic macro-economic feedbacks	Manne and Wene (1992)
Hard-link	BU model as part of GE optimization framework	Böhringer (1998) Böhringer and Rutherford (2008) Frei et al. (2003)
	Dialog between BU <i>ex ante</i> production choice and GE with <i>ex post</i> production functions	Sassi et al. (2010) Bibas and Méjean (2014)

Table 3.1: Usual typology of hybrid models

cal constraints to technology substitution. One can further characterize hybridization attempts through the level of departure from this benchmark concerning the representation of technical systems they include. When the activity analysis of a bottom-up model is used as such in hybrid modeling exercises, it is required to characterize the level of *consistency* with the macroeconomic CGE framework. Our typology makes it finally possible to understand to what extent the structural constraints of the bottom-up approach are taken into account in hybrid models and what can be the remaining limits to the dialog between engineers and economists.

The precise analysis of surveyed approaches eventually led to a typology in three main categories shown in table 3.2. The first category - labeled *top-down expanded representations* - consists of CGE models which expand the sector production function towards the inclusion of identified technologies by means of technology-specific cost structures. Nevertheless, technology substitution mechanisms remain top-down in nature and activity analysis remains “surrogate” in the production function. The second category gathers attempts to embark bottom-up activity analysis as such but with only *partial consistency* with the macroeconomic framework. It includes different approaches such as the replacement of given production-consumption arbitrages in the CGE model by a bottom-up model through iterative computations or the direct integration of a reduced form of a bottom-up model into the CGE model. In any case inconsistencies remain unresolved such as variable linking, mechanisms overlap³ or the incompatibility between micro-economic and macroeconomic behaviors⁴. Finally, the third category includes the models with fully *integrated representations* where the previous issues have been solved. The state of the art for this category reveals two alternatives. The first option for integrated representation consist in the integration of activity analysis as part of the general equilibrium optimization framework. The second option consists in the dialog between *ex ante* production choices described by bottom-up models and the general equilibrium based on *ex post* production functions. Following sections provide a detailed assessment of each category.

3.3 Top-down expanded representations: “surrogate” activity analysis

This category includes the approaches based on an expansion of the usual sector production function by sub-scaling inputs and factors cost structure to the single technol-

³Linked to “inconsistencies in the treatment of common variables and processes due to differences in model structure, data, or definitions.” (Kydes et al., 1995)

⁴Myopic versus perfect foresight for instance.

Scope	Methodology	Archetype	Examples
Top-down expanded representation	Technology information in CES production functions	McFarland et al. (2004)	Sandoval et al. (2009)
		CES technologies in CES nests	Saveyn et al. (2012) Beestermöller and Fahl (2013) Karpplus et al. (2013) Morris et al. (2014)
		Sue Wing (2006)	Eskeland et al. (2012)
		Leontief technology in CES nests	
	Technology information in non-CES production functions	Schumacher and Sands (2007)	Fujimori et al. (2014)
		Leontief technologies in logit nests	
Partially consistent bottom-up integration	Reduced form 1: calibration of top-down elasticity of substitution based on a bottom-up model	Schafer and Jacoby (2005)	
	Reduced form 2: Calibration of a specific function to better mimic bottom-up mechanisms	Chersi and Hourcade (2006)	
	Substitution of a bottom-up model for CGE production/demand trade-offs through iterative simulation	Drouet et al. (2005)	Martinsen (2011) Riekkola et al. (2013) Fortes et al. (2014)
Fully integrated representation	BU model as part of GE optimization framework (e.g., MCP)	Böhringer (1998)	Frei et al. (2003) Böhringer and Rutherford (2008) Böhringer and Rutherford (2009) Tuladhar et al. (2009) Lanz and Rausch (2011) Proença and Aubyn (2013)
			Sassi et al. (2010)
	Recursive dialog between <i>ex ante</i> bottom-up models and general equilibrium based on <i>ex post</i> production functions		

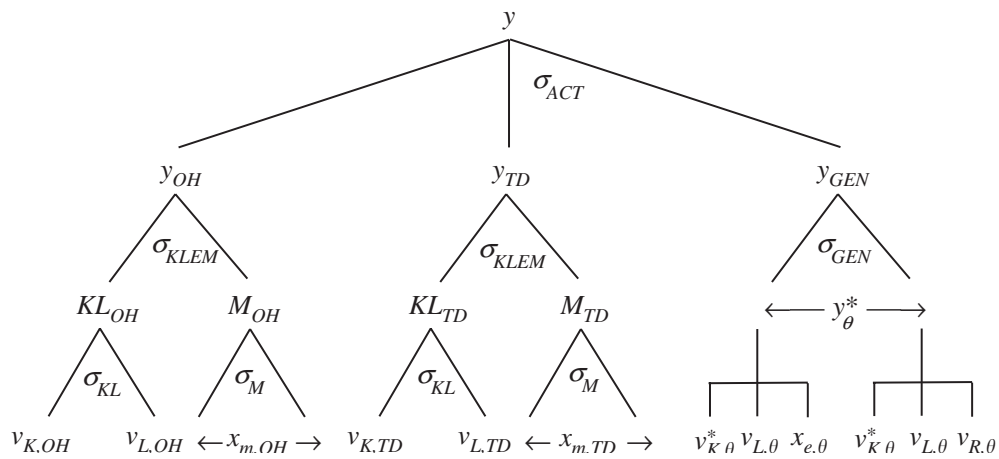
Table 3.2: Typology of hybridization methodologies with examples

ogy level. Furthermore individual technologies are singled out by means of their own cost structure - calibrated on engineering costs - and compete to supply sector output within the production function. Within this category, approaches mainly differ about the type of aggregation of technologies, either a CES or logit aggregation. However these approaches only correspond to a “surrogate” representation of activity analysis because they do not challenge the basics of the neo-classical production function. It implies first an aggregated vision of technology substitution by means of constant elasticity of substitution or logit market shares. Second, capital remains a neo-classical object which mixes up investment decisions and activity remuneration and does not distinguish between production level and capacity, a key feature of activity analysis in bottom-up models.

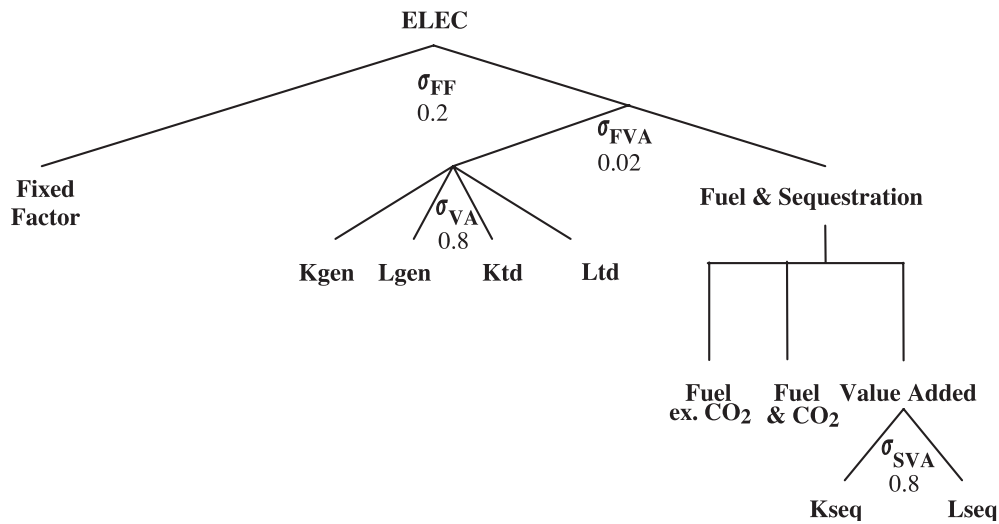
3.3.1 Technology information conveyed in CES production functions

The principles of the approach have been described in two papers: [McFarland et al. \(2004\)](#) and [Sue Wing \(2006\)](#). The approach has been further generalized in many CGE models (EPPA, FARM ([Sands et al., 2014a](#)), PHOENIX ([Sue Wing et al., 2011](#))) at least for power generation. The idea is to expand the usual top-down CES production function into a specific nesting structure including individual technologies by means of Leontief production functions (or CES functions with limited substitution possibilities) calibrated on technology specific costs. Figure 3.1 shows the nesting structures contemplated in [Sue Wing \(2006\)](#) and [McFarland et al. \(2004\)](#).

[Sue Wing \(2006\)](#) shows how it is possible to improve the representation of the power sector within a CES-nesting paradigm by isolating power generation activities and further breakdown global power generation into identified Leontief technologies. Each technology is defined by its own fixed technical coefficients about fuel, labor and capital. The competition between technologies is represented with a CES nest with a finite elasticity of substitution so that *“it allows [the technologies’] marginal costs to differ while ensuring that their activity levels are positive”*. The underlying objective is to get an explicit representation of identified technologies while avoiding the unrealistic “flip-flop” effect when technologies are perfect substitutes. This feature is also supposed to reflect specific technical constraints to technology substitution such as those linked to the load-duration curve of power generation. Representing individual technologies as such can further be used to represent non-extant “back-stop” technologies as in [McFarland et al. \(2004\)](#) on the example of a CCS technology. The penetration of a backstop technology is done by means of a fixed factor, whose endowment increases faster than the level of technology production. This feature makes it possible to control



(a) Electricity sector specification in Sue Wing (2006)



(b) CCS technology specification in McFarland et al. (2004)

Figure 3.1: Technology information in CES production functions – model structures

the cost evolution of the technology and its gradual penetration.

One key issue with such an approach is the calibration of technology specific costs based on bottom-up information. It requires in practice to reconcile SAM based data with technology data at sector level as detailed in [Sue Wing \(2008\)](#). Furthermore bottom-up data about capital, O&M and fuel costs per technology are interpreted as capital, labor and energy cost shares to calibrate the production function. The competition between technologies is then based on their relative levelized costs. Eventually, this approach can be easily combined with a capital vintaging formulation of inter-temporal dynamics.

Expanding a nested-CES production function into identified technologies in combination with capital vintaging is a convenient way to capture some key aspects of technology dynamics, partly because it does not challenge the standard top-down formulation of the CGE. However the nested-CES framework is not without drawbacks regarding the realism of technology substitution and the control of underlying technical processes.

First, as [Sue Wing \(2006\)](#) acknowledges, a CES formulation “*aggregates economic quantities in a nonlinear fashion, conserving value but not physical energy*”. The CES aggregation thus violates the “conservation of mass” in the model and further complicates the accounting of physical flows of energy. In particular total electricity production is not the sum of the outputs per technology outside the benchmark equilibrium. In concrete terms, the initial proportionality between pseudo-quantities and physical quantities cannot be conserved when the initial equilibrium is modified. Therefore the identification of physical quantities might be abusive.

Second, the models are still expressed in monetary flows, even for the description of technologies. Even though, strictly speaking, the accounting in pseudo-quantities within the SAM keeps the proportionality between pseudo-quantities and physical quantities, modeling the technologies in monetary terms presents difficulties. The dialog with engineers is made difficult by the constant need to return to the initial data to infer the changes in physical units (of which [McFarland et al. \(2004\)](#) constitutes an example). Further, the translation of physical constraints must therefore always be translated into monetary terms to be included in this framework. Thus, the evolution of physical quantities may not be transparent and may result in a lack of control.

Third, the standard production functions (in particular the CES) only materialize certain types of technological change: smooth substitution most often with a constant elasticity, AEEI improvement and smooth backstop penetration with fixed factors. However, if the aim is to reproduce realistic technology dynamics, then the model has difficulties in representing complex trade offs resulting in improved energy efficiency

and non economic constraints. It is also very difficult with a sector CES production function to represent radical changes from the initial situation. In that case, the use of a function with constant elasticity of substitution may not be the most suited to reflect real physical limits. It might be advocated that further disaggregation of the CES into a very large number of sector, almost technologies at that point, lead to a model that can simulate bottom-up behavior. However, the simulation of singularities rests on the representation of very important costs (decreasing for a backstop or increasing for a phasing out), whose calibration may be problematic. Therefore, the representation of radical changes (the apparition of a backstop or a technology phasing out) is not easily done. It is all the more debatable when the constraint does not correspond to physical constraint leading to an economic cost or rent, but stems for a political decision.

3.3.2 Technology information in non-CES production functions

Schumacher and Sands (2007) adopts a strategy similar to that of Sue Wing (2006) and McFarland et al. (2004) by incorporating bottom-up information about identified technologies for steel production in a recursive dynamic CGE model (SGM). The main difference rests on the mechanism of substitution between the technologies. Instead of relying on a CES aggregation, as in Sue Wing (2006), the authors use a *logit* nest of fixed-coefficient cost functions (Leontief)⁵. In practice, the logit function determines the market shares of the different technologies in the production mix according to their relative levelized costs.⁶

One important characteristic of a logit nest compared to a CES aggregation is that it preserves the quantity balance of physical flows. The total output of the sector thus continues to be the sum of the outputs of the operating technologies outside the benchmark equilibrium. Furthermore, the output level per technology keeps its physical sense throughout the simulated path. The conservation of the physical meaning of output makes it possible to keep a direct control of physical and thermodynamic indicators of the production mix, such as energy efficiency. The consequence is that there is an identification of top-down and bottom-up variables for the representation of the sector on energy fuel mix, output per technology, thermodynamic efficiency and car-

⁵“Each fixed-coefficient cost function represents a specific technology for producing steel with technical coefficients constructed from engineering data.”

⁶ Even though the logit is used in the same manner as a CES production function there is a fundamental difference between the two. A CES production function represents the production possibilities without any notion of cost. Only the addition of the cost minimization program yields the choice of production process. However, the logit function already encapsulates the choice and the production possibilities. A given set of costs thus results in a unique production choice yielded by the logit function. Therefore, the logit is not analogous to a production function but to the production function combined with the agent’s economic decision.

bon emissions. This feature is consistent with the general approach of the SGM model which is directly based on a “hybrid input-output table”. In this framework, physical flows are described with real physical units (Joules, tons, etc) and material balances as well as physical indicators are maintained throughout the simulated paths. This attempt thus constitutes an improvement over the CES aggregation of technologies.

The objective is the same than with the CES-Leontief approach though: make the energy consumption changes and factor substitution of a given production sector (power, steel, etc) consistent with shifts among identified technologies. This includes the incorporation of improvements of technology characteristics, innovative backstop technologies available at some point in the future and possibly R&D and learning endogenous technical change mechanisms. As a whole it is possible to represent radically novel production structures, very different from base year, in the case of drastic climate policies “*where energy prices can be driven far outside their historical range*”. In comparison, a standard aggregated CES functions is rather conservative towards production factor cost-shares.

3.3.3 Top-down capital allocation *versus* activity analysis

Despite the important improvements described in sections 3.3.1 and 3.3.2, the representation of technology substitution keeps a top-down flavor through its capital representation. As in a standard top-down CGE model, there is no distinction between capital as physical capacities of production - “machine capital” - and financial capital. The capital endowment is in fact a factor used in production – as any other factor including labor – to be remunerated at a rental price corresponding to its marginal productivity. The economy each year makes use of the stock of capital that gets depreciated and expanded through investment. Most CGE models in the E3 field, particularly when considering top-down-bottom-up hybrids, represent some kind of macro capital vintages. In that case, the installed capital in the past cannot be changed back to malleable capital to be redistributed in other sector or technologies. Some models exhibit some degree of malleability where part of the capital may be converted back to malleable capital to be reinvested (“putty semi putty”).

Consequently in the model, the level of output per technology for the last vintage, the corresponding capital need and the capital costs or income are determined simultaneously. More precisely, the production function (whether CES or Logit) represents several economic operations in a single feature: the trade-off between technologies based on levelized costs, the choice of the level of added investment per technology, of the level of output per technology - identical to the capacity level - and of the capital

remuneration of each technology. To do so, the production functions are calibrated as long term production functions (that is over the whole capital stock of economic sectors at base year) and used as short term production functions (only over the portion of capital that is currently being invested in)⁷. The economic choices embodied in such functions reflect myopic expectations⁸. In particular, levelized costs only depend on current prices (energy, labor and capital) and implicitly suppose constant future prices. In addition, this framework can not capture key bottom-up features beyond levelized costs such as the constraints of a load curve or intermittent technologies for power generation. More fundamentally, this framework does not distinguish between level of output and level of production capacity which is a key feature of activity analysis. The capital factor is actually considered as fully employed and the under-utilization of installed capacities is not an option. However the question of over capacity is key for power generation in particular. Furthermore, such a framework does not capture the existing differential rents between technologies nor distinguish new investment from economic dispatch for instance.

In the three examples detailed, the representation of technology specific capital stock or partial capital malleability, allow for some inertia and rigidity mechanisms though. [Sue Wing \(2006\)](#) introduces technological capital that can be transformed back into malleable capital through a constant elasticity of transformation function (CET). However such features do not make it possible to differentiate retrofitting or early scrapping mechanisms from variable utilization rates of installed capacities in the short to medium run. Similarly, [McFarland et al. \(2004\)](#) introduces technological capital stock that is not malleable after investment, except for a fix portion at each time step. [Schumacher and Sands \(2007\)](#) represents a pure “putty-clay” approach where installed capital is no longer malleable. The malleability of capital in the short run in fact refers to two very different realities. It is a proxy to represent both the variation of the capacity utilization rate of the different technologies and the effective changes of capacity levels. At the same time, this trick allows to stick to the rule of full utilization of the capital factor. But retrofitting or early scrapping mechanisms can not be distinguished from variable utilization rates of installed capacities.

However, the bottom-up view of technology scenarios is the investment in “machine” capital, paid for in monetary value, including given performance characteristics and uses the available capacity to produce. Conversely the top-down neo-classical

⁷This assumption relies on an assumption of constancy of the marginal investment, that is supposed to correspond to total investment over a long period.

⁸In fact short-term perfect expectations because the prices of factors governing production choices in intra-period equilibrium are the realized prices.

treatment of capital only rests on the monetary view: capital is considered as a malleable object without material embodiment. In particular, in bottom-up activity analysis, investment in capacities corresponds to a sunk investment. Investment is made based on expectations and expected profits are different from realized profits. Once this investment is made, the machine capital is locked in this form with a fixed technological efficiency. The possibilities of retrofit are especially very limited. Moreover, the partial utilization rate (especially in the electricity sector) allows an increased production without an additional capital investment.

This section echoes the “Cambridge capital controversy”. Indeed, the status of capital in the neoclassical paradigm was challenged. The measure of the capital stock and the profit of revenues was debated since they cannot be independently determined. Moreover, the representation of capital as an homogeneous stock in monetary values for the aggregation to be possible runs into this hurdle. We will not go here into this debate, but refer to the large amount of literature on the debate (see for instance [Cohen and Harcourt \(2003\)](#) and [Robinson \(1953\)](#)). However, we will take this debate as further evidence that top-down capital may not adequately represent the properties of bottom-up capital, in particular heterogeneity and inertia.

When looking outside the economic community, the expression of production capacities in values may render the dialog with engineers difficult. If engineers could agree on a given investment sunk cost for a production unit, they surely would not agree on the value over time of the installed capital (which would then depend on the valuation method, the sectoral and extra-sectoral context, and of course on their expectations for these parameters). Regardless of this impediment, the monetary value of a production unit just does not seem like the adequate measure of a production capacity for engineers: in the power sector, it would be MW, in the oil sector, barrels per day and so on. Thus, even if considering the top-down representation adequate, the problem of dialog with engineers persists.

3.4 Partially consistent bottom-up integration

The difficulties to embark activity analysis and specific engineering based mechanisms directly in a multi-sector CGE model led to the parallel development of alternative hybridization methods based on the *partial* coupling between two existing models: a bottom-up model of part of the energy system and a multi-sector CGE model. Conceptually the goal is to inform a set of techno-economic arbitrages of the CGE model with a bottom-up model. One can distinguish in practice two approaches to perform the coupling: (i) a direct linking between the two models through iterative exchange

of variables until convergence, (ii) the construction of a *reduced form* of the bottom-up model to be included in the CGE model. These approaches do embark engineering based mechanisms but to the price of a partial consistency of the integration. Consistency issues are of three types: (i) the internal vision of the coupled system may show incompatibilities such as about micro-economic behaviors between the two models, (ii) part of the variables of the bottom-up model may not be linked and may *overlap* with their counterpart in the CGE model and (iii) the correspondence between the linking variables in the two models may be indirect and even with direct correspondence, convergence may be imperfect for these common measuring points (CMP) (Wene, 1996).

3.4.1 Substitution of a bottom-up model for CGE production/demand trade-offs through iterative simulation

The first existing approach of model “soft-linking” consists in replacing a set of technoeconomic trade-offs of the CGE model by the equivalent trade-offs resulting from a bottom-up model through variables exchange and iterative simulation until convergence. This coupling approach has gained success owing to the convenient “soft” combination of two existing models. Numerous attempts exist in the literature with the coupling between a CGE model and a bottom-up model for a single sector alone, e.g. residential (Drouet et al., 2005), power sector (Martinsen, 2011) or the entire energy system (Fortes et al., 2014). However the approach raises consistency issues generally not entirely assessed in practice, which entails the risk to lack the needed quality control of the overall energy-economy picture generated.

Drouet et al. (2005) represents an initial attempt of such coupling and makes it possible to enhance the main issues about the general approach. The paper presents the coupling of the dynamic-recursive CGE model GEMINI-E3 with a MARKAL type bottom-up model of residential energy consumption. The method consists in replacing the fuel mix arbitrage in the CGE residential demand by the final energy consumption trade-off computed by the bottom-up model. The iterative method is based on exchanging variables between the two models as detailed in fig. 3.2. First, the CGEM transmits residential useful energy demand levels (with constant budget share of residential services in the CGE) and energy and carbon prices to the bottom-up model. Then, the bottom-up model computes final demands for energy carriers and carbon emissions that become exogenous parameters for the next CGE run. A criterion of convergence on carbon tax levels along the entire path of the economy is used. In the end the pathway of demands for residential energy carriers is consistent with the bottom-up

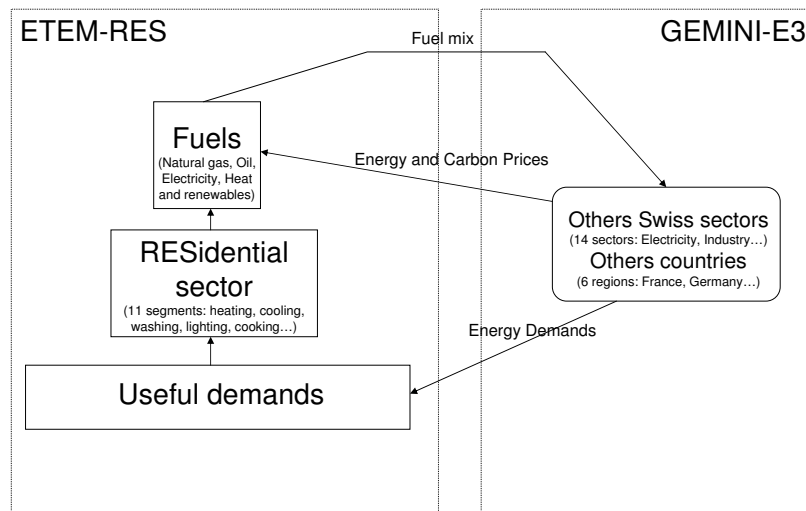


Figure 3.2: Drouet et al. (2005) hybrid model structure

model in relation to the pathway of useful energy demand and fuel prices.

Although the coupling method looks appealing considering its ease of implementation, it raises important consistency issues. First of all, combining two existing models often leads to disregard the difference of economic paradigm about micro-economic behaviors. In Drouet et al. (2005) the modelers seek the convergence between an intertemporal optimizing energy model and a recursive dynamic CGE model. Furthermore one can legitimately questions from the start, the signification of combining an intertemporal optimizing behavior under perfect foresight about residential energy choices with myopic expectations for others non-energy goods. This issue could be quite easily solved by using a bottom-up simulation model with myopic expectations for coupling with the recursive dynamic CGE. Some recent attempts do respect the compatibility of economic paradigms⁹.

In addition Drouet et al. (2005) raises consistency issues about variable linking. First of all, the correspondence between linked variables is indirect because they are expressed in different units in the two models. Subsequently a connection must be made between them such as a “percentage change procedure”, where the energy demands in monetary values (\$) of the CGE vary in proportion with the energy demands in physical units (toe) provided by the bottom-up model. However, the realities underlying the initial values might be very different and may imply a loss of control of variables evolution, especially if the initial database are not reconciled. Database reconciliation is thus a key component to improve integration.

⁹In Fortes et al. (2014) both models perform an intertemporal optimization. Riekkola et al. (2013) further circumvents this difficulty by using a static CGE model.

Second, the convergence criterion determines the potential final gap between the linking variables in the two models. If the convergence criterion basically ignores part of the linking variables, it may result in contrasted values for these variables between the two models. In [Drouet et al. \(2005\)](#) the convergence is guaranteed on the tax paths and not the energy demands, so we do not know the extent of the difference between the model results (it might be that it is very large, but merely the tax paths are consistent). Furthermore, even though they might be consistent, we are not even assured that they might result in the same energy demands.

Eventually, a final type of inconsistency results from the missing links between the two models. For the few variables that are indeed linked, how many more are not. The variables and processes that are not linked represent competing views of same realities between the two models and correspond to overlapping representations¹⁰. In [Drouet et al. \(2005\)](#), the links between the expenditure in housing equipment in the CGE households budget and the corresponding investments in the bottom-up model are missing¹¹. At least two important feed-backs are thus ignored: the price variations of equipment goods happening in the CGE model are not transmitted to the bottom-up model and in return, the variations of housing equipment expenditure consistent with bottom-up technical choices are not taken into account in the CGE households budget. One can further wonder what it means that the technological changes brought about by the bottom-up model, which in the case of climate policies, often go along with an increased capital intensity, are not paid for by capital expenses. The overlap on capital representation between top-down capital and bottom-up equipment with missing linkages is a regular “blind-spot” of model coupling.

3.4.2 Reduced form 1: calibration of top-down elasticity of substitution based on a bottom-up model

The substitution between two aggregated factors in a top-down production function (energy and capital for instance) is supposed to synthesize underlying substitutions between identified technologies embedded in vintages of equipment. Instead of sub-scaling the top-down substitution towards the single technology level within the nested-CES function as in section 3.3.1, one alternative is to keep the CES top-down arbitrage and calibrate a time-dependent elasticity of substitution based on the behav-

¹⁰[Kydes et al. \(1995\)](#) defined “model overlap [as] resulting from inconsistencies in the treatment of common variables and processes due to differences in model structure, data, or definitions.”

¹¹“Non-energy consumption for housing is supposed to change in response to changes in relative household consumption prices (including fuel prices) but is not modified by the energy mix resulting from technology choices in ETEM.”

ior of a bottom-up model which develops the underlying technical dynamics at the technology sub-level. The resulting production function is in this case a *reduced form* of the bottom-up model.

Schafer and Jacoby (2005) explores this track on the transport sector by coupling the EPPA model with a MARKAL model. The top-down nested-CES structure of both household's transport demand and the transport services sector is shown in fig. 3.3. In particular, household's own transport, which corresponds to the services of privately owned vehicles, is provided by the combination of purchasing vehicles and related services (*OIND*) and oil fuels (*REFOIL*). The substitution away from *REFOIL* as fuel price increases represents the switch towards more efficient but more costly private vehicles (light duty or trucks). The hybridization procedure consists in calibrating a time-dependent σ_{RO} elasticity that would make it possible to mimic MARKAL behavior in EPPA about own transportation. To do so, MARKAL is run until the time horizon for a range of fuels prices and the aggregated results are interpolated by a CES function for each time step to yield a logistic curve for the time-dependent elasticity shown in fig. 3.4.

This method is a step forward in incorporating bottom-up mechanisms within the CGE-CES framework. In particular, it allows a time profile for the substitution elasticities, accounting for bottom-up mechanisms such as capital vintages and their replacement. However the partial coupling actually implies consistency issues. Like in Drouet et al. (2005), Schafer and Jacoby (2005) attempt to combine contrasted economic paradigms about microeconomic behavior, which is "*buried in [the] calibration procedure*". While EPPA is recursive dynamic with myopic expectations, MARKAL performs an intertemporal optimization with perfect expectations¹².

The questions of the consistency about variable linking also apply. The linking variables (total transport service, aggregated fuel consumption and vehicle purchase) are expressed in different units and may cover different realities in the two models. Consequently "*a connection must be made between models that are formulated in different units*". In addition, as shown in fig. 3.4, constant elasticity functions depart significantly from bottom-up "data points" for large deviations from the reference¹³. This supports the idea that bottom-up mechanisms can not be appropriately captured by a single constant elasticity function. The implied gap for vehicle - fuel demand ratios for similar relative prices between the two models is similar to the case where convergence

¹²Regarding the effect of this difference, "*the magnitude cannot really be determined without a forward looking version of the EPPA model*", which would solve this paradigm incompatibility.

¹³This incompatibility in fact "*suggests one area where we cannot expect a perfect match in energy use between the MARKAL and EPPA models*".

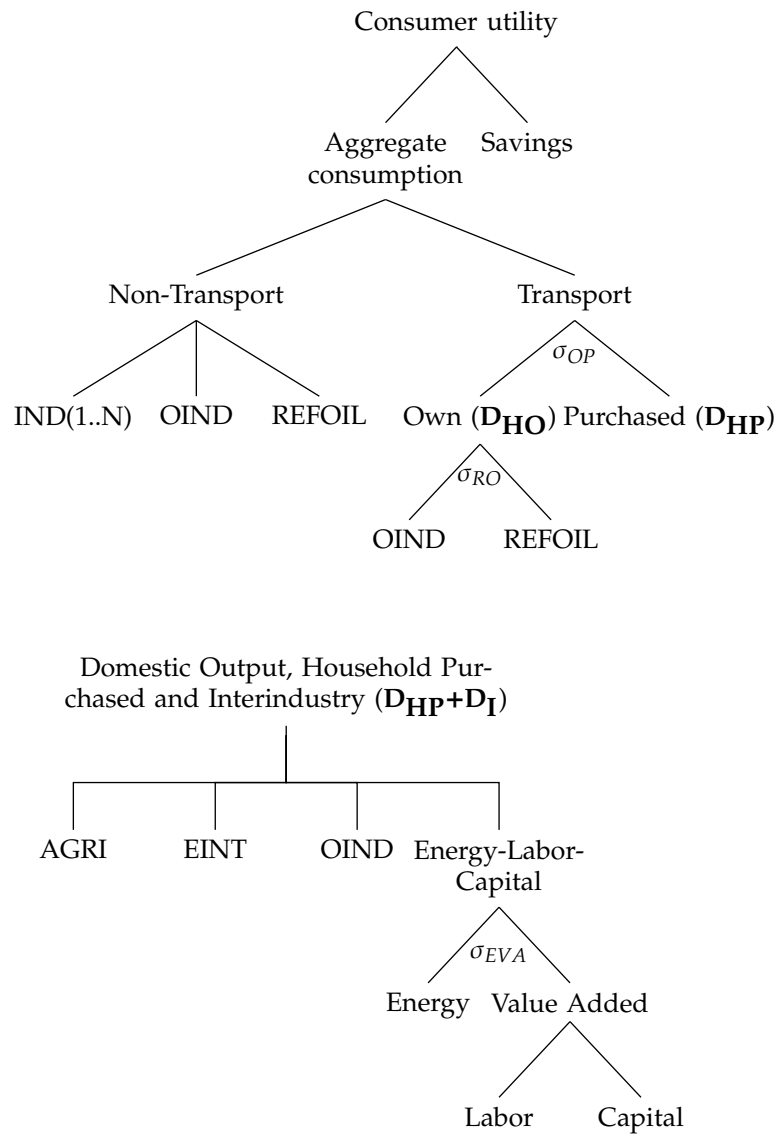
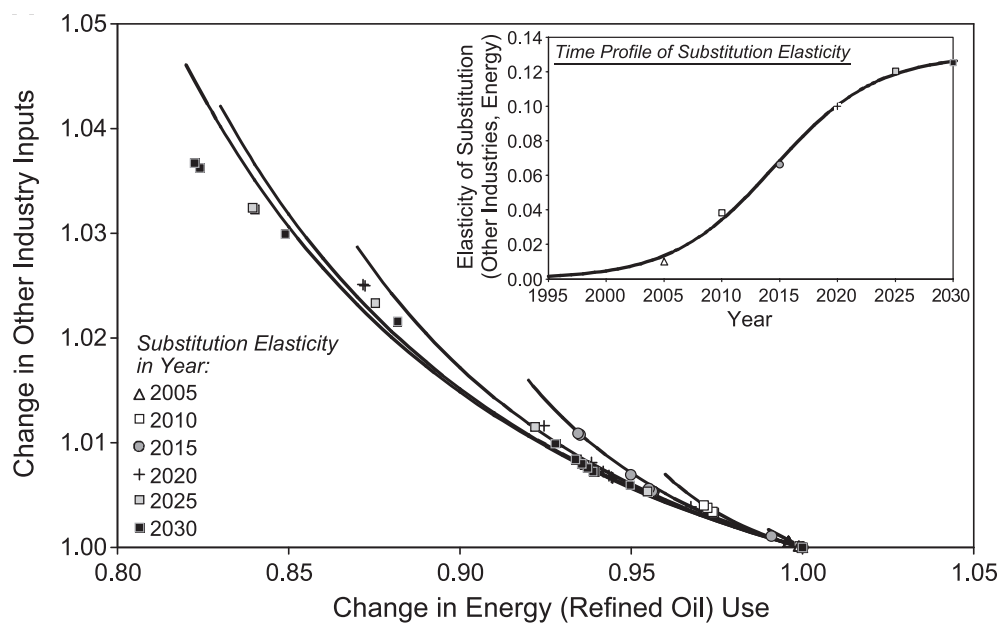


Figure 3.3: Nested-CES structure of the top-down model



“Calibration of substitution elasticities in household-owned supplied transportation. The data points result from MARKAL model simulations, while the continuous CES curves are fitted through the data points of each time step.”

Figure 3.4: Elasticities calibration – from [Schafer and Jacoby \(2005\)](#)

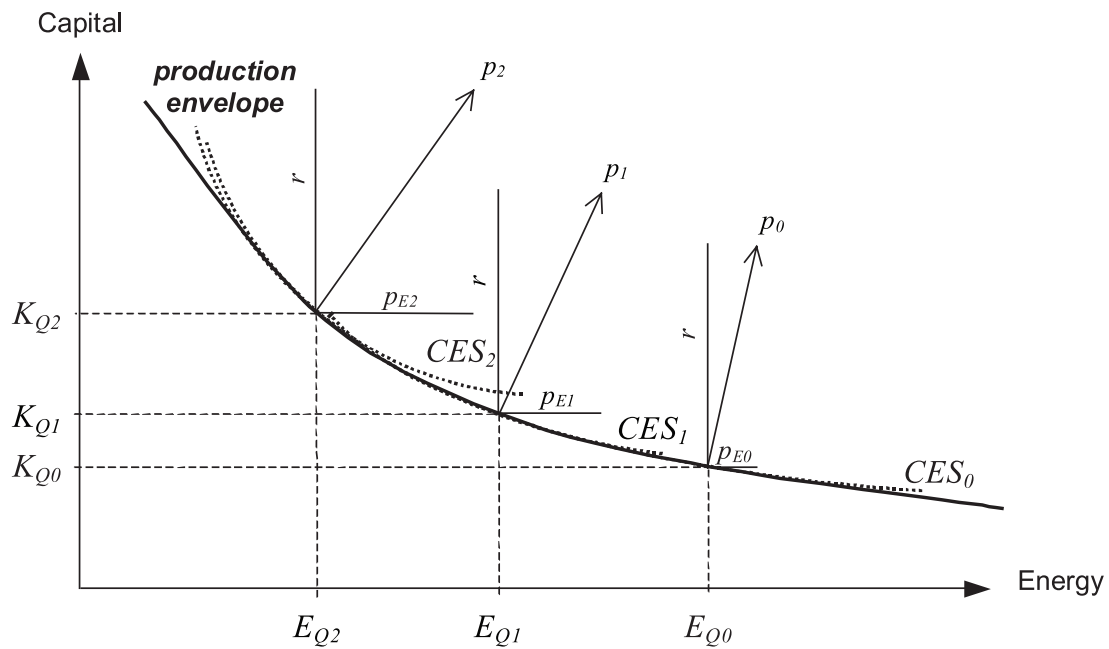


Figure 3.5: Production envelope – from [Gheri and Hourcade \(2006\)](#)

between linked variables can not be met in the case of iterative simulation.

3.4.3 Reduced form 2: Calibration of a specific function to better mimic bottom-up mechanisms

[Gheri and Hourcade \(2006\)](#) presents an attempt at overcoming the difficulty that the CES production function cannot approximate bottom-up behavior for large departures from the reference. As a consequence, they use specific functions instead of the standard CES production function toolkit. The calibration of the reduced forms essentially consists in the production of bottom-up data points for various macroeconomic contexts to fit a reaction function (see fig. 3.5). This reaction function is essentially a top-down function¹⁴ describing the technical trade-offs possible according to the bottom-up model within the top-down framework. These reduced forms allow any kind of behavior, in particular non constant elasticities of substitution and technical asymptotes for substitution. Figure 3.5 illustrates the case of the building from point to point of a variable elasticity of substitution along the isoquant.

In addition, this attempt does not suffer from the same difficulty in variable linking

¹⁴ The reaction function is used similarly to the production function. However, as for the logit function used in [Schumacher and Sands \(2007\)](#), it already contains the bottom-up choice. As such, it replaces both the CES production function and the cost minimization program.

top-down and bottom-up models as [Schafer and Jacoby \(2005\)](#). Indeed, their framework starts with the construction of SAM in values and physical quantities, linked by prices. When simulating changes away from the reference equilibrium, both the SAM in values and physical quantities are deformed. This means that the top-down framework allows them to express the physical quantities in physical units, which is called “dual accounting”. The dual accounting is the same approach as the one used in [Schumacher and Sands \(2007\)](#). The expression of the macroeconomic equilibrium in physical units, prices and values, therefore accommodates a reduced form which links prices and quantities in physical values. That is why the link with the bottom-up model is made more explicit. Furthermore, the dialog procedure is simplified since both models communicate in the same units.

This attempt provides a methodology to incorporate a bottom-up model under a top-down format using a top-down function. While it may considerably enhance the ability of top-down models to incorporate bottom-up behaviors, the capital input fundamentally remains a top-down object different from production capacities of activity analysis. As such, the representation of fine mechanisms such as singularities might be out of reach. Finally, building the reduced form of the bottom-up model with more than two production factors can turn out pretty costly in practice.

3.5 Fully integrated bottom-up representations

Finally, fully integrated bottom-up representations, beyond considering discrete technologies, embark activity analysis in a CGE modeling framework and split between investment dynamics of technology specific capacities - else including advanced technical considerations - and utilization rate of capacities and rent generation. In addition, all coupling inconsistencies are removed through built-in joint evolution and full integration: incompatibility of micro-economic behaviors, variable linking and overlap. We identified two strands of integrated representations, relying on either integrating the bottom-up model as part of general equilibrium optimization framework through solving a *mixed complementarity problem* (MCP) or the recursive dialog between bottom-up *ex ante* investment choice and general equilibrium computation with *ex post* production functions.

3.5.1 Mixed complementarity problem (MCP)

This approach relies on the extension of the definition of general equilibrium problem as an optimization problem under constraints. The general idea is to encode the

bottom-up model to integrate it as part of the optimization framework, especially using the constraints¹⁵.

With this setting, the complementarity feature allows much flexibility in the representation of economic mechanisms. In particular, complementarity can lead to each equation displaying different regimes, which can be used to represent alternative production technologies (which can be derived from bottom-up information). This propriety of MCP makes it a good candidate, not only for general equilibrium practical implementation, but also for bottom-up information integration. The mixed complementarity format can be used with a *static* CGE model (Böhringer, 1998) or extended in *dynamics* within an intertemporal framework (Böhringer and Rutherford, 2008) or else with any type of expectations (Frei et al., 2003).

Böhringer (1998) demonstrates how to embark activity analysis through complementary slackness, illustrated on the electricity sector to yield a fully integrated hybrid static CGE model. The static framework describes capacities as limits to the production for each power generation technologies. Reaching the constraint for one technology then creates an inframarginal rent (the value of the Lagrange multiplier), which corresponds to an activity formulation of the competition between power generation technologies. Of course, the production constraint can also not be reached (when the Lagrange multiplier is equal to zero), leading to capacity under-utilization. Each technology is represented by means of fixed technical coefficients. Finally, representing discrete technologies through complementary slackness translates into responses very different in nature from usual production functions¹⁶.

Böhringer and Rutherford (2008) expands the static framework of Böhringer (1998) to include the investment dynamics for the electricity sector. Investment decisions are made and marginally affect capital stocks. This extension relies on a few additional

¹⁵The specificity of this approach is to allow for weak inequalities (binding or not) and complementarity between variables and functional relationships (Mathiesen, 1985). MCP problems describe a set of equalities and weak inequalities. The MCP problem finds a solution where each constraint satisfies one of the conditions described in the set of equations 3.1, where lower bounds $lb \in \{\mathbb{R} \cup \{-\infty\}^n\}$ and upper bounds $ub \in \{\mathbb{R} \cup \{\infty\}^n\}$.

$$\begin{array}{lll}
 \forall i \in 1, \dots, n & & \\
 F_i(x) = 0 & \text{and} & lb_i \leq x_i \leq ub_i \\
 F_i(x) > 0 & \text{and} & x_i = lb_i \\
 F_i(x) < 0 & \text{and} & x_i = ub_i
 \end{array} \tag{3.1}$$

¹⁶The comparison of the bottom-up model to two different usual top-down specifications with nested CES production functions exhibit different behaviors regarding the substitutability and complementarity of capital and labor. The hybridization with bottom-up exhibits non-monotonic behaviors: the local properties of capital demand vary with prices (first demand decreases with low price increases and then demand increases with high price increases).

equations. First, the efficient allocation of capital (over time) rests on two intertemporal zero-profit conditions on capital formation and on investment opportunity. Second, capital follows geometric investment and depreciation. For demand, intertemporal decisions result from behaviors based on intertemporal utility maximization (of the infinitely-lived representative agent) which allocates income over the whole period. The representation of the mechanisms in bottom-up models translate into a large number of constraints, which in the MCP framework, are explicitly represented by variables to account for monetary transfers following these constraints. Even if any bottom-up model can be expressed in this form, the practical application of this methodology may therefore be limited by the “dimensionality” of the problem.¹⁷

Frei et al. (2003) build on the MCP framework introduced by Böhringer (1998). They also expand the static structure to incorporate investment dynamics of the electricity sector but with more general intertemporal features than in Böhringer and Rutherford (2008). They especially show that their model can include any type of assumptions about agents expectations, which they illustrate with myopic expectations. Moreover, they formalize endogenous investment decisions deriving from a fully integrated bottom-up model. They incorporate this investment behaviors into a top-down framework to describe technology-specific capital formation and utilization. In particular, they conclude that their framework allows for the representation of singularities such as technologies emergence and phasing out, which cannot be embedded in the smooth functions usually used. The linking between models corresponds to the identification of the rate of return of capital between the CGE framework and bottom-up model. At the top-down level, firms are assumed to maximize their expected profits (consisting of revenues for the current year and expected future streams of revenues), which lead the expected returns to be equal to the cost of capital. At the bottom-up level, the revenue of a given technology includes a short-term scarcity rent (also called infra-marginal rent in the electricity sector) as well as a capacity payment for system service, and is reduced by depreciation and adjustment costs. The top-down (usual) equality between marginal productivity of capital with its marginal costs translates in the bottom-up model into technology-specific revenues to be equal to the rate of return of capital, to which the long-term scarcity rent is added. These decisions are made using myopic expectations for future values of prices, quantities, costs. In a nutshell, Frei et al. (2003) attempt at reconciling capital in its financial form in capital markets with

¹⁷ Böhringer and Rutherford (2009) present an attempt to overcome this difficulty by using a decomposition approach of the bottom-up and top-down models in a consistent framework. However, this attempt relies on approximation that may entail a lack of control: “The bigger the size of the energy sector the poorer is the Marshallian demand approximation in the energy sector to the general equilibrium demand.”

capital in its already physical form, once sector-dedicated (even technology-specific) capacities are installed, through endogenous (and sector-specific) return on capital based on myopic expectations.

Finally, the MCP approach succeeds in fully integrating top-down and bottom-up models. Most relevant, the bottom-up capacities are fully integrated with the top-down financial capital expenses. While showing much promise, this strategy has shown difficulties so far in tackling empirical issues. Therefore the case for this strategy remains to be made on an empirical basis. The processing of the bottom-up specificities at a level meaningful for the analysis actually proves often too complex for this methodology.

3.5.2 Recursive dialog between *ex ante* bottom-up models and general equilibrium based on *ex post* production functions

One solution to overcome part of the complexity of MCP in dynamics is to cut off the choice of investment in new productive capacities and the technology arbitrage from general equilibrium computation.

In practice it means to create an iterative dialog between a bottom-up model as an *ex ante* production choice and a general equilibrium computation based on *ex post* production possibilities. The bottom-up model is used to describe the production alternatives, that is all the possible technologies used to produce, before any firm choice in capacity investment. In the sense of Johansen (1972), this corresponds to the *ex ante* production choice. The capacity investment choice is realized by the bottom-up model, which allocates available investment - provided by previous equilibrium - to the different sectors and technologies. Then, the general equilibrium takes as an input the installed capacities of production with given embedded technologies and realizes the *ex post* production choice mainly based on varying the rate of utilization of available capacities to yield effective output levels. In this terminology, *ex ante* and *ex post* refer to the technical possibilities before the capital investment choice (*ex ante*) and the much more restricted technical possibilities after the capital investment choice (*ex post*)¹⁸. This separation is at the core of this strand of hybrid models. From

¹⁸In the words of Johansen (1972), the blueprint for this approach is as follows. “The fundamental assumption underlying the following approach is that the essential technological choice with respect to factor proportion and exploitation of new production techniques has to be made at the stage when investment in new production equipment takes place. At later stages choice is restricting to deciding to what extent the equipment is to be operated within bounds set by its capacity, operation requiring current inputs in fixed proportions as between themselves and in proportion to output. The case for such assumptions is straight-forward: Direct inspections of production processes indicate that such assumptions give a better approximation than the traditional assumption of smooth substitution possibilities at all moments of time.”

the bottom-up point of view, it makes it possible to capture the distinction between production capacities and actual output levels. In the meantime it operates a split between *ex ante* technology costs consideration and *ex post* rental remuneration of capacities¹⁹. Moreover *ex ante* investment choices can be based on quite detailed bottom-up considerations without stumbling over computation limits because it is out of the general equilibrium computation.

IMACLIM-R (Sassi et al., 2010) aims at meeting this blueprint, as illustrated in fig. 3.6. At a given year, technologies are fixed and no substitution between inputs can occur. Input-output coefficients evolve each year according to the engineering information contained in the dynamic modules. The evolution of the production frontier over time is determined by the joint transformation of economic and technical systems. This recursive structure relies on a systematic exchange of information between an annual macroeconomic equilibrium and technology-rich dynamic modules. Hybrid matrices (Gherzi and Hourcade, 2006) ensure a description of the economy in consistent money values and physical quantities (Sands et al., 2005). This hybrid accounting framework represents the material and technical content of production processes and allows for abandoning standard aggregate production functions.

Bibas and Méjean (2014) details the example of the coupling of IMACLIM-R with the electricity sector. In particular, the electricity bottom-up model takes in prices and quantities from the last period and derives expectations on future prices and quantities. Given these expectations, they assess the *ex ante* production choices, that is the power generation technologies. When this assessment is done, the investment is realized for the various technologies. The investment consumes capital and builds capacities whose technical characteristics and performance are fixed. The existing vintages of capacities then provide an *ex post* production functions. For this *ex post* production function, the substitutability relies on a partial utilization of existing capacities. Thus, individual capacities have given performance, but the aggregate production function at the sector level allows for some flexibility through partial use. The aggregation from individual technologies to a sectoral production function rests on capacity utilization estimated from expectations. This translates into a fix coefficient technology described by a Leontief production function which is then inserted in the general equilibrium framework. The adjustment is made at the aggregate level through labor costs increasing with growing utilization rate of the aggregate capacity. This methodology translate the dual production functions that Johansen (1972) explained as capital being a fixed factor in the *ex post* function, while it was an input in the *ex ante* function.

¹⁹Let's recall that standard top-down production functions mix *ex ante* and *ex post* choices which blurs the status of capital in the function, which is among others at the origin of the "Cambridge controversy".

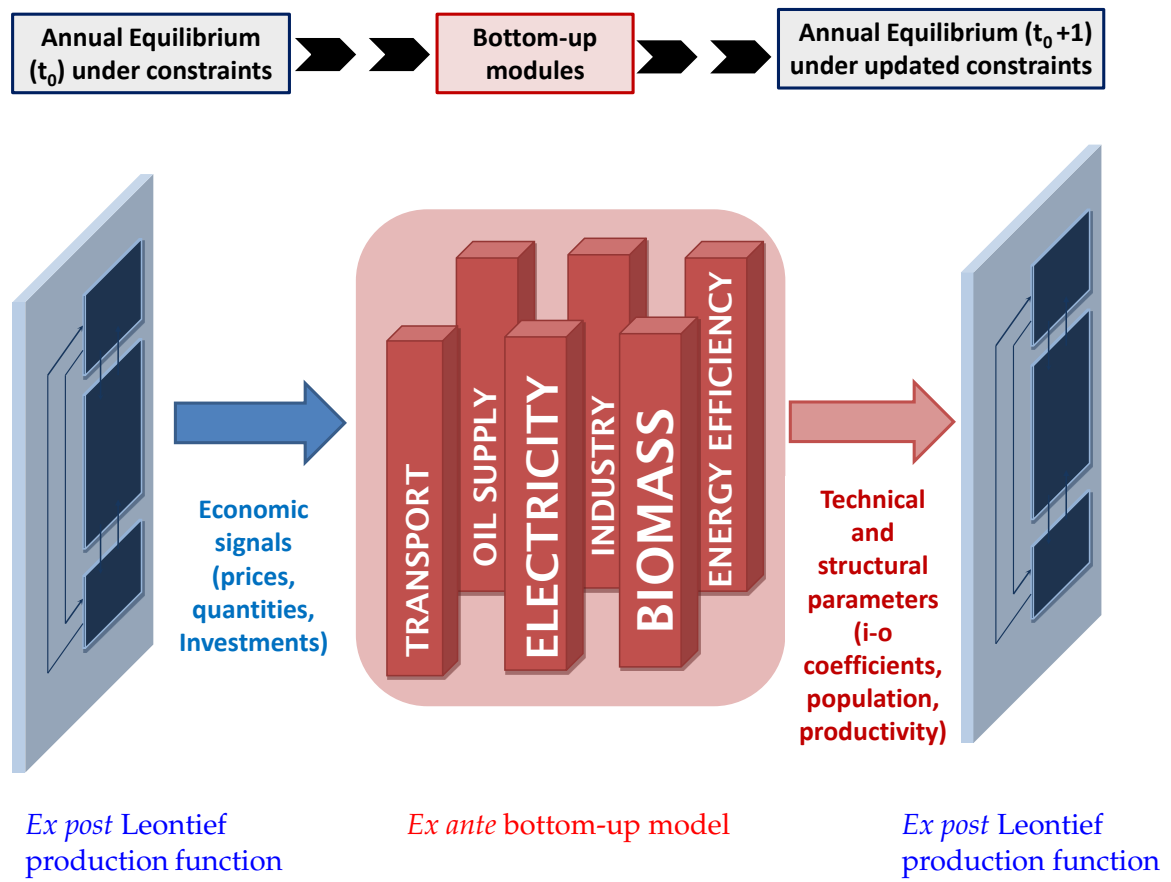


Figure 3.6: IMACLIM-R model schematics

As a whole, fully integrated representations provide a more explicit, transparent and consistent representation of technical systems within multi-sector CGE models. In addition, the hybridization of bottom-up and top-down visions appear more credible especially from an engineering point of view and finally facilitate a stakeholders dialog. However, this higher performance comes at a price. First that of increased complexity. Indeed, that all the technological evolution path may be prescribed based on bottom-up vision implies that a path has to be prescribed. In abandoning the usual production functions, the modelers have to specify the evolution of quantities and prices usually described by substitution elasticities. This means that the dialog with experts (engineers and stakeholders) is not only eased but also needed. The modeler has indeed to become interdisciplinary and be able to discuss with experts. As a consequence, the model has grown in complexity compared to the standard CGE representation. In addition, a prerequisite to build a fully integrated framework is to have a consistent energy-economy database integrating technology and macroeconomic data. The necessary additional amount of data processing before the model creation may constitute an additional difficulty.

3.6 Linking variables and implied data needs

One key element for the appropriate integration of engineering based bottom-up representations into a CGE model relies on the good control of the variables of dialog or linking variables. The consistency between physical volumes, money flows and the price system of the resulting hybrid model is at stake. Standard CGE models rely on accounting all values, including physical volumes, in economic terms²⁰. Similarly, in Sue Wing (2006) and McFarland et al. (2004), all volumes remain expressed in dollar-weighted unit (pseudo-quantity). It is generally considered that the proportional link between pseudo-quantities and the underlying volumes in physical units (quantity) is preserved in simulation. However, as detailed earlier, the CES aggregation of energy flows does not conserve physical quantities²¹. As a consequence, when a CES aggregation is used to represent the non perfect economic substitution between different technologies of production, the physical signification of the intermediary output levels

²⁰“Formally, a CGE model such as EPPA measures all inputs and outputs in the economy in billions of dollars. [...] The limitation of this approach for earth system and longer-term economic modeling is that there is no straightforward way to keep track of important physical flows such as emissions of pollutants, depletion of resources, changes in land use, and the efficiency of physical processes such as conversion of fuels to electricity. This feature further limits the use of engineering data on new technologies.” (Paltsev et al., 2005)

²¹“The CES function [...] aggregates economic quantities in a nonlinear fashion, conserving value but not physical energy flows.” (Sue Wing, 2006)

(pseudo-quantities) per technology as well as the total sector output is unclear. Anyhow the proportional link between quantities and pseudo-quantities is somewhere lost either for the output per technology or for the sector output. This problem creates an ambiguity on the physical flows: the production and thermodynamic efficiency of the technologies of the overall sector is not equal to the sum of that of each technology. Furthermore, the expression of engineering costs ($\$/toe$) has to be translated into economic costs ($\$/\$$) at the risk of misrepresenting the evolution of these costs.

In the case of partial bottom-up integration approaches, the gap in information links remains. The modelers thus have to rely on manipulations to transfer information but not variables. So, in [Schafer and Jacoby \(2005\)](#) and [Drouet et al. \(2005\)](#), the "objects" of the dialog between bottom-up and top-down representations are "volumes" of energy, transport services, etc and/or related prices. Nevertheless, "*the models [...] are formulated in different units*" so that there is in truth two variables with two different units (physical units vs dollar-weighted index) for the same object in the resulting hybrid model and "*a connection must be made*" between the variables. The usual "scaling procedure" consists in imposing a proportional link between the two variables.

One solution to overcome such limits and improve the quality of the bottom-up-top-down hybridization is to account for volumes directly in physical units in the hybrid model while insuring the consistency with money flows through the price system. [Schumacher and Sands \(2007\)](#), [Gherzi and Hourcade \(2006\)](#) and [Sassi et al. \(2010\)](#) adopt this strategy. In addition keeping track of physical flows requires to use model features that preserve quantity balance. For instance in [Schumacher and Sands \(2007\)](#) the usage of a logit nest in the steel production function makes it possible to preserve the quantity balance of physical flows and the total output of the sector (in physical units) is the sum of the output of the operating technologies. In [Sassi et al. \(2010\)](#), relying on Leontief production functions (fixed I-O coefficients for a given year) annually updated by bottom-up modules guarantees the balance of physical flows along the simulated economic path. Without explicitly keeping track of volumes in physical units, it is possible to use dollar-weighted index with price normalization if the initial proportional factor between quantities and pseudo-quantities is preserved in simulation. That's the case in [Böhringer \(1998\)](#), [Böhringer and Rutherford \(2008\)](#) and [Frei et al. \(2003\)](#).

The major prerequisite for this data hybridization is to rely on a consistent database to calibrate the hybrid model, that articulates physical flows with money flows and the price system. In practice, such a database basically results from the integration of national accounts (social accounting matrix), material balances (energy balance) and sector and technology specific data. For example [Lefèvre et al. \(2013\)](#) and [Sands](#)

et al. (2005) discuss the issue of national accounts and energy balance integration whereas Sue Wing (2008) presents a methodology to harmonize bottom-up data on technologies with top-down data for the power sector. As the authors put it, building such databases remain a challenge that need “substantial data adjustments” “due to different accounting methods” and “substantial problems [. . .] in gaining consistency” to be solved. In particular, for integrated representations, “the harmonization of bottom-up data with top-down data may require substantial data adjustments to create a consistent database for the hybrid model” (Böhringer and Rutherford, 2008)²².

3.7 Conclusion

Multi-sector CGE models for energy and climate policy assessment have benefited from significant efforts of hybridization with bottom-up energy models in the last two decades. Combining bottom-up and top-down in CGE models is a key issue for at least two reasons: (i) the structural assumptions about technical systems in CGE models have crucial impacts on energy and climate policy results and (ii) it fosters a dialog between engineers and economists and upgrades the quality control and credibility of model-based policy assessment.

However very few studies provide a detailed comparative analysis of the existing attempts to incorporate engineering based representations of technical systems in CGE models. The present chapter aimed at bridging this gap and proposes a typology based on the *nature* and *consistency* of the integration of bottom-up representations in CGE models beyond algorithmic issues. We consider that the pure engineering representation of technical systems is based on the *activity analysis* of bottom-up models and the representation of discrete technologies embedded in production capacities. Furthermore, starting from the standard CGE toolkit of the aggregated production function, we assess the existing improvements towards bottom-up integration through the departure from the pure activity analysis.

Our typology distinguishes three types of approach:

- *Top-down expanded representations* based on the inclusion of technology costs in standard production functions, first provide an interesting framework to track

²²Frei et al. (2003) sums up the issue: “one of the problems of the bottom-up and top-down merging models is the reconciliation of bottom-up and top-down data stemming from different sources (SAM vs. sector and technology-specific data). Overall data consistency requires that the aggregate cost data of selected energy sectors provided by notional input-output tables match the cost sums of specific inputs added across different technologies in the bottom-up approach. Due to different accounting methods (e.g. different depreciation rules) substantial data adjustments may be necessary before a consistent database for the hybrid model becomes available.”

technology dynamics without challenging the top-down paradigm of the production function. However activity analysis remains “surrogate” in the production function which implies a difference in *nature* from the pure bottom-up vision at at least two levels: (i) an aggregated vision of technology substitution remote from specific technical constraints (power generation loading curve for instance) and more importantly (ii) a top-down vision of capital different in nature from producing capacities working with varying rates of utilization.

- The *partially consistent bottom-up integration* category includes all approaches that mobilize true bottom-up modeling based on activity analysis but to the price of partial *consistency* with the CGE features. One further distinguishes two sub-categories: (i) soft-linking a bottom-up model and a CGE model through iterative simulation and (ii) integrating a reduced form of a bottom-up model in a CGE model. In all cases similar consistency issues arise: (i) the possible inconsistency of microeconomic behaviors between the two models, (ii) the imperfect correspondence and convergence of linking variables sometimes expressed in different units, and missing links between the models which results in overlapping representations. Well designed reduced forms usually provide the best consistency.
- *Fully integrated representations* accommodate activity analysis in technical systems with CGE features through two approaches: (i) the direct incorporation of bottom-up constraints in the CGE optimization framework through a mixed complementarity problem (MCP), (ii) the split between *ex ante* technical and investment choices informed by bottom-up models and the CGE computation with *ex post* production functions. Despite the higher consistency of integrated approaches, their complexity of implementation may be an important practical constraint.

One key prerequisite to build fully integrated hybrid models or to improve partially consistent integration, is to manage the data gap and to build hybrid energy-economy accounting systems. These hybrid databases bring consistency between economic, technological, price and energy flows data. Next chapter tackles the issue of hybrid accounting systems.

Finally, no hybridization method is *a priori* better than an other *per se*. The method chosen should depend on the study objectives. In some cases a partial integration will be sufficient to provide a first layer of dialog between the dimensions of the problem studied and will take benefit from already existing large scale models for

instance. In other cases consistent integration will be an objective for the precise analysis of one given sector integration within the wider economic system. The choice of approach is also often a trade-off between the level of consistency and the level of complexity of implementation and computation. Anyway it is important to keep in mind the consistency issues behind the different approaches and even to clarify it for the scientific relevance of the modeling process and the results generated.

Chapter 4

Construction of hybrid Input-Output tables for CGE models calibration and implications for energy policy analysis

4.1 Introduction

Much compared and commented upon since the Second Assessment Report of IPCC ([Hourcade et al., 1996b](#)), both bottom-up and top-down approaches to energy-economy-environment (E3) modeling have known limits. On the one hand, engineering analyses focused on the representation of technologies do not account for the feedback loops between the energy system and the rest of the economy; on the other hand, traditional economic modeling is ill-equipped to embark even abstract descriptions of the inertias and flexibilities of the complex technical systems underlying energy consumptions. In the last decade, the E3 modeling community has increasingly tended to overtake these limits by developing “hybrid” models ([Hourcade et al., 2006](#)). Notwithstanding their precise modeling choices, hybrid models should by nature rely on benchmark databases that provide dual information on the economic flows in monetary value and in physical units, notably for energy goods - the necessary condition to control the interface between economic and technical systems.

Unfortunately, tables that consistently accommodate monetary and physical flows are still rarely available from official statistical agencies - although the ongoing developments of satellite accounts to the System of National Accounts (SNA) are promising

(Lange, 2007). Beyond hybrid flow accounts, existing data on the underlying price system must also be acknowledged, and should be incorporated in any dataset providing the calibration material of hybrid models. However, most energy-economy modelers are regrettably elusive about how they build such datasets from the raw data, i.e. the series of trade-offs and assumptions that they unavoidably make to reach consistency or fill statistical gaps. The leeway in these trade-offs and assumptions potentially leads to benchmark databases with contrasted descriptions of the energy content of the economy. Paramount benchmark elements like the value of energy flows, the share of firms and households in physical energy consumption, and the different energy purchasing prices faced by agents, may vary, and therefore, may impact the evaluation of economy-wide consequences of energy and climate policies.

This paper focuses on the techniques of data hybridization as methods to build consistent energy-economy databases with energy flows measured in hybrid units: as physical volumes on the one hand and monetary flows on the other, the two related by the price system. More precisely it analyses the impacts of such techniques on the empirical description of an initial state of the economy used to calibrate all hybrid computable general equilibrium (CGE) models of one region. Thus, we do not provide here a discussion of the various methods used for modeling technical change or embarking information on technologies in those models, even though innovations in this area constitute the primary motivation for developing hybrid CGE models. Our first objective is rather to show the importance of making explicit the procedure of data treatment in order to better identify the empirical uncertainties associated with the choice of data and their processing. Our second objective is to detail a data hybridization method that addresses important shortcomings of existing techniques by extending to supplementary data its conciliation of unmodified energy statistics and national accounts data. In particular, it allows accounting for the heterogeneity of the purchasing price faced by domestic economic agents for a given homogenous energy aggregate, beyond the impacts of differentiated taxations - net-of-taxes prices are indeed assumed homogenous across consumers in most CGE models, in contradiction with energy statistics, which report large differences. Prices differences would have important impacts on the way the price system “decentralises” any price-signal policy and induces the responses of economic agents.

Our paper addresses such issues. In section 4.2, we start by reviewing the documented efforts to combine energy statistics with national accounts, and we present our original protocol to build a hybrid energy-economy Input-Output Table (IOT) at a regional scale. We illustrate this protocol with 2010 data for France. For the sake of concision, we only present in the text a simplified version of the hybrid IOT, with

a high level of aggregation (only one energy sector and one non-energy sector). The technical details of the hybridization procedure for France and the real 27-sectors table that have been built are given in appendices (section B.1 and B.2). Then we confront our own method's outcome with a representative alternative hybrid IOT together with the original IOT of French national accounts. The comparative analysis illustrates the diversity of possible empirical material for hybrid CGE models. Such material can be arguably differently relevant towards energy and climate policy assessment. We complement the analysis in section 4.3 implementing the same aggregated two-sector static CGE model describing one open-economy that we calibrate alternatively on the three benchmark input-output tables. Except for some cases detailed after, this model is entirely based on well-known standard neoclassical assumptions and practices that have been used in CGE modeling to represent substitutions and macroeconomic behaviors (section 4.3.1). A growing literature questions the suitability of such approaches to energy policy analysis, especially for non-marginal technical changes and over the long run (Hourcade et al., 2006). We nevertheless retain a standard framework to isolate the specific issue of upstream data processing from the other methodological innovation of the more relevant hybrid approaches - in particular the use of engineering expertise to model future technical change possibilities in place of postulated aggregate production and utility function parameterized with econometrically estimated elasticities. In section 4.3.2, we explore how the hybridization procedure, and the differences in the empirical description it entails, impacts the evaluation of the welfare costs of different energy policies. The contrasted results offer an illustration of the consequences of hybridizing benchmark data.

4.2 Hybrid accounting methods

4.2.1 Existing documented approaches

Originally, standard macroeconomic models, although based on the Arrow-Debreu paradigm (Arrow and Debreu, 1954) - i.e. on a dual representation of the quantity and value flows of goods and services in the economy - are exclusively built on monetary data drawn from national accounts, commonly synthesized in the form of a "Social Accounting Matrix" (SAM). Benchmark quantities are not described in physical units but are deduced from value flows based on an exogenous set of relative production prices. Freely fixed, as only relative price variations matter to the standard macroeconomic approaches, these prices are often normalised to 1 for the sheer sake of simplicity - which amounts to treating the million - or billion-currency output values

as as many levels of quasi-quantities. The need for physical information on underlying material flows, such as greenhouse gas emissions or physical energy consumption, to carry out E3 analysis have led to develop hybrid accounts.

Hybrid accounting systems depart from the standard accounts by collecting and processing additional data on volumes and prices of goods from various sources and by reconciling them with the monetary flows registered in the IOTs of national accounts. To reach consistency in the hybrid description, all hybridization procedures must reconcile data following two basic accounting principles. *First*, both physical and money descriptions must respect the conservation principle: the balances of resources and uses, both in quantities and values. *Second*, physical and money flows are linked by the system of prices: the economic values associated to the production, trade and consumption of each of the energy aggregate described is the product of an aggregate volume and a price consistent with tax and margin systems. Beyond these two principles, the method of data hybridization is not standardized.

A typology of the different procedures can be proposed by considering that the second accounting principle imposes that in the process of making consistent the three sources of data (*volumes, prices and money flows*), only two of these three variables can be regarded as independent of each other for any economic operation described. Then the various procedures are defined by (i) the choice of which statistics are kept unchanged from the raw data sources (*"fixed" variables*) and which variable is modified to meet the accounting constraints (*"adjusted" variables*); (ii) the technical procedure pinpointing the adjustments made to the variables selected for adjustment.

Different methodologies to build energy-economy hybrid databases for E3 model calibration are documented in the literature. The different approaches available are regrouped in table 4.1 and are characterized according to the typology previously framed. The table details for each method the raw data sources, the data that are not altered (fixed variables), and the data that are modified in the process (adjusted variables).

To our knowledge, the bulk of efforts to build and document energy-economy hybrid databases for E3 model calibration has been carried out in the context of the Global Trade Analysis Project (GTAP). The GTAP has produced different generations of hybrid databases referred as GTAP Energy Data Sets (GTAP-EDs): GTAP 4 (Malcolm and Truong, 1999) and (Complainville and van der Mensbrugge, 1998), GTAP 5 (Burniaux et al., 2002), GTAP 6 (McDougall and Lee, 2006). There also exists specific databases like GTAP-EG (Rutherford and Paltsev, 2000) built for specific modeling purposes. One strength of GTAP databases is to provide harmonized national accounts for a large number of countries or regions and to insure the consistency of bilateral trade flows.

Hybrid database	Scope of analysis and data sources (values/quantities)	Fixed variables	Adjusted variables	Used by model
GTAP-EDS	Multi-country (GTAP / IEA)	E volumes, traded E prices, traded	E volumes, domestic E and non-E prices, domestic I-O values E value added	Most global CGE models such as: EPPA (Paltsev et al., 2005) GEMINI-E3 (Bernard and Vielle, 2008)
GTAP-EG	Multi-country (GTAP / IEA)	E volumes, all Most E prices	I-O values E value-added	GTAP-EG model
SGM	One country (national accounts / energy statistics - IEA)	E volumes, all E and non-E sectors value-added	E prices, all I-O values	SGM (Fawcett and Sands, 2005)
IMACLIM	One country (national accounts / energy statistics)	E volumes, all E prices, all Total GDP	E and non-E sectors I-O values and value-added	IMACLIM-S (Combet et al., 2010)

Table 4.1: Four examples of hybridization procedures

This feature imposes specific accounting constraints in the hybridization procedure compared to the single region case and should be taken into account when assessing the resulting hybrid IOT at a given regional level. GTAP-E Data Sets cross the general GTAP accounts with IEA energy balances and various data on prices, margins and taxes. The databases integrate the richness of the information available notably on the variety of user-specific energy purchasing prices at regional scale. Nevertheless the consistency of energy trade flows takes precedence in the hybridization procedure to the detriment of regional input-output flows. As a result, domestic input-output flows are adjusted with fitting and or input-output algorithms so that most initial statistics are altered in the process: energy volumes, energy and non energy prices, input-output values and value-added. A closer look to earlier versions of GTAP-Eds shows that the order of magnitude of final alterations can be significant for key sectors and regions (Sands et al., 2005)¹. This drawback is arguably quite detrimental for energy-policy analysis at the single region scale if the algorithms used to compute domestic IOTs prevent to keep control of key domestic energy statistics. The data treatments in GTAP-EG are somehow different and preserve IEA energy volumes and most of the prices and adjust input-output values and energy value-added.

The Second Generation Model (SGM) procedure (Sands and Fawcett, 2005) was developed to overcome some of the flaws of GTAP approach at regional scale with a simpler method for the sake of transparency and clarity. Moreover authors argue that it is in practice always possible in a multi-region database to dissociate the balance of bilateral trade flows from domestic balance of energy flows. As a consequence the SGM procedure, which details domestic data treatments, can be included in multi-region context as it is the case with the SGM model itself or the PET model of IIASA (Fuchs et al., 2009). The main objective of the SGM approach is to adhere strictly to energy balances so that energy volumes are fixed variables of the procedure. Second it aims at preserving the value-added of energy and non-energy branches as they appear in national accounts so that energy prices and input-output values have to be adjusted to guarantee the accounting principles. To do so the method imposes the matrix of volumes uses (in physical units for energy sectors and in money weighted index – “pseudo-volumes” - for non-energy sectors) on the one hand and the vector of sectors’ value added on the other and simply computes the vector of average net-of-taxes prices of sectors that rebalances resources and uses in money value. The

¹For instance, Sands et al. (2005) reports important alterations for coal and power sectors in China in GTAP-Eds 5 compared to original statistics. Even though coal is the main energy provider in China especially for electricity production, the hybrid database shows a decrease of 58% of the coal price and an increase of 37% of the consumption of coal in *Mtoe* for power generation compared to original statistics.

resolution of a system of n linear equations of n unknowns in a word. This procedure keeps unaltered the economic value of energy flows and the aggregate GDP, but it does not use the information available about energy prices. In addition, it uses the values of energy flows reported by national accounts, which, as we will see below may overestimate the energy bills paid by economic agents.

The data hybridization method proposed in this paper and developed for the IMACLIM modeling framework aims at overcoming the shortcomings of existing methods by improving the integration of energy statistics in macroeconomic frameworks. The method follows two guiding rules. First, the correction of statistical gaps is carried out in such a way that both the total size of the economy (measured by GDP) and the data on energy quantities and prices coming from national energy statistics are preserved and fully used. Thus contrary to SGM approach, the value-added of energy production is deduced from energy price statistics and not the other way around taken from national accounts to derive energy prices. Second, net-of-taxes purchasing price heterogeneities faced by the different economic agents (sectors and households) and reflected in energy statistics are introduced. Therefore, the resulting description of the energy content of national economic activities may be more accurate because preferably derived by aggregating information from specialized data sources at the aggregation level chosen in the model (production sectors and final consumers). Next subsection details the steps for the IMACLIM procedure.

4.2.2 The IMACLIM procedure in practice

In the following we detail and illustrate the IMACLIM method on the 2010 French economy, considering 15 energy products and 12 energy-intensive productions (as described in appendix B.2), i.e. disregarding possible extensions to other similarly homogeneous material flows (e.g. agricultural products or heavy industries). The method develops in two main steps (Figure 4.1).

The *first step* consists in reorganizing the physical datasets - that are the energy balance (in million tons-of-oil equivalent, *Mtoe*) and energy prices (in Euros per *Mtoe*, €/Mtoe) - into input-output formats compatible with that of national accounts. As regards consumptions, this is not only a question of reallocating the physical energy flows of the energy balance to production sectors or households; rather, this entails re-interpreting the flows in national accounting terms, i.e. sorting out those that indeed correspond to an economic transaction between national accounting agents, or even combining some of them to compute such flows (e.g. directly assigning to their accounting sectors the fuel consumptions of electricity autoproducers).

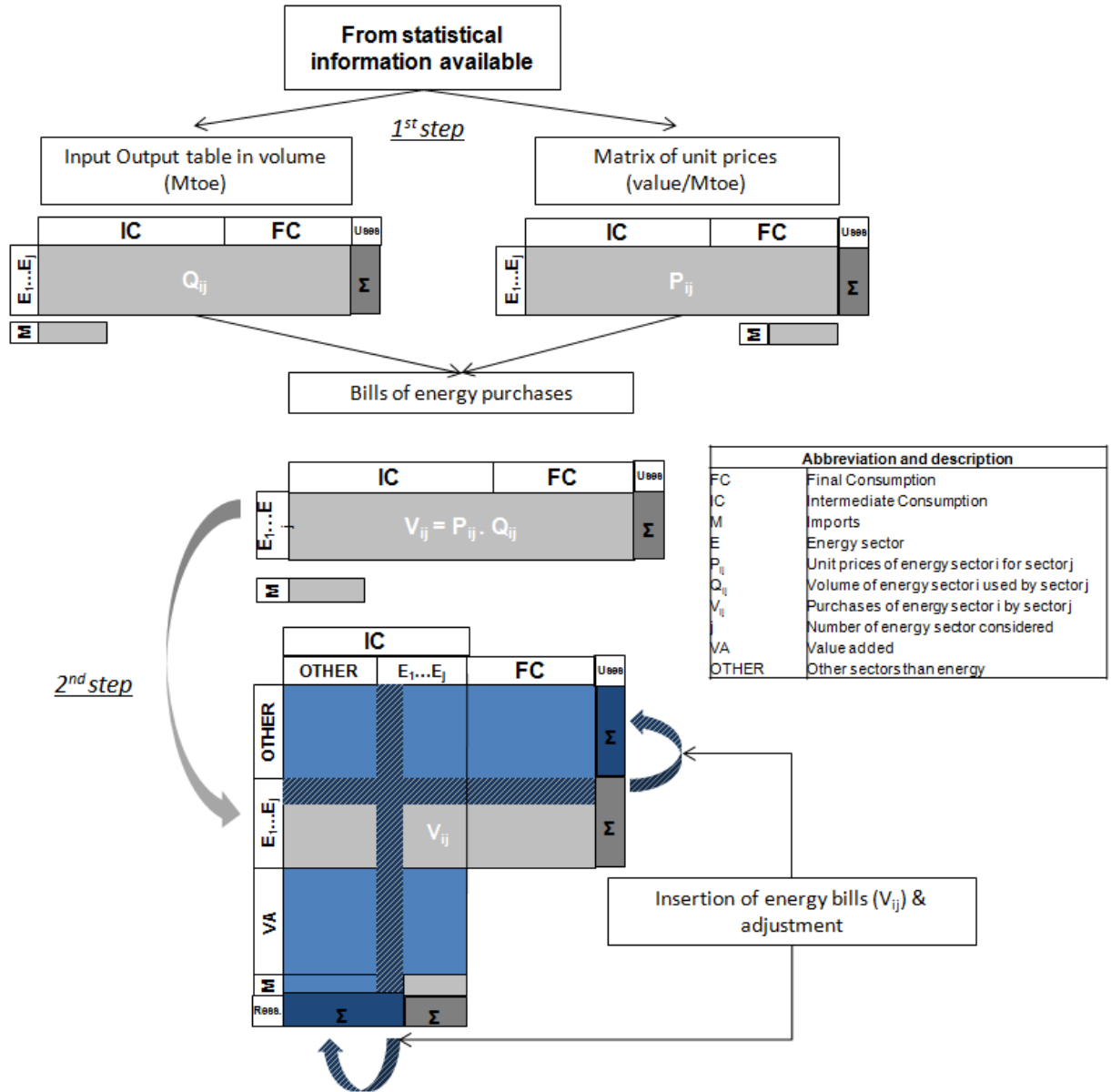


Figure 4.1: Overview of the IMACLIM hybridization procedure

The real singularities of the IMACLIM procedure come up in the *second step* where the trade-offs to adjust variables are made to guarantee the accounting balances. It starts with the reconstitution of energy expenses at the disaggregated level by the term-by-term product of volume and price tables. It then goes on with substituting this table of energy expenditures to that pre-existing in the system of national accounts in order to fully enforce energy statistics within the hybrid IOT. Other components of the system are further adjusted to maintain the accounting identities, without modifying the total value-added of domestic production. This is done (i) for all producing sectors and households, by compensating the difference between the recomputed energy expenditures and the original economic statistics through an adjustment of the expenses on the most aggregated non-energy good—a composite remainder of not specifically described economic activities, usually encompassing all service activities in E3 models; (ii) for the energy sectors, by adjusting all non-energy expenses (including value-added) pro rata the adjustment induced on total energy expenses.

The full technical details of each step are given in appendix B.1.

An important innovative feature of the IMACLIM procedure is the introduction of net-of-taxes purchasing price heterogeneities faced by economic agents. This feature is motivated by observing a wide gap in the unit energy prices faced by firms and households in energy prices statistics. To give just one example, in 2010 for France, the average net-of-VAT purchaser's price of electricity commodity was 105 €/MWh for households vs 72 €/MWh for producing sectors - 45% higher. A closer scrutiny of price data, available both net-of-taxes and all-taxes included, confirms that this gap is not caused by taxation alone. Neither by sole means of transport and trade margins ². It indeed but reflects contrasted pricing policies. It unquestionably translates extra actual costs incurred for the fragmented distribution to individual households ("retail element" of the cost), be they administrative or technical in nature. It is however doubtful that any data outside undisclosed corporate data could allow a meaningful distribution of these extra costs over the cost structure of energy production.

Because of this lack of information we introduce a set of "pricing margins" that aggregate, for each economic user category, the deviations of the producers's price faced by each economic agent from the average producer's price emerging from the cost structure. A user-specific margin rate τ_{SMij} linked to the purchase of energy good i by user j can be introduced to link the user-specific producers' price to the average

²Transport margins are small globally - 1,5% of domestic electricity bill - and trade margins are null for electricity.

producer's price of energy good i :

$$p_{ij} = p_i \cdot (1 + \tau_{SMij})$$

By construction the aggregate margins compensate, and the balance of each energy sector (or the energy aggregate in our numerical example here) is not modified.

In line with SGM methodology, most data hybridization methods enforce the law of unique net-of-taxes energy prices. Keeping in mind the order of magnitude of real price heterogeneities, important variations in the breakdown of energy bill between economic agents in the resulting hybrid IOT are to be expected. Next subsection compares in detail the outcomes of the different approaches in the case of France 2010.

4.2.3 Comparison between SGM and IMACLIM hybrid IOTs for France 2010 together with original national accounts

The discussion around data hybridization procedures could be argued to be purely technical if in practice the three sources of information (for values, prices and volumes) were more or less spontaneously consistent and data hybridization processes would result in similar IOTs. However, as practical results demonstrate, it may not be the case by large amounts.

As a case study, we compare the macroeconomic characteristics of SGM and IMACLIM hybrid IOTs for France 2010 together with original national accounts in order to illustrate the results of contrasted hybridization processes. For the purpose of this paper we have reproduced the SGM method at a disaggregated level consisting of 16 sectors including 4 energy sectors. More details are presented in annex. By sticking to the law of unique price for energy goods, the SGM method is a good benchmark of usual hybridization methods with the additional advantage to exhibit a simple and clear data treatment.

The figure 4.2 presents the three IOTs after aggregation at a two sectors level distinguishing one aggregated energy sector and a composite sector of the rest of the economy.

We portray the salient macro differences through two sets of indicators related to:

- The size of the energy sector within the total economy (Table 4.2)
- The breakdown of total energy expenses and consumption between firms (productive sectors) and households (Table 4.3)

2010 France	National accounts ^a	SGM ^b	IMACLIM ^c	Gap SGM	Gap IMACLIM
Total energy uses (inc. exports), million Euros	265	228	183	-14%	-31%
Share of energy uses in total uses	6.3%	5.4%	4.3%	-13%	-31%
Average energy purchaser's price, Euros per toe	984	848	679	-14%	-31%

^aSource: INSEE (*Institut National de la Statistique et des Études Économiques*)

^bSource: authors calculations - combination of IEA, INSEE and ENERDATA data

^cSource: authors calculations - combination of IEA, INSEE and ENERDATA data

Table 4.2: Macroeconomic differences of energy system in hybrid IOT's

2010 France	National accounts ^a	SGM ^b	IMACLIM ^c	Gap SGM	Gap IMACLIM
Share of firms in energy expenses (exc. exports)	68%	64%	56%	-6%	-17%
Share of households in energy expenses (exc. exports)	32%	36%	44%	12%	35%
Share of firms in energy consumption in volume (exc. exports)	72%	75%	75%	3%	3%
Share of households in energy consumption in volume(exc. exports)	28%	25%	25%	-9%	-9%
Energy purchasing prices ratios households/firms	1.24	1.65	2.26	-	-
Share of firms energy expenses in output	4.8%	3.9%	2.7%	-19%	-44%
Share of households energy expenses in expensed income	7.4%	7.0%	6.6%	-5%	-10%

^aSource: INSEE (*Institut National de la Statistique et des Études Économiques*)

^bSource: authors calculations - combination of IEA, INSEE and ENERDATA data

^cSource: authors calculations - combination of IEA, INSEE and ENERDATA data

Table 4.3: Breakdown of energy between firms and households in hybrid IOT's

National accounts							
2010 - Billion euros	COMPOSITE ENERGY	C	G	I	X	Total uses	
COMPOSITE	1 564	40	1 011	522	377	445	3 958
ENERGY	80	89	80	-	-	16	265
VA	1 711	30					
M	449	64					
VAT	120	15					
EXCISE IC	-	-					
EXCISE IF	-	-					
EXCISE	34	26					
Total supply	3 958	265					

IMACLIM							
2010 - Billion euros	COMPOSITE ENERGY	C	G	I	X	Total uses	
COMPOSITE	1 652	28	1 019	522	377	443	4 040
ENERGY	59	34	72	-	-	17	183
VA	1 718	23					
M	455	58					
SMC	-	9					
SME	-	-17					
SMFC	-	9					
SMG	-	-					
SMI	-	-					
SMX	-	-1					
VAT	121	15					
EXCISE IC	-	7					
EXCISE IF	-	16					
EXCISE	35	2					
Total supply	4 040	183					

SGM							
2010 - Billion euros	COMPOSITE ENERGY	C	G	I	X	Total uses	
COMPOSITE	1 576	41	1 015	522	377	445	3 974
ENERGY	84	52	77	-	-	16	228
VA	1 711	30					
M	449	64					
VAT	120	15					
EXCISE IC	-	-					
EXCISE IF	-	-					
EXCISE	34	26					
Total supply	3 974	228					

Energy Volumes IMACLIM and SGM							
2010 - Mtoe	COMPOSITE ENERGY	C	G	I	X	Total uses	
ENERGIE	87	89	60	-	-	33	269
Y		111					
M		157					
Total supply		269					

Abbreviation			
C	Consumption	Excise E FC	Excise on energy interm. Consumption
G	Government	Excise E IC	Excise on energy final Consumption
I	Investment	Excise oth.	other excise
X	Exports	SMC	Specific margin for composite
VA	Value added	SME	Specific margin for energy
M	Imports	SMFC	Specific margin for FC
VAT	Value added taxes	SMG	Specific margin for G
		SMI	Specific margin for I
		SMX	Specific margin for X

Figure 4.2: Two sectors level (Energy - Composite) IOTs for National Accounts, SGM and IMACLIM

Source: INSEE and author calculations

First of all, data hybridization decreases substantially the share of energy in the economy: the share of energy uses moves from 6.3% in National accounts to 5.4% for SGM and 4.3% for IMACLIM - that is 31% less. The average energy price decreases accordingly. For SGM without a substantive adjustment of the level of auto-consumption of the energy sector, the share of energy would be close to that of national accounts. As a contrast, in IMACLIM the adjustments of energy expenses target all sectors and 24% of initial energy value-added has been allocated to the composite sector.

Second, the breakdown of energy expenses and consumptions between firms and households is modified by data hybridization. Households get a bigger share of total energy expense moving from 32% to 36% for SGM and 44% for IMACLIM - that is 35% more. Interestingly, the share of energy consumption in volume evolves in the other direction³. Accordingly, the energy price ratios households / firms increase even more than energy expenses shares and moves from 1.24 to 1.65 and 2.26.

³For National accounts, energy volumes are derived from energy expenses by assuming a unique net-of-taxes price index of the aggregated energy good. For hybrid IOTs, energy volumes are taken from energy statistics and are identical for the two hybrid IOTs because they both strictly stick to energy balances.

As gaps are substantive, it is required to investigate their origin so as to select the most appropriate data treatment towards the most relevant representation of energy goods circuit within the economy for climate and energy policy analysis. To do so it is needed to look at the issues at the levels of aggregation where the hybridization procedures operate, that is with a disaggregated energy system constituted of several distinct energy sectors. Beyond the unavoidable non measurable statistical gaps linked to data collection and process by different organisations, one manageable source of discrepancy stems from differences of *nomenclature* related to energy flows in the different statistical systems. Nomenclature issue pertains to energy goods definition, on the one hand, and to the nature of flows, on the other.

Indeed in National accounts the energy sector includes, besides fuel production, a large number of other non-energy activities with high value-added (e.g., petroleum products). The sector as seen by national account is thus much larger than direct fuel production, though it is only the latter that will be affected by a given energy policy. In the context of a carbon tax for example the relative carbon burden (carbon price / initial price of related energy good) will vary in a substantive manner. All the more so as branches are generally not as disaggregated as products. In many case a unique branch "petroleum refineries" is distinguished. As a consequence, the relevant energy flows are mixed with other non-energy products or services in national accounts. The nomenclature gap may hinge upon national accounts nomenclature precision and products desagregation. However, the issue is common place for petroleum products and sometimes for electricity. Energy statistics and bottom-up data collection make it possible to select the energy aggregates and related flows that are relevant for energy policy analysis within a broader macroeconomic framework.

The second nomenclature issue concerns the nature of flows and particularly the status of auto-consumptions. A first source of discrepancy specific to the energy sector is indeed the trading of energy commodities, which developed in France in the wake of the markets liberalizations impulsed by the European Union. In the national accounts sector of electricity and gas distribution self-consumption, which can safely be assimilated to trading, amounts to 45 billion Euros. This is a significant share of the observed 82 billion Euro discrepancy. The sector as seen by national accounts is thus much larger than direct energy expenses built by IMACLIM hybridization procedure because it amounts to count several economic transactions for the same underlying volume of energy. For all energy policy purposes other than those focused on energy markets organization, indistinctly treating this trading as any other physical consumption cannot but flaw analysis. In SGM, estimating an average price for each energy good makes it possible to erase such trading effects and base own energy expenses

on volumes of own-uses and losses. Nevertheless the procedure imposes that this self-energy consumption is valued at the average energy price which can be doubtful in some cases.

Once the nomenclature gap is solved, remains in theory the sole statistical uncertainty on figures and the choice of data to be used should contemplate the entire information available and select the most reliable data. In the matter, there is every reason to believe that specialized energy statistics on prices and volumes are the most reliable and often the only available for the nomenclature system chosen that seeks to delimit precisely the economic cycle of energy goods within the entire economy. Any other specific hypothesis beyond nomenclature and data source considerations refer to a particular model for the IOT. A specific model is all the more likely to induce unjustified biases in the final hybrid IOT than it contradicts available information (weither from economic or energy statistics). This applies particularly to the model of unique net-of-taxes energy price.

As mentioned earlier, contrasted pricing policies are commonplace for energy goods. Beyond the french case, US statistics report for instance that for year 2007, net-of-taxes and margins producer's price for electricity for households was double the price invoiced to industry. In addition, national accounts, in the same way as energy statistics, do capture the heterogeneities of energy prices by recording the true energy sales reported by companies and invoiced to the different economic sectors and agents. The energy expenses included in the original IOT thus reflect those heterogeneities even if there is no specific information available in national accounts on the specific extra-costs related - distinct from taxes and margins. That's why the unique price assumption for energy goods contradicts available information. However most, if not all, data hybridization attempts, enforce the law of unique price including GTAP Energy Data Sets. Even if GTAP methods admit the availability of data on user-specific net-of-taxes and margins prices, the hybridization processes end up by enforcing a unique average producer's price for each energy good (McDougall and Lee (2006), p.14). User-specific purchaser's prices differ by sole user-specific tax rates. This has to be related to the modeling constraints of CGE models that are usually calibrated on such databases. Indeed in the standard framework, there can not be different prices for the same good and user-specific prices are typically not compatible with the zero profit condition and marginal cost pricing without further modeling treatments. Solutions exist like further disagregating goods or creating multi-output sectors by means of specific fonctionnal form such as CET functions (Constant Elasticity of Tranformation). Nonetheless, we suspect that in general, modeling constraints determine trade-offs for benchmark data preparation. The consequence may be a biased empirical material

compared to available information and data (from both national accounts and energy statistics) towards the breakdown of energy expenses between economic agents. This can not but impact policy analysis (cf. 4.3).

We can illustrate this bias on SGM IOT. Let's mention first that the aggregation from 4 energy sectors to one unique energy sector IOT, generally cancels the law of unique price. In the aggregated SGM IOT, the bulk of auto-consumption by the unique energy sector is made of crude oil purchases at a relative low price (compared to electricity for example) so that the average purchaser's price is lower for the energy sector than for the composite sector and households that purchase a bigger share of expensive energy like electricity. This is a pure aggregation affect that generally does not erase the initial bias of unique price. SGM method admittedly corrects the biases linked to energy auto-consumption like trading effects. However figure 4.2 shows that the law of unique price at the disaggregated level induces a global transfer of energy expenses from households to the composite sector compared to both national accounts and IMACLIM IOTs.

Differently, the same law of unique price induces a bias in national accounts IOT when estimating the breakdown of energy consumptions in volume this time. Starting from energy expenses, the hypothesis of unique price, generally normalized to one, makes it possible to derive money-weighted energy volumes that are assumed to be in stoichiometric relationship with real physical volumes so that total energy demand equals that of energy balance. However the reality of price heterogeneity and of higher energy prices for households induces in practice a wrong transfer of energy consumption from productive sectors to households compared to energy balance (cf. Table 4.3). Again the unique price assumption is linked to the constraints of standard CGE model.

On the whole, as statistical gaps are important, the energy policy implications are expected to be substantive depending on the hybrid IOTs chosen for model calibration. We have attempted to demonstrate that enforcing energy statistics within a macroeconomic framework as the IMACLIM method does, gives a more accurate picture of the energy system for economy-wide energy or climate policy analysis. Of course our hybridization procedure has its limits. First, the adequacy of the method hangs on the quality and disaggregation of price data. Notwithstanding, we advocate working on explicit, improvable price x quantity disaggregations rather than keeping on using non-disambiguated national accounting aggregates. Secondly, the method is highly data- and time-intensive, even for countries with a developed statistical corpus as France. It is therefore by essence a national method, or a method applicable to integrated regional ensembles for which aggregate statistics, especially price statistics, are

available.

Next section seeks to investigate the sensitivity of energy policy appraisal to the characteristics of the benchmark hybrid IOT used for CGE model calibration.

4.3 Impact on policy analysis

As mentioned in introduction, CGE modelers are in practice very elusive on the data hybridization processes used to create the benchmark SAMs for CGE model calibration. And to our knowledge, no sensitivity analysis of modeling results to benchmark data really exists. The bulk of effort targets sensitivity to sole model structure and parameters (See [Manresa and Sancho \(2005\)](#), [Sancho \(2010\)](#)). Nonetheless we have portrayed that, in practice, benchmark IOTs can be significantly contrasted in the representation of energy systems so that there is a need to appreciate the induced sensitivity of results in a CGE model context. The aim of this last section is to contribute to bridge this gap and study the sensitivity of energy policy results to the benchmark SAM in the case of France 2010 considering that the three IOTs previously introduced and compared are representative of the range of conceivable hybrid IOTs. To do so, we calibrate the same standard computable general equilibrium (CGE) model on the three different two-sectors IOTs extended in three SAMs. Then we explore the welfare costs of energy consumption cuts induced by an excise tax on energy consumptions. For the sake of concision, we postpone the full set of equations of our model to appendix B.3, while the following subsection only synthesises its main features.

We have seen that there could be links between the assumptions made for data hybridization and the modeling features of CGE models, especially through the law of unique price. So there is an issue to explore to what extent a CGE framework can cope with contrasted pricing policies and we have mentioned in section 4.2.3 several existing solutions to do it. However, our goal is more simply here to look at the possible dispersion of results related to the variability of benchmark energy cost-shares and consumption breakdown as it exists in hybrid IOTs.

4.3.1 Model overview

Our illustrative, standard CGE model is of a “KLEM” nature matching the level of aggregation of the input-output data reported above: it disaggregates two primary factors of production, capital (K) and labour (L) and, considering the focus of our study, two goods only, one energy aggregate (E) and one remainder of economic activity, or composite good (M for materials in the “KLEM” acronym, although we

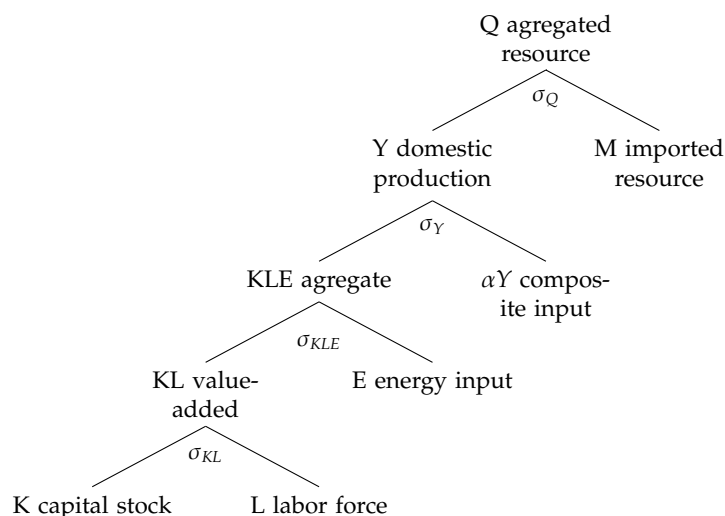


Figure 4.3: Nested production structure of a “KLEM” model

will retain this letter to designate imports).

Production of both goods is represented as a nested structure of primary and secondary factor consumptions that combine following Constant Elasticity of Substitution (CES) functions (Figure 4.3). At the bottom of the structure, acknowledging recommendations of [Van der Werf \(2008a\)](#) and [Okagawa and Ban \(2008a\)](#)⁴, capital K and labour L trade off to produce a value-added (KL) aggregate, which then trades off with energy E to produce a KLE aggregate. This in turn is combined with non-energy secondary inputs to produce domestic output Y . Beyond domestic production, Y itself aggregates with imports M to constitute total resource Q . The four elasticities characterising these trade-offs for each of the two represented sectors are (painstakingly) drawn from the literature (Table 4.4).

Final demand of the two goods is disaggregated in three uses: household consumption (C), consumption of public administrations (G) and investment (I). Households devote to consumption a constant share rC of their income R , the sum of primary factors payments and social transfers. They trade off energy to composite consumption to maximise their welfare, which is a CES function of both consumptions. The elasticity of this trade-off is calibrated to accommodate 0.6579 own-price elasticity of their energy consumptions, as inferred by weighting the GTAP model elasticities for housing utilities and transport and communications ([Hertel, 2008](#)) with the budget shares of domestic and private transportation energy consumptions in total household energy

⁴Both authors demonstrate the higher relevance of the retained “KL-E” structure compared to other possible nested combinations of the K , L and E factors.

Elasticity	Name(cf. appendix 6.3)	ap-	Value, composite production	Value,energy production
Substitution of capital K to labour L	σ_{KL}		0.4200 ^a	0.4501 ^b
Substitution of value-added KL to energy E	σ_{KLE}		0.3518 ^c	0.2374 ^d
Substitution of KLE aggregate to non-energy 2ndary inputs αY	σ_Y		0.6678 ^e	0.2378 ^f
Substitution of domestic variety Y to imported variety M	σ_Q		2.0000 ^g	3.7610 ^h

^aThe elasticity computed by [Van der Werf \(2008b\)](#) for the aggregate French economy on time-series analysis.

^bThe average of the elasticities computed by [Okagawa and Ban \(2008b\)](#) for the Mining and the Electricity, gas and water sectors weighted by the contribution of these sectors in the KL aggregate.

^cThe elasticity computed by [Van der Werf \(2008b\)](#) for the aggregate French economy on time-series analysis.

^dThe average of the elasticities computed by [Okagawa and Ban \(2008b\)](#) for the Mining and the Electricity, gas and water sectors weighted by the contribution of these sectors in the KLE aggregate.

^eThe average of the elasticities computed by [Okagawa and Ban \(2008b\)](#) for several activity sectors weighted by the contributions of these sectors to non-energy output of France 2010.

^fThe average of the elasticities computed by [Okagawa and Ban \(2008b\)](#) for the Mining and the Electricity, gas and water sectors weighted by the contribution of these sectors in the KLEM aggregate.

^gInspired by the Armington elasticities of the non-energy sectors of the GTAP model ([Hertel, 2008](#)).

^hThe average of the corresponding elasticities of the GTAP model for 6 energy goods weighted by the contribution of these goods to the sum of domestic production and imports of energy goods in 2010 France.

Table 4.4: Substitution elasticities of a “KLEM” model of France

expenses. Public consumption G and aggregate investment I regard the composite good only. The former is specified as a constant share of GDP, the latter as a constant share of income. The maintained pre-existing tax rates, together with the explored excise taxes on energy consumptions (cf. *infra*), provide public income. Social transfers to households mechanically balance the public budget.

We must immediately stress that we only resort to such a simple “KLEM” abstraction to set our analysis in a common-knowledge, fully controlled modelling background. Indeed, we recommend great caution in the interpretation of the absolute results of such a model. We have elsewhere criticised the inadequacy of CES functions to faithfully represent the inertias inherent to the complex engineering systems embodied in energy production and consumption (Gherzi and Hourcade, 2006). What is more, to implement such functions we have to resort to ill-adapted elasticity estimates, of various sources of uncertain compatibility, and crudely adjust them (cf. notes to Table 4.4). We also apply them to the modelling of energy consumption constraints probably far beyond the range of their validity - fundamentally limited to the immediate vicinity of the price and quantity fluctuations observed in the time-series or cross-sectional data from which they were estimated. The reader should bear in mind, though, that this is indeed what many modelling studies do when they estimate drastic carbon policies as Factor 4 or Factor 5 (75% or 80% cuts of greenhouse gas emissions) objectives. Also, our purpose is indeed to illustrate the impact of three different benchmarking practices by comparing their policy analysis consequences, not the policy analyses themselves.

We choose to implement a compact two-sectors CGE model instead of a customary applied model of middle size (10 to 30 sectors including 5 energy sectors for example) to be able to control the relationships between model results and the macro characteristics of benchmark energy sectors portrayed in subsection 4.2.3 and avoid the “black box” effect (Wing, 2004). In fact our exercise could be seen as an extension of a simple theoretical CES production function KLEM model that adds the main characteristics of an applied CGE model: IO structure, institutional sectors, trade, etc. However this choice of compact CGE format entails practical difficulties. As we noticed earlier, aggregating the energy sector of the hybrid IOTs creates mechanically price heterogeneities for the aggregated energy good around an average price even for SGM IOT and this is a pure aggregation effect. For IMACLIM IOT, the final effect results from the combination of contrasted pricing policies for individual energy goods and the aggregation effect whilst national accounts IOT keeps the assumption of unique price. The idea is that we basically want to keep both benchmark energy cost shares and energy consumption breakdown in physical terms for analysis at the macro level so as to

respect the characteristics of disaggregated benchmark data. To do so, we make a twist to the standard CGE framework for IMACLIM and SGM IOTs by implementing a set of "agregation" margins (different in nature from "pricing margins" at the disaggregated level) held constant in simulation to differentiate the user prices around the average price (cf. annex B.2). At this stage we have three models ready for simulation: NH model - non-hybrid based on national accounts IOT, H1 model - hybrid 1 based on SGM IOT and H2 model - hybrid 2 based on IMACLIM IOT.

4.3.2 Model implementation and results

We consider three different sets of energy policies depending on the targeted groups of economic agents: (i) the set of *universal policies* targets firms and households indistinctly with a uniform excise tax; (ii) *firms policies* target firms only, with a specific excise tax on intermediate energy consumption; (iii) *households policies* target households only, by means of a specific final demand excise tax. Contrary to standard approaches that uses *ad valorem* taxes, we use a real excise taxes system, that adds to the already existing excise system, and that targets real energy volumes. This feature is crucial in a context of differentiated energy prices. As stated in section 4.3.1, the generated tax proceeds accrue to the public budget, which is in turn balanced by transfers to households once public expenditures have been financed. For each policy set, we explore the full range of energy cuts for the targeted group(s) - from 0% until 99% because by nature, CES functions forbid modelling 100% cuts.

In relation to the characteristics of the benchmark IOTs portrayed in section 4.2.3, we seek to organize the results along two dimensions:

- The impact of benchmark global energy system size on welfare costs
- The impact of benchmark energy expenses and consumption breakdown between firms and households on the sharing of energy cuts efforts

The impact of benchmark global energy system size on welfare costs As put by [Hogan and Manne \(1977\)](#), at first order, the impact of energy cuts on the aggregated economic output depends on the initial share of the energy system in the economy and the elasticity of substitution between energy and the other factors. This is illustrated by the classical CES KLE model that represents the economy by means of a single production function that relates global output to the different factors including energy:

$$y = f(K, L, E) = \left(\alpha_K p_K^{\frac{\sigma-1}{\sigma}} + \alpha_L p_L^{\frac{\sigma-1}{\sigma}} + \alpha_E p_E^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$$

with α_E the initial energy cost share and σ the elasticity of substitution. This result is valid for K and L held constant. For an

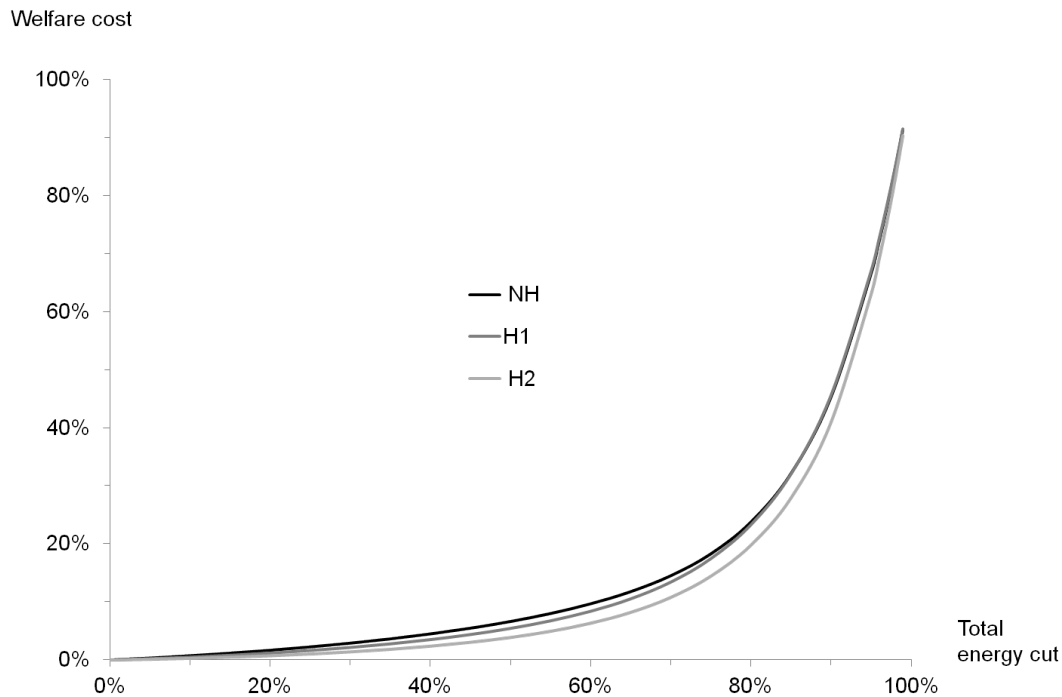


Figure 4.4: Welfare cost of price-induced energy cuts for *universal policies* set

elasticity of one, the relative impact on output is the product of the energy cut by the cost share: a 10% energy cut will imply a 0.4% output decrease in an economy with an energy cost share of 4%. If the elasticity is lower (resp. higher) than one, the impact is higher (resp. lower). For complete energy cuts the outputs tends to zero.

In our case, the model structures and elasticities values - ranging from 2.3 to 6.2 for energy input - are constant across models. The figure 4.4 displays the welfare cost curve of *universal policies* case of total energy cuts for the three models. At first sight, models have very close to each other CES-like convex profiles of welfare response to total energy cuts, starting from zero and converging to 100% for a 100% targeted cut, which is a classical artefact of the CES assumption. Moreover the hierarchy of welfare cost curves is consistent with benchmark energy systems and the theoretical CES model. Welfare cost is all the lower than the benchmark energy cost share is low for the whole range of possible energy quotas. Nonetheless looking closer to small cuts - 0-20% for instance - that in fact correspond to the realistic policies, discrepancies arises. In particular if we compared to the range of CES cost curves that corresponds to the variability of benchmark energy cost shares of our models, we can observe that welfare costs are globally lower for our three models and the dispersion of costs is higher compared to the simple CES model. In the first place, the lower costs could be

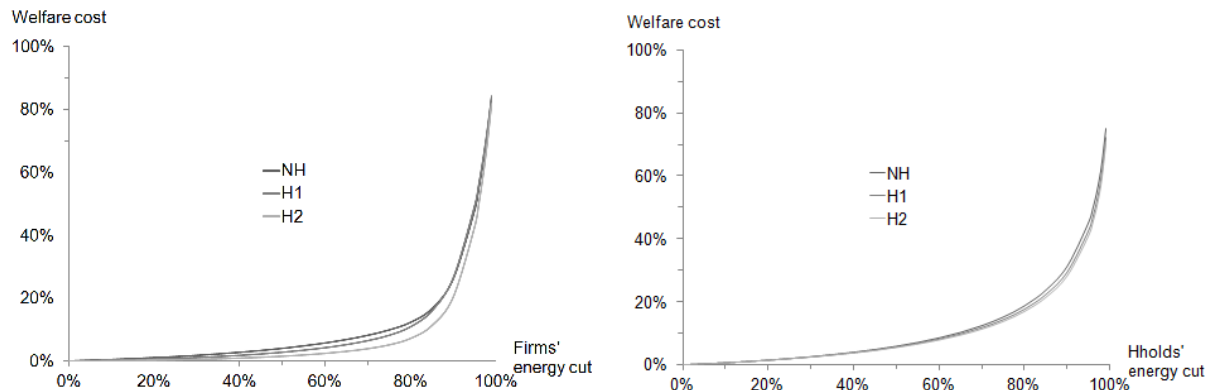


Figure 4.5: Welfare cost of price-induced energy cuts for *firms* and *households* policies sets

explained by the added flexibility of the CGE framework.

Looking at the results of alternative policies sets - *firms policies* and *households policies* - makes it possible to discriminate further the sources of discrepancies (fig. 4.5). In each alternative the hierarchy of costs certainly holds, the higher the energy cost or expense share, the higher the welfare cost. However, the divergence in welfare cost estimates is much stronger for firms than it is for households (and the gaps when targeting total consumption in the *universal policy* case is understandably of intermediate size). These results certainly echo (i) the direction and (ii) the relative sizes of the corrections of the energy expenses of both agents for H1 and H2 compared to NH: in the two cases, hybridization decreases the energy expenses of both agents; but it cuts by respectively 19% and 44% the energy expenses of firms whilst it only adjusts those of households by 5% and 10% (cf. Table 4.3). Nevertheless the simple CES model can not provide for the whole explanation. Figure 4.6 displays the ratios of welfare cost of NH and H1 on its of H2 in function of the level of energy cut in the three sets of policies. Results are much more striking. For *households policies*, the costs ratio never exceeds 1.04 and 1.11 for H1 and NH. This result fits well with the CES model: the gaps in benchmark households energy expense shares directly translate in gaps of same magnitude for welfare costs. Targeting firms' consumptions has much more contrasted repercussions. The deceptively small absolute magnitude of the estimation gap for the lower consumption cuts hides ever-increasing relative gaps as the target's ambition decreases. For a 10% cut of firms' consumptions the welfare cost estimated with NH and H1, although small 0.45% and 0.23%, are 2.8 and 5.5 times that estimated with H2 (0.08%); up to a 70% cut it is consistently more than 1.5 their counterpart in H2. In the case of firms the impact on cost assessment thus largely exceeds the extent of

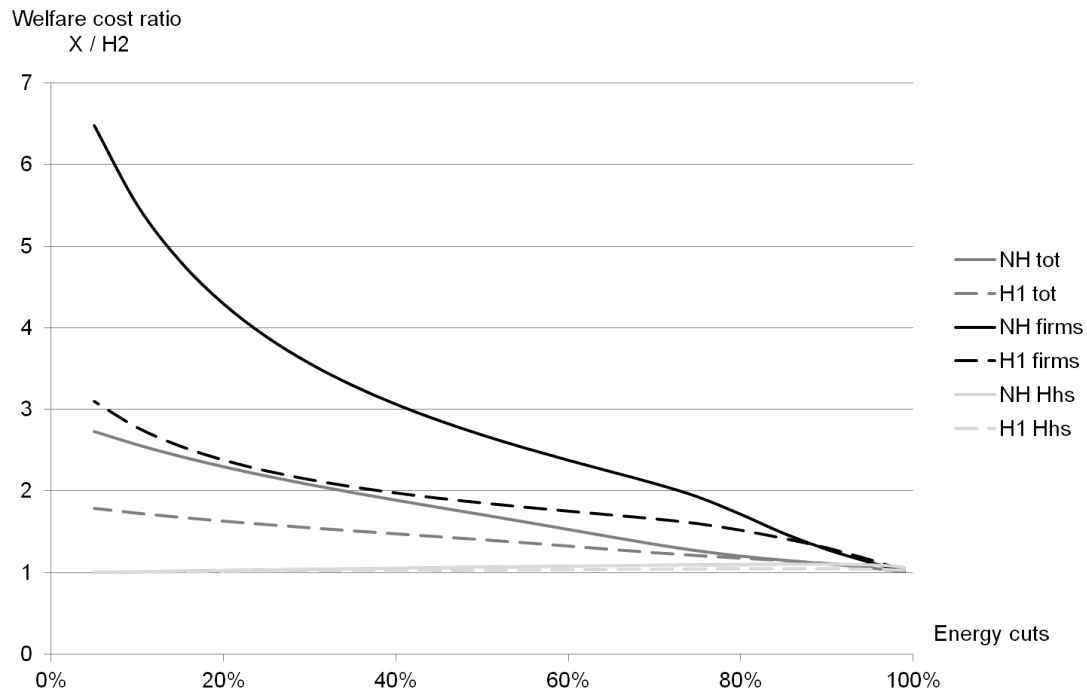


Figure 4.6: Welfare cost ratios of NH and H1 on H2 for the three policies sets

the expense corrections, of 19% and 44%. These results show that the deviations of our CGE models from the standard CES model are substantive. The gap must have to do with the more complex modeling features and behaviors of productive sectors, which includes feedback loops to the energy consumptions of input productions through the input-output matrix, and to the broader macroeconomic framework extending to the primary factors markets and international trade.

We can try to give some clues to disentangle these mechanisms. Generally it should be acknowledged that the link between welfare costs and energy cuts can be interpreted through the CES formulation of the economy. Indeed, final utility is a nested-CES of intermediate goods and production factors. This representation shows that beyond energy cuts, utility will vary mainly depending on (i) production factor variations (K and L), (ii) intermediate consumptions and (iii) levels of imports. The gaps stemming from differences between GDP and utility may be small because expensed income is a constant share of GDP. On this basis the effects can be sorted in three main categories: production factors, I-O and trade effects. The endowment of production factors is fixed in the economy so that the transfer from one sector to the other may have a small effect on utility. The I-O structure of the model induces a

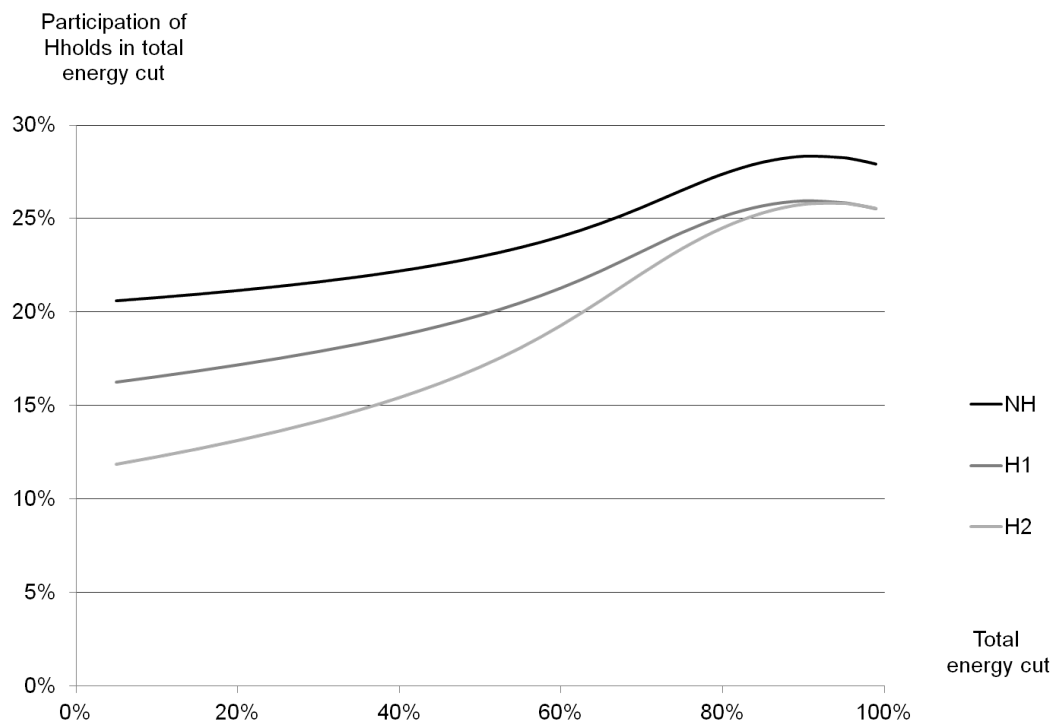


Figure 4.7: Households' participation to total energy cut effort

standard multiplier effect from final consumption to domestic production. Conversely it can play a role of shock absorber of the impacts of energy cuts on production.

We reserve to further research a possible analytical disambiguation of these mechanisms.

The impact of benchmark energy expenses and consumption breakdown on the sharing of energy cuts efforts In a second step we observe as expected that the initial split of the global energy bill between households and productive sectors has a direct impact on the share of global energy cut effort between the two institutional sectors. Thus in Imacim the higher share of initial households energy bill implies a lower energy cut effort for medium global energy cut compared to SGM and INSEE. This has to be related to the links between initial cost or expense shares to the marginal product of energy (towards output or utility).

The results show that the participation to energy cut effort is lower for households than their share of benchmark energy consumption for the three models. This is explained by the fact that energy cut costs are lower for the productive sectors than for households. This depends on the cost shares and production structure. Ultimately

for high cuts the participation tends to the initial share of energy consumption. The differences between models for realist cuts can be directly related to the differences of initial energy prices ratios except for NH where the initial breakdown of energy consumption increases the relative participation beyond initial price effect.

In a nutshell, CGE simulations have shown that benchmark gaps for the economic size of the energy system, translate in gaps even larger for welfare cost estimates of the same universal energy saving policy. The maximal ratio of 1.45 for benchmark energy system sizes - already significant with actually +45% of energy size for NH compared to H2 - translates into a maximal ratio of 2.57 for welfare costs in the case of a total 10% energy cut; that is a qualitatively different appraisal for the same energy policy. Benchmark energy cost shares of productive sectors within the IO matrix are of paramount importance to explain the dispersion of the welfare costs. In addition, the gaps in the breakdown of benchmark energy bills and energy volumes consumed, between productive sectors and households, induce gaps at least as important for the assessment of energy cut effort sharing between the two institutional sectors. As a conclusion benchmark data hybridization does matter for empirical energy policy assessment.

4.4 Conclusion

A first objective of this paper was to underline the fact that building a hybrid social accounting matrix has a non-marginal impact on the empirical description of the initial state of an economy, and therefore, on the policy evaluations drawn from hybrid CGE models of this economy. The hybridization procedures used to reconcile energy data on price and quantities with input-output tables coming from national accounts have a direct impact on the description of empirical features that cannot but matter for energy policy evaluation: the economic size of energy flows, the relative share of energy bills paid by productive sectors and final consumers, the relative energy prices paid by economic agents and hence the relative energy consumption volumes of economic agents.

This methodological problem is general as the statistical gaps across energy and economic sources are not only due to sample bias, but to differences in the content of statistical aggregates that describe energy items. The solution proposed in this paper can be extended to the description of other material flows than energy - like surfaces (m²) or distances (passenger-km, ton-km) - or to other countries or years, and it can allow the development of new generations of hybrid CGE models useful for sustainable development analysis. Compared with the other hybridization techniques,

our solution replaces the nomenclature of material flows in the input-output matrix by the nomenclature used in material balances and statistics. This allows for keeping unchanged the whole size of the economy, as recorded in national accounts, while including without alteration the quantitative information about material flows, prices and quantities that come from specialised statistics. The “validity” of the description will therefore be based on the accuracy of those statistics and their aggregation. The real contribution of the technique - besides giving a basis for the dialogue between macroeconomic and technical analyses - is to give a measure of empirical uncertainties in available data. The CGE model may then be used to analyse the sensitivity of the results to those uncertainties.

A second objective of this paper was to show that this impact of the hybridization techniques on the empirical description of the initial state exists with all types of CGE models, even with a small and highly aggregated “standard” neoclassical model like the one used in this paper. The magnitudes of the impacts will nevertheless vary with the modelling assumptions about technical change and the macro functioning of the economy, as well as with the levels of aggregation of productive sectors and economic agents, and with the specific data at hand (year, country, and sources). In particular, the differences between the policy evaluations drawn from hybrid CGE models and “standard” neoclassical CGE models are of course magnified by the use of bottom-up models and engineering expertise in place of aggregate production functions calibrated on econometric estimations. But this impact of the modelling and aggregation choices has already begun to be discussed elsewhere, but has not been isolated from the impact of hybridization techniques on the initial empirical description.

The primary motivation for elaborating hybrid social accounting matrices remains of course to embark in CGE frameworks the experts’ information about future technical change and energy saving possibilities at different time horizons. Therefore, it will be a natural follow up to this paper to compare the impact on evaluation of the different techniques and assumptions used to realise this dialogue between bottom-up engineering expertise and top-down macroeconomic modelling.

Transition

The first part of the thesis has explored from a methodological perspective the landscape of state-of-the art integrated models used to study mitigation issues. The following sums up the main points developed.

The entry point of the analysis has been the IPCC AR5 scenarios about transformation pathways and the integrated models from which they are derived. These models and scenarios are a representative sample of the state-of-the art tools and studies targeting the techno-economic assessment of low carbon pathways. We have shown that the quantitative scenarios emphasize the interplay between (i) the technological pathways - with a special focus on energy supply, power generation and carbon dioxide removal (CDR) technologies and (ii) alternative GHG emissions pathways based on regional staged accession and delayed action scenarios including possible overshoot. The analysis provides insights about the implications in terms of technology portfolio, Kaya's decomposition, aggregate macroeconomic costs and the regional breakdown thereof mostly in perfect economic environment. These scenarios provide very useful benchmarks to understand the global low carbon challenge in its technological, regional and aggregate economic dimensions. However, there are reasons to claim that they are as such not sufficient to inform current policy debates and provide operational guidance to take forward decision-making in climate action at both global and regional scale. To take only one example, the scenarios assume different schemes of delayed action without questioning the reasons of these expected delays linked to possible techno-economic impediments and the solutions to overcome them and bifurcate towards low carbon pathways.

We have in fact identified a set of insufficiently addressed issues in current scenarios which can be summed up in four points:

- The articulation between decarbonization pathways and development patterns in the medium to long run and the energy content of development pathways linked to end-use energy demand, lifestyles, structural changes, dematerialization, infrastructures, urban dynamics, etc.

- The articulation between decarbonization and others socio-economic objectives in the medium run taking into account key second-best features of economies (imperfect foresight, labor market rigidities, trade patterns, adjustment costs, etc.). This opens the road to the analysis of economic co-benefits of low carbon pathways.
- The conditions of the transition in the short to medium run to bifurcate towards low carbon pathways and the tools to trigger that transition.
- The articulation of complementary policy tools beyond pure carbon prices at different time horizon (fiscal reforms, norms, energy efficiency policies, labor market policies, investment in infrastructure, etc.)

The subsequent question aimed at understanding to what extent the missing issues were also linked to missing model features beyond the question of priorities given to specific issues in scenario building. To contribute to this debate we needed to go further existing model typologies to reveal the fine internal vision of state-of-the art models. Therefore we built a model guide to scrutinize and synthesize models internal vision in order to assess their domain of relevance. The framework has made it possible to highlight some limitations of existing models regarding the set of overlooked issues previously enhanced. For instance aggregated optimization models are very good at assessing the decarbonization of the energy system in perfect economic environment. However, they are pretty poor to inform the dynamics of end-use energy sectors, the articulation to development patterns, the economic co-benefits of low carbon pathways and transition issues. Multi-sector models provide a more comprehensive treatment of structural changes and end-use sectors dynamics. However they are often limited concerning the capture of technical constraints and the representation of induced technical change mechanisms. The perfect economic environment in the medium run included in most CGE models also limits the possibility to explore economic co-benefits and transition issues in a second-best world.

One could try to nuance this diagnostic by considering that the relevant issues and therefore the relevant models fundamentally depend on the geographic level between global and regional scale. In this view, the limitations mentioned about the articulation mitigation-development, second-best aspects of economies, transition issues or else policy packages should be more appropriately assessed at the regional level and consequently the gap in model features would not really be an issue for global models. This statement as such would suffer at least two counter arguments. First of all, a clear dichotomy between regional and global scales is not really consistent

with the recent paradigm shift in climate negotiations and the framework of loose coordination of national commitments. Global scenarios derived from global models should especially be the place to assess the aggregation of regional commitments based on the search for an articulation of mitigation and development goals and taking into account specifics of regional economies. Second, most of the models used to assess low carbon pathways at regional scale are based on the same model paradigms than global models and the research questions are generally close⁵. In addition numerous regional studies are carried out with global models where the region under focus is one given region of the model (Fawcett et al., 2009; Gurgel and Paltsev, 2014; Mathy and Guivarch, 2010). Finally the limitations highlighted about global models could be even more problematic in the context of regional analysis.

Having said that, we have enhanced how multi-sector models provide a more comprehensive vision of the interplay between energy, non-energy sectors and macroeconomic mechanisms. However these models have been historically criticized for their lack of technical realism. In the last two decades important efforts have been carried out to combine bottom-up and top-down models to yield hybrid models and improve the dialog between engineers and economist to provide more credible climate policy assessments. Nevertheless, if the concept of hybrid modeling has been stabilized for more than one decade (Hourcade et al., 2006), few studies really clarify the technical issues and resulting internal visions of existing hybrid approaches. That's why we built and detailed a typology of existing approaches on the way to embark engineering based representations of technical systems in multi-sector CGE models. Our typology highlights that the integration of bottom-up representations in CGE models can vary a lot between approaches and raises important consistency issues that are not always made clear in modeling exercises. One key prerequisite to build consistent hybrid multi-sector models is to work under a hybrid accounting framework based on the dual vision of economic flows both in physical units (when relevant like energy) and money value. We also showed how the processing of available information about regional accounts, material balances and prices determines the nature of the empirical material with key consequences on model results.

The second part of this thesis applies part of the methodological lessons learned in the first part, to the empirical analysis of the low carbon transition in the medium run in Brazil. The choice of a regional focus like Brazil fits into the new climate architecture and the search to reconcile mitigation and socio-economic objectives to define and meet

⁵One can nuance this statement by noting that more macro-econometric models are used at regional scale to inform transition issues in the medium run taking into account second-best aspects and adjustment constraints of regional economies.

nationally determined climate commitments. In this way, our empirical contribution aims at complementing the global scenarios examined in the first part of the thesis and at discussing some of the missing issues identified, on the specific case of Brazil. In particular our analysis targets the articulation between climate and energy policies with other socio-economic objectives (employment, trade, public budget, inequalities, etc.) in the medium run (2030) and the related policy packages (carbon tax policies, etc.), taking into account the specifics of the Brazilian energy-economy system including key second-best aspects of the economy.

Exploring these issues required a relevant modeling tool in view of the methodological lessons previously learned. Therefore we built a new model of the Brazilian economy belonging to the *IMACLIM* model family, which integrates the key features of a hybrid multi-sector CGE model. In particular the model is based on a carefully built energy-economy accounting system and includes specific reduced forms of bottom-up models. In addition it embarks key second-best features of the Brazilian economy in the medium run including labor market rigidities and imperfect markets of goods.

The four chapters of the second part of the thesis are built as follows. Chapter 5 introduces the Brazilian energy-GHG-economy context and highlights the main challenges at this interface at time horizon 2030. The literature review about climate policy assessment in Brazil reveals that key policy issues still need assessment for the medium run. Chapter 6 then introduces the *IMACLIM-BR* model, clarifies its status in light of the methodological lessons learned and details its core equations. Then chapter 7 analyzes at length with *IMACLIM-BR* the issue of implementing carbon tax policies until 2030 to reach simultaneous mitigation and socio-economic policy objectives. Eventually, chapter 8 focuses on the articulation between climate policy and the exploration of the oil resource until 2030.

Part II

Low carbon transition and climate policy in Brazil

Chapter 5

The Brazilian context - economy, energy and GHG emissions: prospects post-2020 and policy issues

This chapter introduces the Brazilian context which is the regional focus of the empirical part of this thesis. The questions of the low carbon transition and of the articulation between climate policy and economic development arise in a rather specific manner in Brazil. First of all, Brazil has very peculiar GHG emissions and energy profiles among emerging economies, which has enabled the country to appear as a leader in climate action. Until recently the bulk of emissions came from land-use activities mainly through deforestation and cattle rising. In parallel, Brazil has developed a strong renewable energy system based on hydropower and bioenergy. The recent drop of deforestation rates, the adoption of the National Plan on Climate Change (PNMC) in 2009 and the ambitious INDCs adopted in 2015, illustrate the ambition of Brazil to strengthen its leading role in climate action.

In this view, a new challenge will happen for Brazil beyond 2020, with the need to moderate the growth of its energy-related emissions in a context of strong economic development and the exploration of new oil resources. Because Brazil ambitions to become a major oil province at the same time, owing to the exploration of the large deep water “pre-salt” oil resources discovered during the last decade. However, as the recent period shows, a strong economic development based on the continuing expansion of commodities markets and oil and gas sectors especially, does not seem to

be an easy road any more. Brazil will have to develop a more robust economic system supported by productivity gains and diversification while continuing reducing income inequalities. As we will detail in this chapter, the challenges for Brazil at the interface energy-environment-economy in the medium run are both huge and very specific.

The chapter is structured as follows. Section 5.1 introduces the present Brazilian context at economy-energy-GHG emissions interface. Section 5.2 details the main prospects beyond 2020, and enhances the specific challenge to control the rise of energy related emissions, else in the context of the up-scaling of oil exploration. Then section 5.3 provides a literature review about the existing integrated studies about climate policy in Brazil. Finally section 5.4 concludes on relevant policy issues to be addressed and draws specifications for an appropriate modeling tool to tackle them.

5.1 The Brazilian context

5.1.1 An emerging economy

Ranking fifth by area (8.5 Mkm²) and population (201 Mhab - 2013) and seventh by GDP (2246 G\$- 2013), Brazil is one of the biggest economy in the World. It is one of the five major emerging economies usually identified as the BRICS (Brazil-Russia-India-China-South Africa). Despite stagnation in 2009 due to the economic crisis, the Brazilian economy has experienced a **3.5% average GDP growth rate** over the last decade¹. Nevertheless, GDP per capita (US\$11208 - current, ppp, 2013) remains more than four times smaller than in the US.

The Brazilian economy is dominated by **services**, which stand for 66.8% of GDP in 2011 (EPE, 2013), while **industry** and **agriculture** represent 27.8% and 5.4% respectively². Main industrial productions include mineral and fossil energy resources, steel, petrochemicals and automobile production. **Agriculture and agroindustry** – which together represent one quarter of GDP - are powerful sectors in Brazil owing to the generous natural endowment of 340 Mha of arable land. A dynamic agribusiness has made Brazil one of the major producers and exporters of agricultural goods and the country is currently the largest exporter of coffee, soybeans, beef, sugar cane, ethanol and frozen chickens. The share of trade flows (exports plus imports) in GDP, around 25%, is pretty low compared to others emerging economies. This is partly explained by the large and growing domestic economic market. Among other macroeconomic indi-

¹For the last two years though, the growth engine has stalled because of a high inflation, a decrease of households consumption with a morale down and a difficult socio-politic environment with corruption scandals.

²For a comparison, Agriculture represents only 1.2% of GDP in the US.

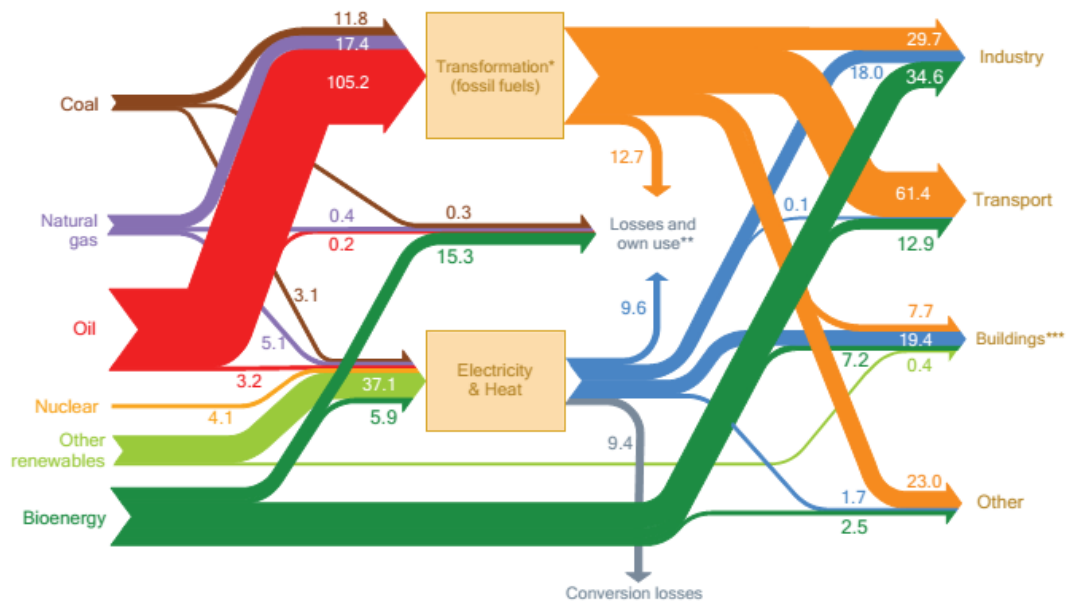
cators, **unemployment rate** is low (around 5% in 2014), and so is the saving rate (18.8% of GDP - average 2007-2011). The trade balance has been positive in recent years, around 0.5-1% of GDP. Public deficit and debt are pretty high and have amounted to 2.6% and 40.3% of GDP respectively on average over the 2007 - 2011 period.

As an emerging economy, Brazil has a young population and a high share of active population. **The rate of urbanization is also particularly high** (84% of total population lived in cities in 2010). In addition, Brazil is known for **strong social inequalities**, though the situation has improved rapidly in recent years. In fact, Brazil Gini coefficient has decreased from 0.596 in 2001 to 0.543 in 2009 (IPEA - www.ipeadata.gov.br). Persisting inequalities can be explained by multiple factors, including very heterogeneous levels of education, important urban - rural contrast, unequal land ownership and a regressive tax system. Specific income transfer policies (such as the *Bolsa Familia* - Family Allowance - programme), have made it possible for around 25M people to enter the middle-income group during the 2003-2009 period only (SAE, 2013).

5.1.2 A very specific energy sector

Brazil stands out with a particularly enviable endowment of natural and energy resources and the energy potential largely exceeds the country current needs. Such favorable conditions have made it possible for Brazil to develop a **strong and “green” energy system** to sustain its economic growth. Close to global auto-sufficiency, the Brazilian energy system has notably provided an almost universal access to electricity and has supplied for the growing energy needs of a fast developing middle class. Moreover, the Brazilian energy matrix is actually one of the most “renewable” and least carbon intensive in the world with a share of almost **45% of renewable energy** in primary energy demand.

Over the last two decades, energy demand in Brazil has closely followed GDP growth with even a small increase of the global energy intensity of domestic product. Overall, **energy demand has doubled since 1990** to reach 270 Mtoe in 2011. With the exception of natural gas, which now amounts for 10% of primary energy demand, the structure of the primary energy mix has not changed significantly over this period. The fast growth of the GDP per capita coupled with the decrease of income inequalities has boosted the demand for end-use sectors energy, especially for specific electricity in residential and commercial sectors and for liquid fuels for passenger transportation. Regarding the latter, the growth in mobility demand and in private vehicles ownership has driven a 4% per year increase of liquid fuel demand. The industrial sector remains the largest end-use energy sector though, with a 3.5% per annum growth of final energy



* Transformation of fossil fuels (e.g. oil refining) into a form that can be used in the final consuming sectors.
 ** Includes fuel consumed in oil and gas production, transformation losses and own use, generation lost or consumed in the process of electricity production, and transmission and distribution losses. *** Includes energy use in residential, commercial and public buildings.

Figure 5.1: Brazil domestic energy balance, 2011 (Mtoe)

Source: IEA (2013)

demand, driven by steel and paper industries among others (IEA, 2013).

Figure 5.1 represents the Brazilian energy balance in 2011. As can be noticed, Brazil stands out from most countries by its energy demand pattern that displays many specificities. Salient features of the Brazilian energy system include large demand by industry, a power generation system dominated by hydropower, a large share of bioenergy use (30% of the primary mix) especially in the industry and in the form of liquid fuels for transportation, and the fact that oil represents the bulk of fossil fuel consumption (41% of primary energy demand) - mainly in transportation.

In terms of **power generation**, hydropower still accounted for 70% of installed capacities and 81% of power generated in 2011. However, the share of other generation technologies is growing fast. Bioenergy now represents 6% of power generation - mainly through auto-production in the sugar industry and the combustion of "bagasse", a by-product of sugar cane. Thermal generation represents 10% of the mix (half of which is natural gas) and the rest is composed of nuclear (two plants) and other renewable technologies. Although still small in share, wind and other renewable energy sources are expanding rapidly and should take a substantive part of the power

generation mix in the coming decades.

Another singularity of the Brazilian energy system is the prominent share of **bioenergy**. This is the result of voluntary public policies initiated with the so-called “Proalcool” plan in the 70s. In the wake of the first oil shock, the Plan aimed at developing domestic production of ethanol from sugar cane for energy security purposes. Nevertheless, bioenergy today takes varied forms in the energy matrix. First, traditional biomass still accounts for a significant share of households energy consumption - 25% of firewood demand - but is decreasing fast with rising average income per capita and the adoption of modern energy sources. Bioenergy is also a major supplier of industry energy needs. In fact, 75% of Brazil firewood production is used in the industry, including 35% that is transformed into charcoal for steel production. Agricultural residues, like bagasse, are also extensively exploited especially in the paper industry. Liquid fuels from biomass stand today for a steady share of transportation fuel demand. Beyond ethanol from sugar cane, the use of biodiesel made from soybean oil is increasing - it is incorporated with traditional diesel through a rising blending mandate.

However, **ethanol** remains by far the main biofuel. It has been supplying between 13-21% of Brazil total demand for fuel of road transport in the last two decades. In practice, ethanol final consumption can assume two forms: either blended with gasoline in an anhydrous form at 25% share (gasoline C as opposed to pure gasoline A) or in a pure hydrated form (AEHC). In parallel, the fleet of light vehicles has been adapted: so-called “flex-fuel” cars, which can accommodate both gasoline C and AEHC or any blend of the two, represent around 60% of the total fleet of light duty vehicles and most of new sales. One consequence of this flexibility on the demand side is a ratio between the demand for ethanol and for gasoline that is highly sensitive to relative prices. In recent years, the price competition has been detrimental to ethanol for several reasons³. Better conditions are expected for ethanol in the future with lower production costs owing to productivity gains and right market pricing for gasoline.

A final salient trait of the Brazilian energy system is that Brazil is an important **oil** consumer and producer. On the demand side, oil stands for 41% of primary energy demand and petroleum liquid fuels represent more than 80% of total transport energy demand. The two main fuels are diesel, essentially used by trucks and buses, and gasoline used by light duty vehicles. On the supply side, Brazil has become an important oil producer since the 1980s - through the development of Petrobras, the

³Government has artificially maintained low gasoline prices to contain inflation and has thus boosted gasoline consumption. At the same time, there has been constraints on the ethanol supply side with high sugar prices - which have incited sugar cane producers to produce sugar instead of ethanol - combined with weak harvests.

main domestic oil company - notably owing to the development of off-shore deep-water fields. Since 2006, Brazil has even been more or less self-sufficient (despite temporary imports of liquid fuels depending on domestic demand). 90% of Brazil proven reserves are off-shore deepwater reserves. Since 2006, the huge deep-water discoveries qualified “pre-salt”⁴, in the Santos basin have revived the ambition of the country towards the oil sector. The exploitation of pre-salt fields is just beginning and nurtures Brazil’s ambition to be a major exporter of crude oil and a possibly significant gas producer in the coming decades.

5.1.3 A peculiar GHG emissions profile

Brazil is characterized by a rather **low level of GHG emissions per capita** - around 6.5 tCO₂eq/cap in 2010 - compared to other emerging economies with similar GDP per capita. For example, China and South Africa respectively emitted around 7 and 11 tCO₂eq/cap in 2010 whereas their GDP per capita PPP were 20% and 17% lower than Brazil. This below-average level of emissions comes together with a very specific emissions profile. Indeed, as fig 5.2 shows, the bulk of Brazil emissions are not energy-related historically, but come from agriculture processes, forestry and other land-use sectors (AFOLU). At the same time, energy-related CO₂ emissions per capita are very low - less than 2 tCO₂ /cap in 2010 - owing to the low carbon intensity of the energy system.

Until recently (2009-2010), the largest share of emissions was coming from **land-use changes and forestry (LULUCF)**, especially from deforestation in the Amazon region - resulting from the expansion of the agricultural frontier (pastures for cattle-rising especially) to the detriment of the rainforest. However, deforestation rates have decreased significantly in recent years (with 279 MtCO₂, LULUCF accounted for 23% of total emissions in 2010) and **Agriculture and Livestock sectors** have become the main emitting sectors with 35% of the total in 2010 (437 MtCO₂eq), which illustrates the importance of Agriculture and Agro-industry sectors in Brazil. Agriculture and livestock emissions are not energy-related⁵. They come mostly from production processes and from the enteric fermentation of one of the largest bovine herd in the world (methan emissions).

The low level of **energy related emissions** (375 MtCO₂ in 2010 - around 30% of total) and its decomposition across sectors is directly related to the structure of the

⁴Because hydrocarbons are trapped deep in the ground (5000 m under sea bed) under a thick layer of salt.

⁵Emissions from fossil-fuel combustion for trucks and farm equipment are accounted for in the energy sector.

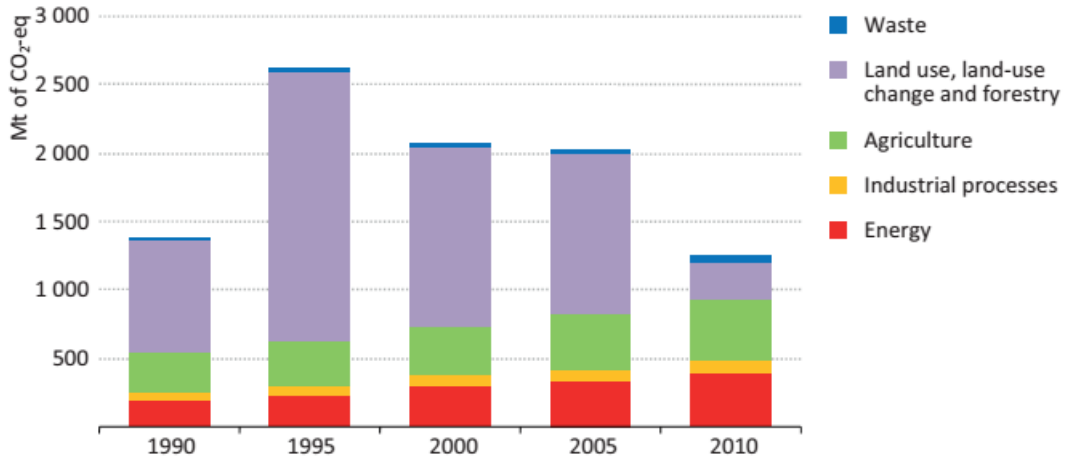


Figure 5.2: Brazilian GHG emissions by source 1990-2010

Source: Ministry of science and technology

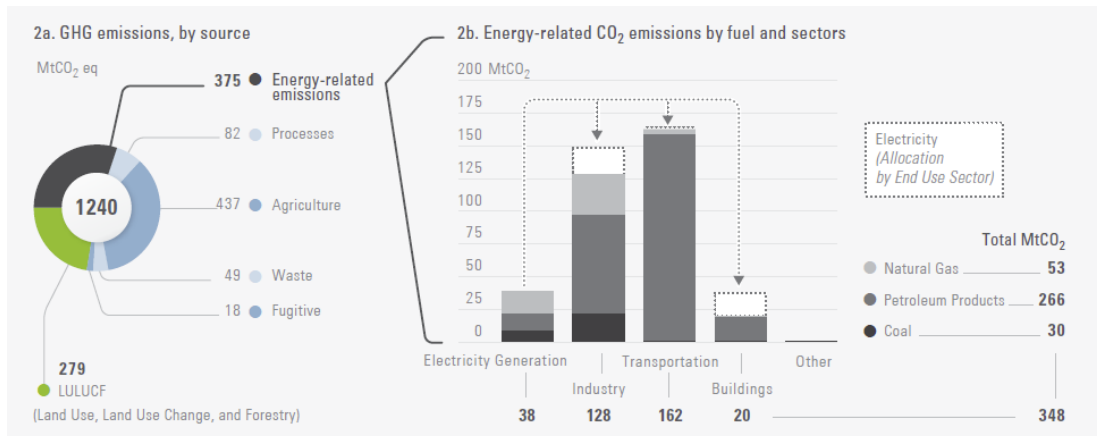


Figure 5.3: Decomposition of GHG and Energy CO₂ Emissions in 2010

Source: SDSN and IDDRI (2014)

energy system described above. The two pillars of the low carbon energy system are the **hydro power system** and the large use of **bioenergy**. As expected, owing to the important hydropower capacities, power generation contributes little to emissions, contrary to what happens in most countries. It amounts to only 10% of total energy-related emissions in Brazil, against 40% and more than 50% in China and South Africa respectively. Emissions from buildings are also limited because of the still important use of traditional biomass and the low need for heating owing to the favorable climate. As a result, the bulk of energy-related CO₂ emissions comes from industry (128 MtCO₂-37% - 2010) and transportation (162 MtCO₂- 46% - 2010). Yet even in these sectors the widespread use of bioenergy leads to carbon intensities below world average. For example the carbon intensity of Brazilian industrial energy is close to 1 tCO₂/toe whereas it is higher than 1.5 tCO₂/toe in most other countries. In the transport sector, the impact of biomass use is less clear-cut. First, biofuel mainly concerns light vehicles passenger transportation. On-road freight transportation typically uses trucks running on (traditional) diesel. The expansion of biodiesel is only beginning. Second, the share of road transportation in total transportation is very high. As a result, the carbon intensity of passenger transportation energy is well below average whereas the carbon intensity of freight transport energy is close to average.

To sum up, the recent drop in deforestation rates coupled with an energy system of historically low carbon intensity has enabled Brazil to improve its position as a low-carbon economy. Nevertheless, the share of fossil fuel combustion in total GHG emissions is increasing fast—from 16% to 32% during the period 2005-2010. Brazil faces now the challenge to build on its historical low level of GHG emissions while continuing to improve the living standards of its population.

5.2 Key prospects at energy - economic development - decarbonization interface

5.2.1 The Brazilian National Plan on Climate Change 2009-2020 (PNMC)

The recent drop of emissions from deforestation illustrates the ambitions of the country to undertake mitigation efforts. At COP15 in Copenhagen, Brazil announced voluntary mitigation goals for the 2009-2020 period. These pledges further became mandatory in the law in December 2009 through the National Plan on Climate Change (PNMC) coordinated by the ministries of Environment and of Science and Technology. Federal Law No. 12187 establishes the target to **maintain total GHG emissions in 2020 from 36.1% to 38.9% below a business as usual scenario** built under the su-

Emissions MtCO ₂ eq/year	2005 inven- tory data	2020 BAU sce- nario	Variation 2005-2020 BAU (%)	Avoided emissions in 2020	
LULUCF	1268	1404	11		
Agriculture/husbandry	487	730	50		
Energy	362	868	140	234 (27%)	
IPPU + wastes	86	234	172		
Total	2203	3236	47	1168-1259 (36.1- 38.9%)	

Table 5.1: Brazil's GHG emissions and mitigation goals in 2020

Source: Brazil's Federal Decree No. 7390, 9 December 2010

pervision of the Brazilian Forum for Climate Change (BFCC). This voluntary pledges falls into the framework of NAMAs (National Appropriate Mitigation Actions) under the United Nations Framework Convention on Climate Change (UNFCCC). Federal Decree No.7390 (2010) published in COP 16 in 2010 enforces the mitigation goals of avoided GHG emissions until 2020⁶ which are detailed in table 5.1.

The Brazilian PNMC sets a global mitigation target without specifying the sectoral breakdown of the effort except for the energy sector, which should cut its emissions of 27% compared to BAU. Meeting the PNMC pledge would result in emissions in 2020 lower than those in 2005, which seems a particularly ambitious plan compared to others emerging economies. Comparatively, countries like China or India have simply pledged to reduce the GHG intensity of their GDP⁷.

In fact, the appreciation of Brazilian ambitions is complicated by both its peculiar GHG emissions profile and the methodology based on counterfactual scenarios compared to a BAU. It is acknowledged that the LULUCF sector should make around 65-70% of the total mitigation effort through avoided deforestation. Yet if emissions from deforestation are maintained at the historically low level observed in 2010 (279 MtCO₂ in 2010 from LULUCF sector) until 2020, the LULUCF sector alone will be sufficient to meet the pledge. In addition, this recent strong drop of deforestation rates (-78% for 2005-2010 period) suggests that decoupling GDP growth from LULUCF emis-

⁶To reach the mitigation goal, the Decree creates a process for developing action plans to reduce the deforestation rates in the Amazon Basin by 80% and in the cerrado by 40%, and to restore 35 million hectares of degraded land. The Decree also sets a deadline of December 15, 2011, for each of twelve major greenhouse gas-producing sectors to submit action plans for emissions reductions. The resulting targets may form the basis for emissions trading.

⁷China and India have respectively pledged to lower their CO₂ emissions per unit of GDP by 40-45 and 20-25 per cent by 2020 compared with the 2005 level. Assuming GDP growth continues at comparable rates over the coming decade, China and India's GHG emissions should still be higher in 2020 relative to 2005. On the contrary, if Brazil meets its pledge, its GHG emissions in 2020 will be 6-10% lower than in 2005.

sions is much easier than from energy-related emissions. Brazilian global ambitions, mainly based on LULUCF efforts towards 2020, are thus not directly comparable to ambitions from countries like China that mainly show energy-related emissions.

In addition, the BAU scenario contemplates a 140% increase of energy related emissions per year for the 2005-2020 period together with a 5% per year increase of GDP⁸. The underlying assumptions are a decrease in the share of renewables in the energy mix between 2005 and 2020 with, in particular, no new expansion of hydropower or other renewables beyond 2010 - new generation is assumed to be gas-fired power plants, and no expansion in the demand for biofuels - additional demand is assumed to be for gasoline and traditional diesel. The mitigation goal assigned to the energy sector (234 MtCO₂ abatement compared to BAU) in fact corresponds to the implementation of the Ten-Year National Energy Plan (PDE) 2019 (EPE, 2010)⁹. The implementation of the plan would result in a 75% increase of energy related emissions per year for the 2005-2020 period. PDE 2019 includes the development of added hydro-power capacities, investments in energy efficiency and the ongoing penetration of ethanol for transportation. In a nutshell, one could consider that the BAU allowance of GHG emissions is pretty generous with an increase of energy emissions intensity of GDP in 2020. Nevertheless, the level of energy-related emissions per capita in 2005 is already far below average and Brazil has thus a much smaller mitigation potential than other emerging economies. In any case, the growth of energy-related emissions announces further challenges for decarbonization beyond 2020.

5.2.2 Challenges beyond 2020

The recent trends of GHG emissions marked by the drop of deforestation rates together with the expected implementation of energy plans suggest that Brazil is in a very good position to meet its mitigation goals at time horizon 2020. Beyond, the country will face a similar challenge as other emerging economies: to control the fast growing **energy-related emissions** linked to a dynamic economic growth and the rise of living standards. Yet the margins of maneuver to decarbonize the energy system beyond current trends seem narrower in Brazil than in other countries. As explained earlier, China and South Africa for example, show higher mitigation potentials with a current power generation system dominated by coal-fired power plants. However Brazil will have to adopt new decarbonization strategies for the energy sector if it wants to keep its leadership in low carbon development. This path will have to be articulated with

⁸15% increase of energy-related emissions intensity of GDP between 2005 and 2020.

⁹The Ten-Year plans are released every year and represents official guidelines for the development of the Brazilian energy system.

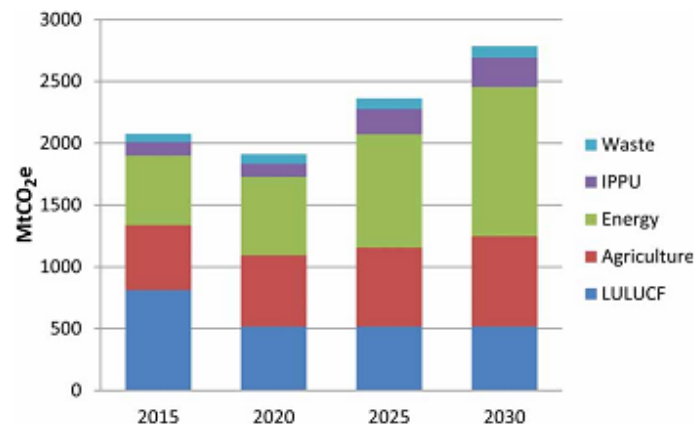


Figure 5.4: Total GHG emissions in Brazil, 2015–2030, in Scenario B

Source: La Rovere et al. (2013)

the unprecedented economic and energy context: the size of the Brazilian economy is expected to double over the 2015-2030 period, with an economic development partly driven by oil and gas industries.

The three scenarios developed in La Rovere et al. (2013) illustrate the mitigation challenges that Brazil is expected to face post 2020. The first scenario (Scenario A) is close to the PNMC BAU scenario extended to 2030: a pessimistic counter-factual including the persistence of high deforestation rates and no development of renewables beyond 2009. The second scenario (Scenario B) corresponds to the achievement of the PNMC (until 2020), constant deforestation rates from 2020 to 2030 and 2020-2030 energy trends resulting from a combination of the PDE 2019 and the 2030 National Energy Plan (PNE 2030). Released by the Energy Planning Agency, the PNE 2030 embodies the long run strategy of expansion of the Brazilian energy system¹⁰. Finally, the third scenario (scenario C) includes further mitigation efforts relative to B in all sectors: afforestation, further penetration of renewables, energy efficiency programmes, etc. In short, scenario B can be considered as an early reference governmental scenario until 2030. Figure 5.4 displays the GHG emissions path of scenario B for the different sectors.

Scenario B clearly shows a **shift in the emissions pattern around 2020**. Total GHG emissions decrease from 2005 to 2020 owing to the PNMC, but starts rising again afterwards. This rise, which leads the total level of emissions beyond historical records in 2030, is driven by energy-related emissions which become the main source

¹⁰PNE 2030 has recently been partly updated with the PNE 2050.

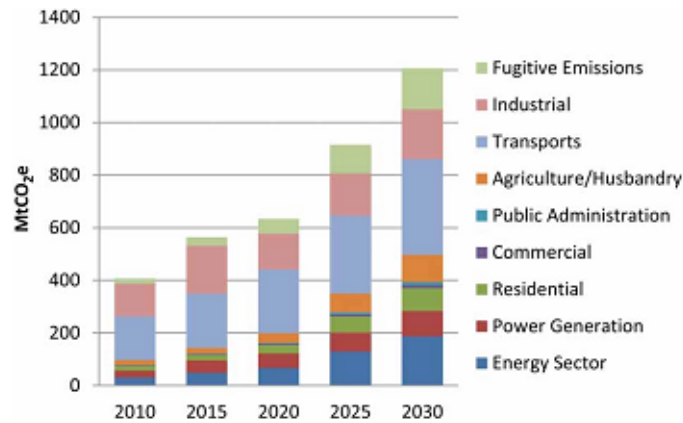


Figure 5.5: Energy-related GHG emissions in Brazil, 2015–2030, in Scenario B

Source: La Rovere et al. (2013)

of emissions (around 45% of total in 2030). This increase of energy-related emissions - around 5% per year for the 2020-2030 period - is embedded in current energy plans and reflect expected trends.

Figure 5.5 details the contribution of each sector to energy-related emissions in Scenario B. Power generation and the residential sector remain small contributors, as a result of the development of renewables embedded in energy plans. Eventually, energy-related emissions beyond 2020 are mainly driven by **the fossil-fuel consumption from transportation and industry sectors**¹¹.

Future energy-related emissions are primarily driven by population and economic growth and the rise of the demand for energy services. Existing energy-economy scenarios indeed contemplates a rate of GDP growth around 4% per year in average until 2030. In addition, the rise of living standards will drive up some structural changes that may aggravate emissions on top of the growth driver. The rising income per capita are expected to increase demand for passenger mobility and to result in a strong increase in private vehicles ownership. One key aspect will be the extent

¹¹ In the longer run - beyond 2030, the power generation question may regain importance and the availability of new technological options may reframe the discussions about mitigation issues in Brazil. As analyzed in Lucena et al. (2015), without specific mitigation policies, coal and natural gas based thermal power may represent the bulk of supplementary capacity needs beyond the limits of hydro power potential. In addition, technological progress in energy supply may change mitigation discussions. Technologies such as carbon dioxide capture and storage (CCS) with fossil fuels as well as CCS with biomass (BioCCS) could drastically reduce the needs to enhance renewables and energy demand management. Nevertheless, enhancing renewable energy and energy demand management in early periods, enables to hedge against the risk of delays with key technologies and may provides co-benefits related to non-climate purposes (urban planning, energy security, etc).

to which low-carbon urban transportation modes and fuels switches develop in a country with a weak public transportation systems and the dominant use of private cars. Likewise, without specific actions to introduce low-carbon inter-urban freight transportation systems (e.g. railways or waterways), freight transport is likely to continue relying massively on road transport and the usage of heavy-vehicles running on diesel. Eventually, economic growth will be driven by industry production growth (including agro-industry) which will be needed to supply for a fast growing domestic market and possible future trade markets.

Nevertheless, such dynamic economic growth - which would make it possible for Brazil to partially catch-up with developed countries GDP per capita and living standards in 2030 - is not warranted. Certain recent climate policy scenarios in Brazil contemplate much lower average growth rates close to 2% per year in the medium run (Lucena et al., 2015). Recent economic situation actually shows that the Brazilian growth engine is still fragile. Economic growth has stopped in 2014 (0.1% growth rate) and the GDP may even contract in 2015. This is probably the result of multiple temporary factors such as low international feedstocks prices, high interest rates, high inflation and fiscal austerity policies, which result in both low investment and consumption. The morale of households is also pretty bad in a context of corruption scandals. Beyond current economic conditions, Brazil will have to overcome specific structural weaknesses in the medium run to make solid economic growth achievable. These include the deficit of modern infrastructures of transport and sanitation, lack of a sufficiently large skilled labor force and the institutional constraints and complex regulatory environment known as the "*custo Brasil*". However recent national plans express optimism. According to EPE (2014a), investments in education and in innovation should bring the needed productivity gains in the medium and long run and improve the competitiveness of domestic productions. Moreover, improved stability of institutions and the macroeconomic policy should help in the future to secure the productivity gains and the efficiency of investments.

If this scenario is to be the reference, then key variables for GHG emissions at time horizon 2030 will be **energy intensity levels of end-use sectors and the extent to which bioenergy replaces fossil fuels in heavy industry and road transportation**. In the heavy industry sector, the trade-off will concern for instance the level of penetration of natural gas and the level of penetration of charcoal in the steel industry. The issue is even more crucial in the road transportation sector. On the one hand, on-road freight transport is more or less locked-in diesel, despite the expected 5% to 10% blending of biodiesel. On the other hand, important margins of freedom exist for light vehicles passenger given the massive expected penetration of flex fuel cars (85% of the total

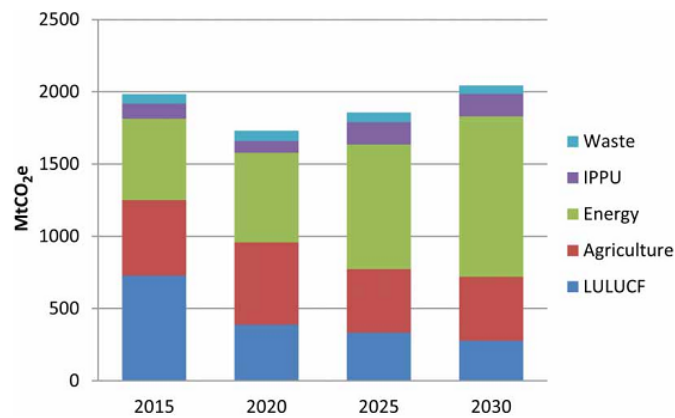


Figure 3 Total GHG emissions in Brazil, 2015–2030, in Scenario C
 Source: La Rovere et al. (2011).

Figure 5.6: Total GHG emissions in Brazil, 2015–2030, in Scenario C

Source: La Rovere et al. (2013)

fleet in 2030)¹². The penetration of bioethanol to replace gasoline will depend upon numerous variables such as the production constraints of bioethanol and the domestic oil price. As explained before, the government is currently imposing artificially low oil and gasoline prices to control inflation, a move that is detrimental to ethanol demand. Government intervention towards domestic oil and gasoline prices will be a decisive driver of the future relative share of ethanol and gasoline in transportation fuel demand and further an important driver of future energy-related emissions levels in Brazil.

Most recent government plans are in fact closer to scenario C of La Rovere et al. (2013) (see fig. 5.6). They include the up-to-date energy plan targets (EPE, 2014a) and, more importantly, more ambitious AFOLU policies as reflected by the plan for prevention and control of deforestation in the legal Amazon and the Low Carbon Emission Agriculture Program (ABC). In this recent trend governmental scenario, the switch of emissions pattern towards dominant energy-related emissions is even more pronounced and confirms the challenges previously framed.

Eventually, prior to COP21, Brazil presented end September 2015 its INDCs until 2030, which include new ambitious emission targets. Brazil committed to reach a 1.2 GtCO₂eq level of total GHG emissions in 2030, that is a reduction of 43% compared to 2005 level. To do so, the government intends first to reduce AFOLU emissions to an unseen level by stopping illegal deforestation, restore specific forest area and

¹²Electric and hybrid vehicles are expected to remain marginal till 2030 (5% of the fleet) but may represent a substantive share of the fleet in 2050 (EPE, 2014b).

strengthen the ABC program for Agriculture among others. The second pillar of course, will be to hold back the increase of energy-related emissions sufficiently to meet the new global emission target.

We can thus summarize the challenge ahead for Brazil until 2030 as the one to favor economic development and growth - through investing in infrastructure, education, favoring employment, modern lifestyle for all - along a low carbon energy pathway based on the ongoing decarbonization of industry and transport sectors.

5.2.3 The oil question

The trade-off between bioenergy and fossil fuels represents a crucial junction point for the articulation between energy system decarbonization and the economic development of oil and gas resources. Even if Brazil has always been an oil producer, with the discovery of “pre-salt” oil reserves in the Santos Basin, Brazil has the ambition of becoming a major player in the oil market. On average, existing forecasts bet on a production of around 5 Mba per day in 2030 - that is a doubling of the production for the 2010-2030 period per day in 2030 (Goldemberg et al., 2014). Natural gas production is expected to be multiplied by four to reach around 80 Gm³ in 2030. Hydrocarbon resources exploitation thus represents an important source of economic development in the coming decades, and is expected to drive the development of a whole industry. For example, oil exploration and production will require machines and equipment - potentially offering a strong boost to domestic machinery production.

Potential revenues from oil exports are very difficult to anticipate, given the combination of uncertainties on production, domestic demand and international oil price. The most optimistic forecasts mention that oil exports could generate up to US\$100 billion in 2030 (IEA, 2013). Yet even in this case, contrary to most large oil exporters, this would still represent a small share of GDP (2.5%). This figure leads IEA experts to believe that the risk of “Dutch disease” is low, unless the effect could be amplified in conjunction with the others export commodities. However, the risks associated with the volatility of international oil markets remains. Oil activity is eventually expected to generate important fiscal resources which are planned to be invested in education and health programs. At this stage large uncertainties remains concerning the pace of production that will be reachable for the next twenty years. These uncertainties are about the deep-water extraction that should stand for 90% of oil production in 2030 and coming mainly from the Santos basin. Uncertainties also concern the whole supply chain of a very capital-intensive activity. Delays could happen in the context of technical difficulties, supply chain constraints and availability of investments for

projects that are of the most complex ever undertaken in oil industry. Almost the entire responsibility fall to Petrobras that will have to manage the major part of the US\$60 billion per year needed for oil production. Eventually there is a risk that a lasting context of low international oil prices may delay the current plans.

How this oil is used, and in particular to what extent it is used domestically is critical for the country GHG emissions. As recent years show, the temptation exists to set low oil prices to curb inflation down, thus driving domestic consumption up. Today the main scenarios and plans (IEA, 2013; EPE, 2014a) suggest the contrary. The bulk of new resources is planned to be exported and renewables should increase shares in domestic demand. And it is very important for the feasibility of decarbonization in Brazil to avoid the domestic use of the newfound resources because it would weaken the efforts to develop energy efficiency and renewable energy use.

5.3 Existing energy plans and mitigation studies

In this section, we review the main existing integrated studies about energy-economy-decarbonization pathways in Brazil.

5.3.1 National Energy Plans (PNE 2030 - 2050)

Brazil has a well developed institutional structure for the energy sector equipped with operational services for prospects and planning. The main organisation is the Energy Research Office (EPE) that provides for the energy plans and studies to the ministry of Mines and Energy (MME). The study of reference is the long term expansion plan at time horizon 2030 referred as PNE 2030 (EPE, 2007) released in 2007. PNE 2030 has been partially updated with PNE 2050 (EPE, 2014a) with an extension of the time horizon. These plans aimed to provide the guidelines for a national strategy of development of the energy system. The scope of the plans encompasses the whole energy system from supply to end-use in consistency with a long term macroeconomic projection.

5.3.1.1 Methodology

The numerical content of PNE scenarios is the result of a standard methodology which starts from macroeconomic assumptions that feed bottom-up models to compute supply and demand of energy. More precisely, a macroeconomic scenario is built with a Long Term Macroeconomic Consistency Model (LTMCM) which is mainly composed of a standard balanced growth model. It starts with exogenous hypothesis on macroeconomic indicators such as GDP growth rate, population growth, world trade growth,

fiscal and monetary policy, foreign investment and factor productivity gains to compute the other variables of the consistent macroeconomic picture: investment rate, trade balance, public debts, etc. The macroeconomic picture includes assumptions on world oil and gas prices. Macroeconomic variables further feed one demand module and one supply module. The demand module computes final energy demand on the basis of macroeconomic assumptions on activity levels, energy prices and sectoral hypothesis on technologies and energy efficiency. The supply module computes the supply energy system required to supply for the final energy demand taking into account production constraints. Both supply and demand modules adopt a least actualized cost formulation. Supply and demand results are consolidated within a Brazilian version of the energy optimizing MESSAGE model (Messner and Strubegger, 1995).

5.3.2 Bottom-up studies and Marginal Abatement Cost Curves (MACCs)

The main existing study for Brazil in this category is the so-called Low Carbon Study (LCS) conducted in 2010 by the World Bank (de Gouvello, 2010). The study makes a comprehensive analysis of the mitigation actions available in Brazil at sectoral level for the 2010-2030 period. These mitigation options are studied from a microeconomic and technological point of view along four different sectors: LULUCF, energy sector (excluding transportation), transport sector and waste sector. The study includes the construction of a reference scenario by sector and the estimation of the cost of each mitigation measure compared to this reference scenario. Finally the study shows the global mitigation cost curve and builds a low carbon scenario based on the implementation of measures under 50 US\$/tCO₂eq. The microeconomic appraisal is complemented with a short macroeconomic analysis of the low carbon scenario with a simple Input-Output model. The study globally "emphasized a consultative, iterative approach" about the collection of information and data and the building of the low carbon scenario. Others analysis using the MACCs methodology exist such as Borba et al. (2012) which focuses on energy related emissions.

5.3.2.1 Methodology

The methodology used follows the standard mitigation cost curve approach largely used since for example Ellerman and Decaux (1998). First of all a reference scenario is built for each sector for the 2010-2030 period based as much as possible on existing long term plans. The team used the PNE 2030 for the energy sector, a mix of different plans for the transport sector and built the whole reference scenario for the LULUCF sector.

In the second step relevant mitigation options by sector compared to the reference are identified and mitigation costs are estimated.

Two options are used for the metric of mitigation costs: the net present value (NPV) of social mitigation costs and the break-even carbon price. The first option makes it possible to compare the different mitigation options from a social point of view whereas the second corresponds to the specific sectoral conditions of microeconomic decision. However the calculations are similar because the break-even carbon price corresponds to the NPV of mitigation costs estimated with a discount rate equals to the internal rate of return (IRR) of the given sector. Each mitigation option besides corresponds to an abatement path compared to the reference for the 2010-2030 period. Finally for each mitigation option, the abatement cost per avoided tCO₂eq for the 2010-2030 period is the NPV of the total mitigation program divided by the total of emissions avoided during the same period.

In addition, the abatement costs considered are technical costs estimated from a bottom-up perspective. The abatement programs generally do not modify the "activity levels" of sectors and the costs are calculated given exogenous price paths. For instance the cost of mitigation of an energy efficiency program in the steel industry will be estimated with the variation of capital and fuel costs compared to the reference with given paths of steel production level and prices of fuels and capital. In a word the mitigation costs estimated in the study are technical mitigation costs over the long run (for a 20 years long period). For some sectors such as transportation, these technical costs are adjusted by taking into account co-benefits of mitigation (reduced congestion, air pollution, etc). Eventually mitigation costs are gathered in MACCs in order to build the low carbon scenario.

The short macroeconomic appraisal is based on a simple I-O model. It consists in estimating the variations of sectoral outputs implied by the different mitigation measures - including the sectoral breakdown of fixed capital variation. These variations are used to shock the I-O table in order to give some insights about the macroeconomic consequences in terms of GDP, employment of the mitigation options.

5.3.2.2 Main figures and messages

In terms of quantitative results, the breakdown of total GHG emissions in the reference and low-carbon scenarios is given in table 5.2.

The first thing to note is that total GHG emissions are pretty low in 2030 in the reference scenario compared for example to Scenario B in [La Rovere et al. \(2013\)](#) (see fig. 5.5). LULUCF emissions are of similar levels but energy related emissions (Energy

Sector	Reference MtCO ₂ eq	2030	Low-carbon MtCO ₂ eq	2030
LULUCF	533		196 (-63%)	
Agriculture/husbandry	383		338 (-12%)	
Energy	458		297 (-35%)	
Transport	245		174 (-29%)	
Waste	19		18 (-5%)	
Total	1718		1023 (-40%)	

Table 5.2: Brazil's GHG emissions for the reference and low-carbon scenarios per sector

Source: [de Gouvello \(2010\)](#)

+ Transport in LCS) and emissions from Agriculture are much lower, around -40% and -50% respectively. As for the mitigation scenario, around half of the abatement is allocated to the LULUCF sector and mainly corresponds to the decrease of deforestation. In addition the estimated mitigation costs of avoided deforestation are close to zero (between -2\$ and +2\$ /tCO₂) and mainly based on the cost incurred to reach higher yields per hectare for cattle rising. This confirms the idea that dramatically reducing deforestation and maintaining very low deforestation rates in the future is an achievable objective for Brazil that may not incur a significant economic burden.

As far as energy related emissions are concerned, the low-carbon scenario contemplates a -33% decrease of emissions (from 703 to 471 MtCO₂). For the energy sector alone the scenario is mainly achieved with energy efficiency gains in industry and refineries. Power generation contributes very little to mitigation. In the transport sector, around half the abatement concerns shifts in transport modes especially for passengers (metro, BRT). The other half is realized with an added penetration of bio-ethanol to replace gasoline. In the low carbon scenario, around 10 Mtoe of the 32 Mtoe of gasoline consumed in the reference scenario are replaced by bio-ethanol. As for mitigation costs, the striking fact is that they are highly negative or close to zero except for modal shifts in transportation. This negative costs actually corresponds to the "no regret" options identified by engineers and refers to the debate on the "efficiency gap" already introduced earlier in this thesis. On the whole, what should be highlighted for our own analysis is that the LCS suggests that energy related emissions can decrease around -33% to pass from 703 to 471 MtCO₂ at time horizon 2030 with a 50\$/tCO₂ carbon price.

Eventually, the limits of a bottom-up approach earlier introduced in this thesis, apply here. In particular, the sectoral MACC approach ignores the feed-backs of the rest of the economy on sectoral mitigation costs. These feed-backs operate through sectoral interrelations as well as the endogenous variations of price and activity levels.

These endogenous effects cause in return changes in sectoral mitigation costs and can in fact modify the ranking of mitigation measures. That's why the authors themselves call for an integrated analysis based on a general equilibrium framework to extend their study: "*It is always desirable to assess GHG mitigation options based on their effects on the overall economy.*" "*A Computable General Equilibrium (CGE) model is preferable for assessing the macroeconomic impacts of GHG mitigation policies.*"

5.3.3 CGE assessments of climate policies in Brazil

A few studies exist that investigate specifically the economic implications of Brazilian climate policy with economy-wide modeling tools. Early attempts such as [Tourinho et al. \(2003\)](#) and [Margulis et al. \(2011\)](#) were based on top-down static neoclassical CGE models for Brazil (see chapter 2). The studies analyze the impact of a carbon tax over the Brazilian economy at a given base year. The results of [Margulis et al. \(2011\)](#) show that a given 50US\$/tCO₂ carbon tax implies a direct 1.82% reduction of emissions together with a -0.13% decrease of GDP. The result from [Tourinho et al. \(2003\)](#) are of same magnitude. In fact such appraisals concern the direct impact in the short run of the carbon tax without medium run adaptation of sectors to the new fiscal conditions like changes of technology. This is the reason of the low impact of the carbon price both on the emissions level and the GDP. On the contrary, the LCS studied the mitigation potential of the same 50US\$/tCO₂ carbon price in the long run. The MACCs built represent the adaptation of sectors and agents to the carbon price - in terms of change of technology and mitigation measure - that should happen in the long run in a cost-efficient perspective. Eventually, short term static CGE-based analysis can not really help to assess the economic implications of climate policy in Brazil over 10, 20 or 30 years.

Two recent attempts tackle this task and analyze the economic consequences of different mitigation scenarios over the long run with recursive dynamic CGE models: [Chen et al. \(2013\)](#) and [Gurgel and Paltsev \(2014\)](#)

5.3.3.1 Methodology

The two studies use similar modeling tools but the focus of the study is slightly different. These models enter the category of hybrid recursive dynamic CGE models. (see chapter 2)

First of all, [Gurgel and Paltsev \(2014\)](#) is based on the EPPA model ([Paltsev et al., 2005](#)) already introduced in this thesis (see chapter 2 and chapter 3). Brazilian mitigation scenarios are analyzed with this global model where Brazil is one of the regions.

Production and consumption structures as well as the sectoral breakdown are standardized for the different regions together with the elasticity parameters. The sole benchmark data and some exogenous parameters (population, labour productivity, etc) are region specific. Such a formulation makes it possible to represent endogenous boundary conditions for Brazil region but may be detrimental to the specificity of the integrated assessment at regional scale. In addition, the model includes an endogenous representation of land-use changes and deforestation. Brazil - and all regions - is endowed with a given level of land factor which is allocated between agriculture sectors including forestry. Deforestation is simply the endogenous consequence of a decrease of the land factor level allocated to the forestry sector.

Conversely, the model in [Chen et al. \(2013\)](#) is national and represents Brazil as an opened economy. The model structure is very similar with EPPA and inspired by it. Some elasticity values are also taken from [Paltsev et al. \(2005\)](#). Nevertheless production and consumption structures, also based on nested-CES functions, are slightly different from EPPA. In addition the number of sectors is higher and the sectoral breakdown more specific to the Brazilian case with individual sectors like sugarcane industry and biofuels sector. Contrary to EPPA, deforestation is not endogenous and it is implemented exogenously depending on the scenario through variations of the land endowment for agriculture.

In the neoclassical CGE tradition, both models work under a first-best setting and mitigation targets (including avoided deforestation in [Gurgel and Paltsev \(2014\)](#)) are reached by means of carbon prices.

The sets of mitigation scenarios of the two studies, although different, both explore the economic consequences of the implementation of the PNMC further extended to 2030 and 2040 respectively. [Gurgel and Paltsev \(2014\)](#) focuses on the economic implications of (i) the sectoral objectives achieved jointly ("*Copenhagen*"), (ii) separately and of (ii) the global objective reached with a unique carbon price ("*Copenhagen – C market*"). [Chen et al. \(2013\)](#) studies the economic implications of the achievement of the global target according to different levels of achievement of the isolated LUC (deforestation) target. The gap between the LUC target of PNMC and the level of LUC abatement actually realized is an exogenous scenario variable. In the scenarios, this gap is offset by a surplus of abatement in the others sectors in order to reach the global target.

5.3.3.2 Main figures and messages

The results of [Gurgel and Paltsev \(2014\)](#) can be summed up as follows. First the achievement of LUC goals alone can be realized at almost null costs (with a 1-3 US\$/tCO₂). In the scenario, the emissions from LUC decrease below 200 MtCO₂ in 2030, as in the LCS. These results are remarkably consistent with the LCS and confirm the very low economic burden of the LUC mitigation effort in Brazil. Therefore the real economic impacts on welfare and GDP of the implementation of PNMC comes from Agriculture and Energy sectors. In addition the results show classically that a unique carbon price leads to lower welfare and GDP costs to achieve the extended PNMC than with sector objectives reached with sector specific carbon prices. In this last case, the attainment of PNMC extended objectives for non LUC sectors (around -35% abatement in 2030) with a single carbon market leads to a 3% GDP loss in 2030 with a 100 US\$ carbon price.

As for [Chen et al. \(2013\)](#), the economic implications are a bit more optimistic. In case when only half of LUC objectives are achieved, the others sectors combined would have to reduce of around the same 35% of their BAU emissions in 2030. This would be achieved with a quite high carbon price of 399 R\$/tCO₂ in 2030 that would only incur a 1.82% GDP loss compared to the reference case. Interestingly, the study analyses different recycling schemes of carbon revenues including the decrease of payroll taxes and the subsidy of wind power. It especially shows that a weak double dividend can be achieved.

5.4 Conclusion: specifications for new research questions and a new modeling tool

In light of the prospects post-2020 and the literature review of integrated studies for Brazil, we can identify key issues which, to the best of our knowledge, lack investigation and represent a relevant base for further work. We have first portrayed the challenge of deeper decarbonization for the 2020-2030 period in Brazil beyond the implementation of existing climate policy (PNMC) and energy plans. From now on, this challenge is very concrete, as Brazilian INDCs has adopted today an ambitious absolute emissions target for 2030. In this debate, we have highlighted the prominent role of energy-related emissions especially related to end-use sectors (industry and transports), and their link to future economic growth. Eventually we have mentioned the importance of the oil question in the debate. Yet, existing studies only partially address these specific and intertwined policy questions. Bottom-up approaches like

de Gouvello (2010) address mitigation issues of the energy system until 2030 beyond current energy plans but lacks the analysis of implications for the wider economy because of the partial equilibrium setting. General equilibrium studies bridge this gap but focus on the assessment of existing climate policies (extended PNMC), whereas new appraisal is urgently needed in the context of new commitments. In addition these studies do not provide specific insights about the energy system, the details of supply and demand for energy as well as identified mitigation measures. The authors actually do not compare their projections with energy plans nor check consistency with them. Another limitation is that the studies are focused on mitigation cost assessment and do not discuss the articulation of mitigation issues with other social and economic objectives (specific investment trends, trade, unemployment, income distribution, etc.). Eventually, these studies do not take into account the new oil context in Brazil and thus do not explore the key question of the articulation between emissions targets and the development of oil and gas sectors.

Building upon these conclusions, we define two axes of research for our further work around the macroeconomic, social and sectoral implications of deeper, energy-related mitigation scenarios - reflecting decarbonization levels close to recent INDCs:

- The assessment of macroeconomic climate policy tools (carbon tax policy) used to achieve energy-related emissions targets - consistent with new INDCs - until 2030 and the coordination of various climate, economic and social objectives.
- The study of the articulation between the development of the oil sector and the decarbonization of domestic transport and industry sectors until 2030.

To carry out this research program, we require a new modeling platform consistent with an appropriate forward-looking analysis. In practice, this tool should among others (i) be capable of simulating the energy and material content of future economic development pathways in Brazil and (ii) enable uncertainty management through scenarios analysis, exploratory approach, and stakeholders' dialog. This calls for the following modeling criteria:

- a SAM-based economy-wide model with multiple economic sectors balancing both energy and economic flows
- consistent with bottom-up analysis regarding technical constraints for energy supply and end-use demand sectors
- able to represent alternative visions of the economic system in the medium run, including second best and specific structural features (markets imperfections, structural behaviors, etc).

- able to represent unprecedented energy-economy futures.

These specifications form the basis for the construction of the IMACLIM-BR model developed in this thesis. Next chapter introduces in detail the purpose and characteristics of IMACLIM-BR .

Chapter 6

The IMACLIM Brazil model

The IMACLIM modeling approach, which we already have introduced in part I, has been developed at CIRED since the early 90s. At the core of the blueprint has been the objective to build hybrid modeling architectures to articulate energy system and economy-wide representations to explore energy-climate-economy futures (Hourcade, 1993; Hourcade et al., 2006; Gherzi and Hourcade, 2006). Today the IMACLIM approach comes in several modeling platforms including a global multi-region recursive-dynamic version - IMACLIM-R WORLD (Sassi et al., 2010; Bibas et al., 2015) and national versions for France either recursive-dynamic - IMACLIM-R FRANCE (Bibas, 2013) - or in comparative statics - IMACLIM-S FRANCE (Combet, 2013). Recently, several national versions have been developed mainly for emerging economies like Brazil and South Africa. The development of the IMACLIM platform for Brazil - called IMACLIM-BR , which is at the core of this thesis, is the result of an ongoing collaboration with the COPPE of the University of Rio de Janeiro. A first version of the model has been published in an other PhD thesis (Wills, 2013) and the IMACLIM-BR platform has been recently used to build policy-oriented national and stakeholder-based scenarios and assessments (Wills et al., 2015; La Rovere et al., 2015).

In this chapter, we present the IMACLIM-BR model versions developed for the specific research objectives of the present thesis. We start by introducing the rationale and main features of the modeling approach in a compact format in order to highlight the main specifics. The rest of the chapter details the complete modeling features of the model versions used to provide the analysis of the two last chapters.

6.1 IMACLIM-BR at a glance

IMACLIM-BR is a hybrid CGE modeling platform of the Brazilian economy specifically designed to build consistent projections of the energy-GHG emissions-economy system in Brazil over the medium to long term. It makes it especially possible to assess the macroeconomic implications of price or quantity-based carbon and energy policies over the medium to long term. IMACLIM-BR departs from more standard neoclassical CGE models in several features.

First of all, like standard CGE models, IMACLIM-BR rests upon the representation of walrasian markets of goods and services with global income balance. In addition, like most hybrid CGE models, IMACLIM-BR is based on an energy-economy hybrid accounting framework where economic flows *and* physical flows (with a special focus on energy balances) are balanced (see chapter 4 for the issue of energy-economy hybrid accounting frameworks). However it first departs from the neoclassical approach in that its description of the consumers' and producers' trade-offs, and the underlying technical systems, are specifically designed to facilitate calibration on bottom-up expertise in the energy field, with a view to guaranteeing technical realism to the simulations of even large departures from base year point.

Second, IMACLIM-BR represents "second best" economic systems - distant from the canonical competitive economy - and computes future accounting balances and walrasian markets of goods and services characterized by possible underemployment of production factors (labor) and imperfect markets (goods and factors). To do so, the model relies on a specific representation of capital and on other structural assumptions. In this feature it can be related to the tradition of structuralist CGE models (Taylor, 1990).

Third, IMACLIM-BR computations rely on the method of comparative statics (Samuelson, 1983; Kemfert, 2003): the model generates medium-run energy-economy projections in a single time step and compares, at the time horizon studied, these different projections as different counterfactuals driven by alternative sets of parameters and policy packages. The insights provided are valid under the assumption that the policy-induced transition from base year to a given policy-constrained future, is completed, after a series of technical and economic adjustments whose duration and scope are embedded in the behavioral functions retained for the time horizon under consideration. The transition process itself is however not described, but implicitly supposed to be smooth enough to prevent e.g. multiple equilibria, hysteresis effects, etc.

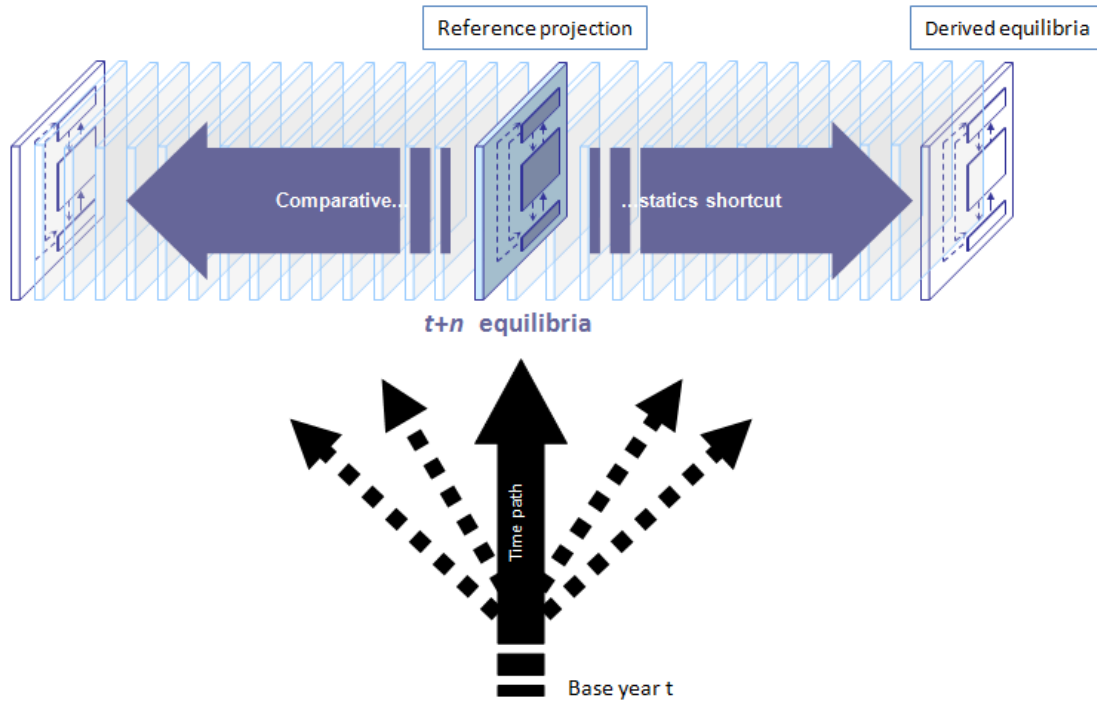


Figure 6.1: Single-step projections and comparative statics

6.2 Characterization of the model in a compact format

As IMACLIM-BR departs from more standard - even hybrid - CGE models in specific features, it is required to characterize clearly the nature of the model and these specifics. We provide in this section a compact description of the model. It enables to draw a synoptic characterization of the model also in light of the methodological assessment of part I.

6.2.1 Key equations

The comparative statics framework boils down to a set of simultaneous equations at the time horizon studied:

$$\begin{cases} f_1(x_1, \dots, x_n, \bar{\phi}_1, \dots, \bar{\phi}_m) = 0 \\ f_2(x_1, \dots, x_n, \bar{\phi}_1, \dots, \bar{\phi}_m) = 0 \\ \dots \\ f_n(x_1, \dots, x_n, \bar{\phi}_1, \dots, \bar{\phi}_m) = 0 \end{cases}$$

$(x_i)_{i \in \{1, \dots, n\}}$ are the variable of the model.

$(\bar{\phi}_i)_{i \in \{1, \dots, m\}}$ is a set of exogenous parameters.

$(f_i)_{i \in \{1, \dots, n\}}$ is a set of exogenous functions, linear or non-linear.

The f_i constraints are of two quite different natures: (i) one subset of equations describes the accounting constraints that are necessarily verified to ensure that the accounting system is properly balanced and (ii) the other subset translates the technical and economic choices.

A compact version of model is made of the following blocks:

- Domestic price formation:

$$\text{Price of production} \quad P_Y = P \cdot \alpha + w \cdot l + p_K \cdot k + p_{LD} \cdot ld + P_Y \cdot \text{diag}(\Pi) \quad (6.2.1)$$

$$\text{Average price} \quad P = \left[\frac{p_{Yj} \cdot Y_j + \overline{p_{Mj}} \cdot M_j}{Y_j + M_j} \right]_j \quad (6.2.2)$$

- Income generation and usage:

$$\text{Closure rule} \quad R_{CONS} + R_{INV} = \overline{sh} \cdot \left[\sum_j (w \cdot l_j + p_K \cdot k_j + p_{LD} \cdot ld_j + p_{Yi} \cdot \pi_j) \cdot Y_i \right] \quad (6.2.3)$$

$$\text{Investment} \quad R_{INV} = p_{COMP} \cdot I_{COMP} \quad (6.2.4)$$

- Demographic driver:

$$\text{Active population} \quad NS = NS \cdot (1 + \overline{\delta_{NS}}) \quad (6.2.5)$$

- Productivity drivers and production trades-off:

$$\text{Input intensity of production} \quad \alpha = [f_{ij}(P, w, p_K, p_{LD}, \overline{\phi_{ij}})]_{ij} \quad (6.2.6)$$

$$\text{Labor intensity of production} \quad l = [f_{Lj}(P, w, p_K, p_{LD}, \overline{\phi_{Lj}})]_j \quad (6.2.7)$$

$$\text{Capital intensity of production} \quad k = [f_{Kj}(P, w, p_K, p_{LD}, \overline{\phi_{Kj}})]_j \quad (6.2.8)$$

$$\text{Land intensity of production} \quad ld = [f_{LDj}(P, w, p_K, p_{LD}, \overline{\phi_{LDj}})]_j \quad (6.2.9)$$

- Final consumption trades-off:

$$C = [f_{Cj}(R_{CONS}, P)]_j \quad (6.2.10)$$

$$(6.2.11)$$

- Breakdown of value-added:

$$\text{Wage curve} \quad w = f_w \left(1 - \frac{L}{NS} \right) \quad (6.2.12)$$

$$p_K = p_{COMP} \quad (6.2.13)$$

$$p_{LD} = \overline{p_{LD}} \quad \text{or} \quad p_{LD} = g_{LD}(LD) \quad (6.2.14)$$

$$\text{Mark-up pricing} \quad \Pi = \overline{\Pi} \quad (6.2.15)$$

- Trade:

$$X = \left[f_{X_j}(p_{Y_j}, p_{M_j}, \overline{X_j}) \right]_j \quad (6.2.16)$$

$$M = \left[f_{M_j}(p_{Y_j}, p_{M_j}, Y_i) \right]_j \quad (6.2.17)$$

- Markets - accounting balances in volumes:

$$\text{Market of goods} \quad Y = Y \cdot \alpha^t + C + I + X - M \quad (6.2.18)$$

$$\text{Labor market} \quad L = \sum_j l_j \cdot Y_j \quad (6.2.19)$$

$$\text{Implicit capital balance} \quad \sum_j k_j \cdot Y_j = \overline{\beta} \cdot I_{COMP} \quad (6.2.20)$$

$$\text{Land market} \quad LD = \sum_j ld_j \cdot Y_j \quad (6.2.21)$$

6.2.2 A set of distinctive features

6.2.2.1 A SAM-based CGE model

First of all IMACLIM-BR is a CGE model with multiple economic sectors based on a standard Social Accounting Matrix (SAM) and a square Input-Output matrix (α represents the matrix of technical coefficients). It follows the Arrow-Debreu formulation of volumes (Y, C, I, X, M, L, LD (land), etc) and prices ($p_Y, p, p_M, w, p_K, p_{LD}$) for goods and production factors, solves walrasian markets of goods and insures the usual accounting identities of the SAM in volumes and money flows for the different markets (goods and factors) and institutional sectors budgets (one single representative domestic agent in this compact version and the rest of the world). It also represents an opened economy with trade effects and the closure rule (in this compact version only) is based on an exogenous trade balance ratio in total domestic income (\overline{sh}). Eventually production and consumption trades-off are modeled by means of aggregated functions (f). The

model includes three factors of production (labor(L), capital (K) and land (LD)).

6.2.2.2 An exogenous growth engine with implicit capital accumulation

The first specific of the model pertains to its growth engine. Usually, CGE models are either “static” or “recursive dynamic”. In the first case, the model simulates counterfactuals at a given date with fixed labor and capital endowments. There is no growth model and final demand of investment goods do not increase capital endowment. In the case of recursive-dynamic CGE models, the growth engine is usually based on an exogenous growth model with *explicit* recursive capital - investments dynamics, a demographic driver and exogenous technical change (Harrod’s neutral technical change in the example below based on labor productivity gains):

$$K_t = (1 - \delta) \cdot K_{t-1} + I_t \quad (6.2.22)$$

$$L_t = L_0 \cdot e^{\delta \cdot t} \quad (6.2.23)$$

$$Y_j = f(K, e^{\phi_L \cdot t} \cdot L, E, M) \quad (6.2.24)$$

Our model aims at exploring future states of the economy in the medium and long run, so it needs to model economic growth. To do so, it includes a growth engine based on usual demographic drivers and technical change features but with an *implicit* representation of capital accumulation, else consistent with the comparative statics framework and the generation of future states of the economy in one single step. Therefore, although the model’s computations rely on comparative statics, it is not a static CGE (in the sense of fixed factors endowment) and it does model economic growth in the medium to long run.

In practice, as in a standard growth model, it includes both an exogenous demographic driver and factor augmenting productivity coefficients ($\bar{\phi}$) consistent with the time horizon studied. However, it substitutes for the equation of *explicit* capital stock dynamics, a simpler link of proportionality between a proxy of total capital stock (total fixed capital consumption - $\sum_j k_j \cdot Y_j$) and real investment flows (fixed capital formation - I_{COMP}) at the year of projection: $\sum_j k_j \cdot Y_j = \bar{\beta} \cdot I_{COMP}$. This feature in fact surmises a smooth economic growth between base year and the time of horizon for a given projection. It should be noted that this does not mean that the economy is on a stabilized growth path in Solow’s sense as a perpetual steady state. On the contrary, the model aims at representing unbalanced trajectories with sub-optimal employment of factors. The model just circumvents the representation of complex transitional se-

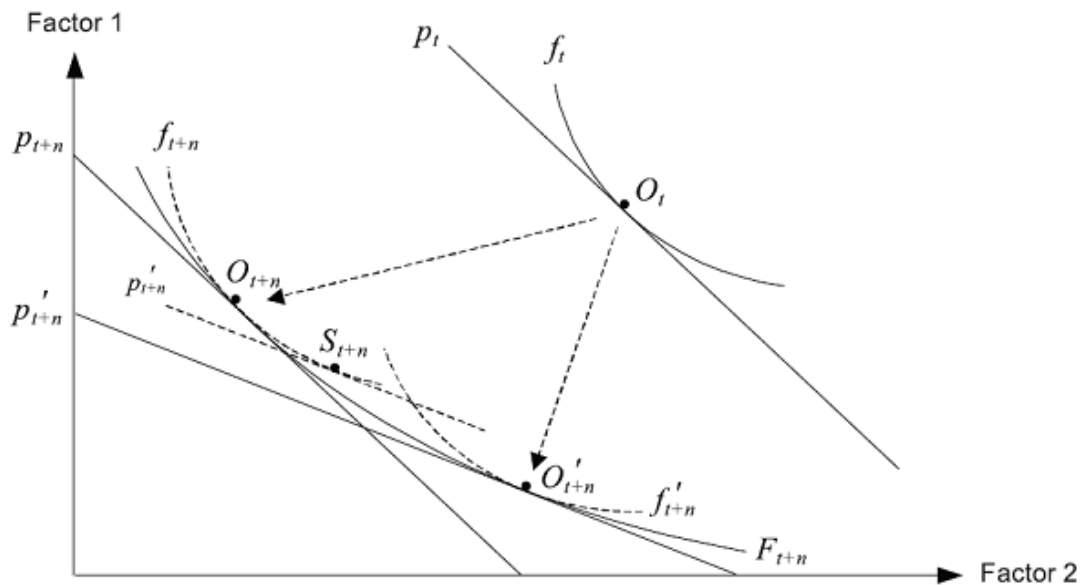


Figure 6.2: Production frontier and innovation possibility curve

Source: (Gherssi and Hourcade, 2006)

quences and averages a growth rate between base-year and the time of projection for more simplicity.

6.2.2.3 A reinterpretation of the production function

In most CGE models, production trade-offs are modeled by means of production functions. Historically production functions have been used to represent the trade-off between production factors according to their relative prices in the long run along steady growth pathways. However the same production functions are used to model production trade-off in intra-temporal equilibrium (short to medium run) of recursive dynamic CGE models. Following (Gherssi and Hourcade, 2006), IMACLIM-BR embodies a renewed interpretation of the production function as the envelop of technical choices respective to a given time horizon. The envelop of technical choices per sector is embodied by the set of functions $f_{ij}, f_{Lj}, f_{Kj}, f_{LDj}$ (see the equations in section 6.2.1). As in fig. 6.2, technical choices at $t + n$ are the results of given relative prices regimes between t and $t + n$ and can include implicit price-induced technical change¹.

The resulting envelop of technical choices or “innovation possibility curve” (Ahmad, 1966) is eventually the envelop of all the possible isoquants linked to different

¹A durable regime of high relative price of factor 1 will trigger biased technical change towards a relative decrease of factor 1 intensity in production.

relative prices regimes. This interpretation of the production frontier at a given time horizon provides new options for bottom-up - top-down hybridization as detailed in chapter 3. In this view, the envelop of production can be built as a reduced form of bottom-up projections and thus mimic possible bottom-up singularities beyond constant elasticity of substitution. One prerequisite to implement this method is to keep physical accounting in the CGE model in order to embark the technical information provided by the bottom-up model (about energy efficiency for instance). In practice, few complete reduced forms have been mainstreamed in IMACLIM-S models. In [Gherzi et al. \(2011\)](#) for instance, the IMACLIM-S FRANCE model embarks bottom-up information about technical asymptotes in standard CES functions. However, this is a simple and convenient mean to inform some technical boundaries and imply non-constant elasticities of substitution as the system gets closer to its technical limits. For preliminary exercises not reported in this thesis, we have implemented reduced forms of MAC curves for industry sectors in a specific version of IMACLIM-BR ([Wills, 2013](#)). The modeling choices for the versions of IMACLIM-BR used in this thesis are discussed in section 6.3.5.2.

6.2.2.4 Specific capital and labor markets and imperfect markets of goods

An other specific of IMACLIM-BR is the representation of capital. The capital “consumption” for production $K = k.Y$ is not modeled as the standard capital stock and the model does actually not track capital stock. In fact, the capital factor of production in real terms corresponds to the fixed capital consumption or the depreciation of capital as a proxy of capital stock. In addition, no explicit capital market is modeled and production sectors do not trade-off capital with other production factors according to a standard return on capital. Instead, trade-offs about the capital content of production are based on the price of the composite good (a weighted average of the different investment goods in the expanded model) as the price of the “machine” capital ($p_K = p_{COMP}$). The return on capital (as the economic productivity of capital) beyond depreciation is aggregated into a sector specific mark-up (Π coefficients). The underlying idea is to depart from the standard assumption about a capital market where the return on capital equals its marginal productivity, which is often a heroic assumption taken from microeconomic theory. In addition the marginal assumption is generally coupled with the zero-profit hypothesis, so that pure profit does not exist (with constant return to scale). Instead, we choose to model capital choices based on the technical content of capital (the “machine”). The reminder of the value-added beyond pure capital consumption, which corresponds to profits in the larger sense, is modeled

with a mark-up. This mark-up also reflects different trend levels of goods markets imperfections (oligopolistic or monopolistic trends for instance). As a whole no explicit capital market is modeled and capital “consumption” determines investment needs at the year of projection through the β coefficient or vector.

In addition, the model includes several features about labor markets that depart from standard assumptions. First of all, the model measures the labor factor in full time equivalent jobs and does not derive it from benchmark labor cost shares. This has important implications for the relative levels of apparent labor productivity across sectors. Finally, IMACLIM-BR includes the representation of involuntary unemployment and trend rigidities in the medium run on labor markets by means of a global wage curve (Blanchflower and Oswald, 1995). This wage curve is an empirical relationship between the average wage (whether nominal or real wage depending on the assumption) and the global unemployment rate of the economy.

6.2.2.5 Dual accounting and hybrid I-O framework

The consistency of projections is managed through maintaining a double account of flows both in physical and value units when generating the projections. As mentioned, it also enables to embark bottom-up information in an explicit manner. For this to be valid, the model should only include modeling features that maintain balance of physical volumes. For instance traded energy goods are supposed to be perfect substitutes and do not follow standard Armington’s assumption as opposed to non-energy goods. Keeping up double accounting eventually supposes an important data work to build the initial state of the system. Chapter 4 shows the impact of data treatment on modeling results.

6.2.3 Conclusion: positioning of IMACLIM-BR in CGE modeling

In the literature of climate policy assessment and energy-economy models, CGE modeling usually refers to a narrowed type of modeling approaches, although majority, inspired by the micro-economic theory of Arrow-Debreu general equilibrium. In this dominant approach inherited from recent decades, economic behaviors are supposed to be micro-founded and to reflect rigorous micro-economic theory based on surplus maximization of economic agents and market (goods and factors) clearing. In practice economic behaviors are most of the time informed by constant return-to-scale CES production functions and markets are assumed perfect with zero profit conditions (Wing, 2004). The underlying goal is to embody the competitive equilibrium of micro-economic theory in empirical macroeconomic models. Sub-optimum is possible in

this framework though, through tax distortion, market failures or market power but economic behaviors remain based on rigorous micro-economic theory.

However historically, CGE models are first and foremost macro-balancing models² and the accounting balance of the SAM is the primary characteristic of a CGE model. In particular, accounting and income balance do not necessarily imply market clearing or full employment of factors, which constitute very specific cases. [Thissen \(1998\)](#) provides a larger definition of CGE modeling in this direction: “A CGE model may be defined as the fundamental macroeconomic general equilibrium links among incomes of various groups, the pattern of demand, the balance of payments and a multi-sector production structure”. In a word, CGE models are primarily macro-balancing models before possible empirical translation of general equilibrium micro-economic theory.

IMACLIM models, and IMACLIM-BR especially, fit into this broader vision of CGE modeling and emphasize the idea of macroeconomic *interdependence* between demand patterns, inter-industry structure and income flows from decentralized representative economic agents. In this view the mechanisms of interdependence are fundamentally constrained by supply-use equilibrium and the accounting balance of the SAM, which is the base of the equilibrium concept. In addition, IMACLIM models build on the price-quantity formulation of flows and stocks of goods and production factors to generate consistent energy-economy projections and control underlying technical systems.

Beyond accounting balance and dual accounting of energy flows, IMACLIM-BR is based on the computation of walrasian markets of goods (with simultaneous price and quantity adjustment) in the medium to long run combined with and implicit growth engine. However it abandons the systematic reference to rigorous micro-economic theory to the benefit of structural assumptions and empirical realism. Economic behaviors are represented by structural assumptions embedded in the functional forms retained. These functions can be reduced forms of bottom-up models when it is relevant. Structural assumptions also pertain to the structure of markets like for instance the abandonment of the representation of a capital market balanced with a rate of return on capital. These structural assumptions make it finally possible to represent specific second-best trends of the economy such as imperfect markets of goods through mark-up pricing (relaxing the zero-profit condition) and imperfect labor markets with involuntary unemployment.

²Leif Johansen is often credited with being the first CGE modeler and has proposed a model that combines macro-balancing equations with a Leontief production structure ([Johansen, 1960](#)). This stream of modeling significantly developed during the 70's ([Taylor and Black, 1974](#); [Adelman and Robinson, 1978](#)). The inclusion of a link to Arrow-Debreu micro-economic theory happened only later in the 80's through the connection with Applied General Equilibrium (AGE) modeling based on Scarf's simplex method ([Shoven and Whalley, 1972](#)).

The modeling approach retained is finally consistent with the forward-looking analysis contemplated. The primary modeling objective is to generate consistent energy-economy futures pending interdependence constraints (final demand and trade patterns, production structure, income distribution, etc.), second-best mechanisms (imperfect markets, labor market rigidities, etc.) and technical constraints (technical change, substitution possibilities, etc.). The approach favors variant analysis about structural assumptions informed by stakeholders dialog (engineers and economists for instance) and swaps part of the internal rigor for higher expected empirical relevance.

6.3 The complete modeling features of the IMACLIM-BR reference version

This section details the complete features and equations of the reference version of IMACLIM-BR , which distinguishes 6 economic sectors - referred to as IMACLIM-BR 6 or simply IMACLIM-BR . Next section develops the specifics of the 6-sectors version detailing 6 households groups - IMACLIM-BR 6-6 - and the 12-sectors version with an expanded demand system and focus on oil, liquid fuels and transport sectors -IMACLIM-BR 12-ext. The three model versions are used to provide the analysis of the last two chapters.

6.3.1 Accounting framework: SAM (Social Accounting Matrix)

The IMACLIM-BR versions used in this thesis, distinguish 6 or 12 productive sectors (table 6.1). The 6-sectors versions consider three energy sectors (bioenergy, fossil fuels and electricity) and three end-use sectors (agroindustry, general industry and services - including transportation services). The 12-sectors version distinguish six energy sectors (bioenergy, coal, crude oil, natural gas, refined oil and electricity) and six end-use sectors (load transportation, passenger transportation, livestock, agro-industry, general industry and services). All versions include three primary production factors: labor, capital and land.

The interactions between productive sectors and factors are included in the larger accounting framework of IMACLIM-BR summarized by its SAM (see table 6.2).

Sectors		Production factors
6-sectors version	12-sectors version	
	Energy	Labor
Bioenergy (BIO)	Bioenergy (BIO)	Capital
	Coal (COAL)	Land
Fossil fuels (FF)	Crude Oil (OIL)	
	Natural Gas (GAS)	
	Refined Oil (ROIL)	
Electricity (ELEC)	Electricity (ELEC)	
	Non-Energy	
Agroindustry (AGRI)	Livestock (CATT)	
	Agro-industry (AGRI)	
General industry (INDUS)	Industry (INDUS)	
	Load Transportation (LOAD)	
Services (COMP)	Pass. Transportation (PASS)	
	Services (COMP)	

Table 6.1: Sectors and production factors

	Sectors	Labor	Capital, Profits, Margins	Land	HH	Firms	GOV	ROW	INV	FINCAP	Others
Sectors	$p_Y \cdot IC_{dom}$				$p_Y \cdot C_{dom}$		$p_Y \cdot G_{dom}$	$p_Y \cdot X_{dom}$	$p_Y \cdot I_{dom}$		
Labor	$w \cdot l \cdot Y$										
Capital	$p_K \cdot k \cdot Y$										
Land	$p_{LD} \cdot ld \cdot Y$										
Profits	$\pi \cdot p_Y \cdot Y$										
Margins	$BM + TM + SM$				$BM + TM + SM$		$BM + TM + SM$	$BM + TM + SM$	$BM + TM + SM$		
HH		$w \cdot l \cdot Y$	$\overline{\omega_{Kh}} \cdot GOS$	$\overline{\omega_{LDh}} \cdot LAND$		$\rho_f \cdot N$	$\rho_g \cdot N$				OT_h
Firms	TL_f		$\overline{\omega_{Kf}} \cdot GOS$	$\overline{\omega_{LDf}} \cdot LAND$	T_{hf}						OT_f
GOV	$T_{CONS} + TL_g + T_Y$		$\overline{\omega_{Kg}} \cdot GOS$	$\overline{\omega_{LDg}} \cdot LAND$	$T_{CONS} + TI_h + T_{hg}$	TI_f	T_{CONS}	T_{CONS}	T_{CONS}		OT_f
ROW	$p_M \cdot IC_{imp}$				$p_M \cdot C_{imp}$		$p_M \cdot G_{imp}$	$p_M \cdot X_{imp}$	$p_M \cdot I_{imp}$		OT_m
INV					$GFCF_h$	$GFCF_f$	$GFCF_g$				
FINCAP					$FCAP_h$	$FCAP_f$	$FCAP_g$	$FCAP_m$			
Other transf.											

Table 6.2: IMACLIM-BR Social Accounting Matrix (SAM)

Each sector produces one single good so that commodities and activities match and the Input-Output table is square. Productive sectors generate income through productive factors. The national income is further distributed to representative institutional agents in the same pattern as in national accounts. The model distinguishes 4 institutional agents or sectors: *households* (HH), *corporate firms* (FIRMS), *public administrations or government* (GOV) and the *rest of the world* (ROW). On the whole IMACLIM-BR keeps the orthogonal logic between productive sectors and institutional agents in order to keep the detail of primary income distribution. This makes it possible to identify the shares of capital, land income and generated profits that primary accrue specifically to autonomous producers (Households: family farms, individual entrepreneurs, landlords (agriculture and housing), etc), corporate firms or public administrations (public companies). Therefore households, firms and government have separated accounts in our model and may have different structural behaviors. CGE models usually shortcut this aspect by assuming that households eventually own the total endowment of production factors. Only households are endowed with labor in the model.

Furthermore, through secondary income distribution, institutional agents break down their income between goods consumption, investment, tax payments and transfers. The model considers a detailed system of taxes and transfers essentially between the triangle of domestic agents. We will detail this system later in the model description. Owing to the split of accounts of institutional agents, IMACLIM-BR also considers the breakdown of total *gross fixed capital formation* (GFCF) between agents. It further identifies for each agent the share of income that is not directly invested in GFCF, which is called financial capacity (FCAP). The rest of the world classically interacts with domestic agents through trade of goods and capital balance.

The rest of the section details the equations of the model through different blocks: (i) *price system and income generation*, (ii) *institutional sectors accounts*, (iii) *production and households consumption trade-off* and (iv) *market balances*. The equations of the model are of two quite different natures: one subset of equations describes accounting constraints that are necessarily verified to ensure that the accounting system is properly balanced; the other subset translates various behavioral constraints, written either in a simple linear manner (e.g. households consume a fixed proportion of their income) or in a more complex non-linear way (e.g. the trade-offs of production and consumption). It is these behavioral constraints that ultimately reflect, in the flexible architecture of IMACLIM-BR a certain economic “worldview”.

The equations distinguish three kinds of components: (i) the variables computed by the model, which represent the endogenous elements of the projected energy-economy picture at the time horizon studied, (ii) the parameters that are calibrated on

the base year SAM and (iii) the other non calibrated parameters coming from external sources. In the equations, the calibrated parameters are identified with an over-line and base year variables are indexed with 0. Although most equations are written in an generalised n-goods format, when necessary good-specific variables are indexed by the subscripts detailed in table 6.1. Variables names are also consistent with the SAM.

6.3.2 Price system - Income generation

As already introduced with the compact form of IMACLIM-BR , prices and income generation are first channels to impose structural constraints in the model as a first source of departure from a neoclassical CGE model. It includes (i) the representation of non-zero profits through mark-up pricing, (ii) the inclusion of specific margins for energy goods (in the way introduced earlier in chapter 4), (iii) sector specific wages and (iv) a specific price for capital consumption.

6.3.2.1 Prices

First of all, p_{Yj} , the producer's price of good-sector j is following the cost structure of the production of good j plus a pure profit component. p_{Yj} is thus built as the sum of intermediate consumptions, labour costs, capital costs, land costs (for land-use sectors only) a tax on production, and a rate of profit.

$$p_{Yj} = \sum_{i=1}^n p_{ICij} \cdot \alpha_{ij} + p_{Lj} \cdot l_j + p_k \cdot k_j + p_{LDj} \cdot ld_j + \bar{\pi}_j \cdot p_{Yj} + \bar{\tau}_{Yj} \cdot p_{Yj} \quad (6.3.1)$$

Technical coefficients α , l , k and ld are expressed in real terms. Technical coefficients for intermediary consumption of energy are specifically expressed in ktoe per unit of output.

The rate of profit $\bar{\pi}$, which corresponds in practice to the net operating surplus, is constant and calibrated at base year for all sectors in the reference version.

This mark-up pricing is used to translate both the specific structural conditions of the different market of goods and all costs that are not pure capital consumption costs. We detail the meaning of this capital consumption in section 6.3.5. The specific structural conditions embody the departure from the perfect competitive case of a first best setting.

p_{Mi} the price of imported good j is good-specific and the international composite good is the *numéraire* of the model; its price is assumed constant and equal to unity.

$$p_{M_{COMP}} = p_{M_{COMP_0}} = 1 \quad (6.3.2)$$

The prices of others goods evolve according to an exogenous rate $\delta_{p_{Mi}}$:

$$p_{Mi} = (1 + \delta_{p_{Mi}})^t \cdot p_{Mi_0} \quad (6.3.3)$$

$\delta_{p_{Mi}}$ parameters is used to simulate alternative world energy prices scenarios.

CGE models usually adopt the assumption of goods differentiation between domestic and imported goods and the implementation of an Armington specification (Armington, 1969). However the Armington specification has the disadvantage of creating “hybrid” good varieties, whose volume unit is independent from that of the foreign and national varieties they hybridize. This prevents to maintain an explicit accounting of the physical energy flows and thus an energy balance. Consequently, in order to keep the account of physical volumes (which is a fundamental of our modeling approach), imported and domestic energy goods are assumed to be homogeneous:

$$p_i = \frac{p_{Y_i} \cdot Y_i + p_{M_i} \cdot M_i}{Y_i + M_i} \quad (6.3.4)$$

Nevertheless, imported and domestic energy goods can coexist in the domestic market even with different prices (see subsection 6.3.6). For the sake of simplicity, non-energy goods are treated similarly.

p_{iCij} the purchaser’s price of good i consumed for the production of good j , is equal to the resource price of good i plus trade and transport margins, specific margins and a rate of aggregate *ad valorem* tax on consumption (sales tax):

$$p_{iCij} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSiCij}}) \cdot (1 + \overline{\tau_{CONSi}}) \quad (6.3.5)$$

The purchaser’s price of good i for households consumption (p_{Ci}), public administrations (p_{Gi}) and investment (p_{Ii}), and the export price of good i (p_{Xi}), are constructed similarly³:

³ p_{iCij} and p_{Ci} are possibly increased by a carbon tax as detailed in subsection 6.3.8.

$$p_{Ci} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSCi}}) \cdot (1 + \overline{\tau_{CONSi}}) \quad (6.3.6)$$

$$p_{Gi} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSGi}}) \cdot (1 + \overline{\tau_{CONSi}}) \quad (6.3.7)$$

$$p_{Ii} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSIi}}) \cdot (1 + \overline{\tau_{CONSi}}) \quad (6.3.8)$$

$$p_{Xi} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSXi}}) \quad (6.3.9)$$

One exception is the export price of fossil fuels (FF) which is indexed on world price:

$$p_{X_{FF}} = p_{M_{FF}} \cdot \frac{p_{X_{FF0}}}{p_{M_{FF0}}} \quad (6.3.10)$$

We also introduce the pre-tax price system:

$$p_{BTiCij} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSiCij}}) \quad (6.3.11)$$

$$p_{BTZi} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSZi}}) \text{ with } Z \in \{C, G, I\} \quad (6.3.12)$$

Specific margins are calibrated at base year and held constant to reflect the difference of tariffs (taxes excluded) of energy goods according to the different consuming agent/sector.

Business margins τ_{BMi} and transport margins τ_{TMi} , identical for all intermediate and final consumption of good i , are calibrated at base year and kept constant - except those on freight transport and trade activities aggregated within the *COMP* sector, which are simply adjusted, to have the two types of margins sum up to zero :

$$\begin{cases} \tau_{BM_{COMP}} = \overline{\tau_{BM_{COMP}}} \\ \tau_{TM_{COMP}} = \overline{\tau_{TM_{COMP}}} \end{cases} \quad (6.3.13)$$

$$\begin{aligned} & \sum_{j=1}^n \tau_{BM_{COMP}} \cdot p_{COMP} \cdot \alpha_{COMPj} \cdot Y_j + \tau_{BM_{COMP}} \cdot p_{COMP} \cdot (C_{COMP} + G_{COMP} + I_{COMP} + X_{COMP}) \\ & + \sum_{i \neq COMP} \sum_j \overline{\tau_{BMi}} \cdot p_i \cdot \alpha_{ij} \cdot Y_j + \sum_{i \neq COMP} \overline{\tau_{BMi}} \cdot p_i \cdot (C_i + G_i + I_i + X_i) = 0 \end{aligned} \quad (6.3.14)$$

$$\sum_{j=1}^n \tau_{BMCOMP} \cdot p_{COMP} \cdot \alpha_{COMPj} \cdot Y_j + \tau_{BMCOMP} \cdot p_{COMP} \cdot (C_{COMP} + G_{COMP} + I_{COMP} + X_{COMP}) + \sum_{i \neq COMP} \sum_j \overline{\tau_{Bmi}} \cdot p_i \cdot \alpha_{ij} \cdot Y_j + \sum_{i \neq COMP} \overline{\tau_{Bmi}} \cdot p_i \cdot (C_i + G_i + I_i + X_i) = 0 \quad (6.3.15)$$

IMACLIM-BR accounts for labor service in full-time equivalent jobs and thus deals with sector specific wages. Labor costs are further equal to the sector specific net wage w_i plus payroll taxes that correspond to employers social contributions for private and public employees social care (pensions, health care, etc). These taxes are levied based on average sector specific rates and calibrated at base year:

$$p_{Li} = \left(1 + \overline{\tau_{Lfi}} + \overline{\tau_{Lgi}}\right) \cdot w_i \quad (6.3.16)$$

In addition, wages evolve with a common rate of change:

$$w_i = a \cdot w_{i0} \quad (6.3.17)$$

The average wage - defined by:

$$w = \frac{\sum_{i=1}^n w_i \cdot l_i \cdot Y_i}{\sum_{i=1}^n l_i \cdot Y_i} \quad (6.3.18)$$

is subject to variations that are dictated by the supply side of labor markets which relates, by means of a wage curve, the average wage to the average rate of unemployment of the economy (see labor market balance in subsection 6.3.7).

The cost of capital is understood as the cost of the “machine” capital (see the description of the production trade-offs in subsection 6.3.5). It is obtained as the average price of investment goods:

$$p_K = \frac{\sum_{i=1}^n p_{Li} \cdot I_i}{\sum_{i=1}^n I_i} \quad (6.3.19)$$

As mentioned earlier, it is a specific of our modeling approach where a standard CGE model compute a rate of return on capital.

6.3.2.2 Gross operating Surplus

Capital costs, profits and specific margins determine the gross operating surplus (GOS) (income from land excluded) of the economy:

$$GOS = \sum_{i=1}^n (p_K \cdot k_i \cdot Y_i + \bar{\pi}_i \cdot p_{Y_i} \cdot Y_i) + M_s \quad (6.3.20)$$

By construction, the specific margins on the different sales M_s sum to zero in the base year equilibrium (this is a constraint of the energy-economy data hybridizing process), however they do not in the future equilibrium, their constant rates being applied to varying prices. The total specific margin generated M_s is then computed as:

$$M_s = \sum_i \left(\sum_j \bar{\tau}_{MSiCij} \cdot p_i \cdot \alpha_{ij} \cdot Y_j + \bar{\tau}_{MSCi} \cdot p_i \cdot C_i + \bar{\tau}_{MSGi} \cdot p_i \cdot G_i + \bar{\tau}_{MSXi} \cdot p_i \cdot X_i \right) \quad (6.3.21)$$

The Agriculture sector (*AGRI*) generates total available land income:

$$LAND = p_{LD_{AGRI}} \cdot ld_{AGRI} \cdot Y_{AGRI} \quad (6.3.22)$$

GOS and *LAND* are further broken down between institutional sectors as described in subsection 6.3.3.

The consumer price index *CPI* is computed following Fisher, i.e. as the geometric mean of a Laspeyres index (variation of the cost of the present basket of goods from the present to the future set of relative prices) and a Paasche index (variation of the cost of the future basket of goods from the present to the future set of relative prices):

$$CPI = \sqrt{\frac{(\sum_i p_{Ci} \cdot C_{i_0}) \cdot (\sum_i p_{Ci} \cdot C_i)}{(\sum_i p_{C_{i_0}} \cdot C_{i_0}) \cdot (\sum_i p_{C_{i_0}} \cdot C_i)}} \quad (6.3.23)$$

6.3.3 Institutional sectors accounts

The equations related to institutional sectors accounts basically reflect the constraints of accounting balance embodied in the SAM. Compared to most CGE models, *IMACLIM-BR* keeps the accounting logic of national accounts with the distinction between households, firms and public administration as different institutional sectors. Again this results in the specific break down of capital income between institutional sectors (as different legal entities that owns production factors) as well as the keeping track of their specific contribution to gross fixed capital formation (GFCF). In a standard CGE model the representative household, endowed with all production factors, receives

total factors income as a global transfer. Furthermore its total GFCF - effective total investment - is generally deduced from the difference between its total savings and the capital balance. In this formulation, public administrations economic transactions are reduced to tax collection, social transfers and final services consumption.

6.3.3.1 Households (HH)

The gross primary income or revenue before tax (RBT_h) of the representative household corresponds to the sum of the elements of the HH row of the SAM:

$$RBT_h = \sum_{i=1}^n w_i \cdot l_i \cdot Y_i + \overline{\omega_{Kh}} \cdot GOS + \overline{\omega_{LDh}} \cdot LAND + \rho_f \cdot N + \rho_g \cdot N + OT_h \quad (6.3.24)$$

The gross primary income is constituted of the following elements:

- Total net income from labor computed as the sum of wages generated by the different economic sectors: $\sum_{i=1}^n w_i \cdot l_i \cdot Y_i$
- Total income from capital of households computed as an exogenous share of total GOS: $\overline{\omega_{Kh}} \cdot GOS$
- Total land rent earned by households as landlords computed as an exogenous share of total income from land $LAND$: $\overline{\omega_{LDh}} \cdot LAND$
- Social transfers as the sum of two aggregates: social transfers from private source (like private care insurances) and social transfers from public source. The computation is based on the product of an exogenous level of transfer per capita and the total population. Finally: $R_{fh} + R_{gh} = \rho_f \cdot N + \rho_g \cdot N$
- A residual level of transfers computed as an exogenous share of a global pool of others transfers: $OT_h = \overline{\omega_{OTh}} \cdot OT$

The gross disposable income R_h of the representative household is obtained by subtracting from RBT_h the tax on income TI_h levied at a constant average rate on RBT_h minus transfers (Equation 6.3.35), and two others direct taxes T_{hf} and T_{hg} (respectively paid to $FIRMS$ and GOV) that are indexed on GDP:

$$R_h = RBT_h - TI_h - T_{hf} - T_{hg} \quad (6.3.25)$$

R_{CONS} , the income expensed in consumption goods is inferred from disposable income by subtracting savings. The savings rate $\overline{\tau_s}$ is exogenous in the model.

$$R_{CONS} = (1 - \overline{\tau_S}) \cdot R_h \quad (6.3.26)$$

Furthermore the model specifies the share of savings directly invested in gross capital formation as an exogenous value calibrated at base year:

$$\frac{GFCF_h}{R_h} = \frac{GFCF_{h_0}}{R_{h_0}} \quad (6.3.27)$$

Eventually the net financing capacity of *HH* is the remainder of its income:

$$FCAP_h = R_h - R_{CONS} - GFCF_h \quad (6.3.28)$$

HH can be creditor or debtor on capital and financial markets if $FCAP_h$ is positive or negative.

6.3.3.2 Firms (*FIRM*)

The gross primary income (RBT_f) of the representative firm corresponds to the sum of the elements of the *FIRMS* row of the SAM:

$$RBT_f = \overline{\omega_{Kf}} \cdot GOS + \overline{\omega_{LDf}} \cdot LAND + TL_f + T_{hf} + OT_f \quad (6.3.29)$$

It is constituted of the following terms:

- Total income from capital (capital equity) earned by firms computed as an exogenous share of total *GOS*: $\overline{\omega_{Kf}} \cdot GOS$
- Total land rent earned by firms computed as an exogenous share of total income from land *LAND*: $\overline{\omega_{LDf}} \cdot LAND$
- A part of payroll taxes addressed to private financial institutions to finance private care and linked to the social transfers R_{fh} . TL_f is levied with an exogenous tax rate on wages: $TL_f = \sum_i \overline{\tau_{Lfi}} \cdot w_i \cdot l_i \cdot Y_i$
- A residual tax levied on households and proportional to labor income: $T_{hf} = \overline{\tau_{hf}} \cdot RL$
- A residual level of transfers computed as an exogenous share of the global pool of others transfers: $OT_f = \overline{\omega_{OTf}} \cdot OT$

The gross disposable income R_f of *FIRMS* is obtained by subtracting from RBT_f total corporate tax TI_f levied at a constant average rate (Equation 6.3.35), and the

private transfers directed to HH , R_{fh} .

$$R_f = RBT_f - R_{fh} - TI_f \quad (6.3.30)$$

Eventually the specific gross capital formation of firms ($GFCF_h$) which represents the bulk of investment is given by the rest of the model and especially constrained by the domestic investment balance (see Equation 6.3.61)

As for HH , the total financing capacity of $FIRMS$ is the remainder of the income:

$$FCAP_f = R_f - GFCF_f \quad (6.3.31)$$

6.3.3.3 Public administrations (GOV)

Taxes and social security contributions form the larger share of government resources. We distinguishes: payroll taxes (TL_g), taxes on production (T_Y), a remainder of tax levied on HH (T_{hg}), taxes on HH income (TI_h), taxes on $FIRMS$ profits (TI_f) and sales taxes (T_{CONS}) levied on intermediate and final consumption:

$$TL_g = \sum_i \overline{\tau_{Lgi}} \cdot w_i \cdot l_i \cdot Y_i \quad (6.3.32)$$

$$T_Y = \sum_i \overline{\tau_{Yi}} \cdot p_{Yi} \cdot Y_i \quad (6.3.33)$$

$$T_{hg} = \overline{\tau_{hg}} \cdot RL \quad (6.3.34)$$

$$TI_h = \overline{\tau_{Ih}} \cdot (RL + RK_h + \Pi_h + M_h + RLD_h) \quad (6.3.35)$$

$$TI_f = \overline{\tau_{If}} \cdot (RK_f + \Pi_f + M_f + RLD_f) \quad (6.3.36)$$

$$T_{CONS} = \sum_i \left(\sum_j p_{BTICij} \cdot \overline{\tau_{CONSi}} \cdot \alpha_{ij} \cdot Y_j \right) + \overline{\tau_{CONSi}} \cdot (p_{BTCi} \cdot C_i + p_{BTGi} \cdot G_i + p_{BTIi} \cdot I_i) \quad (6.3.37)$$

The total tax income T is thus given by:

$$T = TL_g + T_Y + T_{CONS} + T_{hg} + TI_h + TI_f + T_{Carb} \quad (6.3.38)$$

Furthermore, public administration income balance follows the GOV row of the SAM:

$$R_g = T + \overline{\omega_{K_g}} \cdot GOS + \overline{\omega_{LD_g}} \cdot LAND + OT_g - R_{gh} \quad (6.3.39)$$

Total available income R_g is thus defined as the sum of:

- Total income from taxation: T
- Total income from capital endowment of public companies computed as an exogenous share of total GOS : $\overline{\omega_{K_g}} \cdot GOS$
- Total land rent earned from public land computed as an exogenous share of total income from land $LAND$: $\overline{\omega_{LD_g}} \cdot LAND$
- A residual level of transfers computed as an exogenous share of the global pool of others transfers: $OT_g = \overline{\omega_{OT_g}} \cdot OT$
- A negative contribution linked to the social transfers for HH : $-R_{gh} = -\rho_g \cdot N$

Public expenditures are assumed to be indexed on national income, and therefore represent a constant share of GDP:

$$\frac{p_{COMP} \cdot G_{COMP}}{GDP} = \frac{p_{COMP_0} \cdot G_{COMP_0}}{GDP_0} \quad (6.3.40)$$

Both private and public social transfers per capita follow GDP per capita:

$$\frac{\rho_g}{\rho_{g_0}} = \frac{\rho_f}{\rho_{f_0}} = \frac{GDP \cdot N_0}{GDP_0 \cdot N} \quad (6.3.41)$$

As for public expenditure, public gross capital formation represents a constant share of GDP:

$$\frac{GFCF_f}{GDP} = \frac{GFCF_{f_0}}{GDP_0} \quad (6.3.42)$$

Finally $FCAP_g$, the financial capacity of GOV is given:

$$FCAP_g = R_g - p_{COMP} \cdot G_{COMP} - GFCF_g \quad (6.3.43)$$

6.3.3.4 Rest of the World (ROW)

The closure of the model is made through the balance of capital flows between the three domestic institutional sectors and the rest of the world:

$$FCAP_m = - (FCAP_h + FCAP_f + FCAP_g) \quad (6.3.44)$$

The sum of Equations 6.3.44 and 6.3.61 gives the savings-investment balance of the model.

According to Walras law, the last accounting balance, the balance of payments, which balances the ROW budget, is given as a linear combination of the others equations of the model:

$$FCAP_m = \sum_i p_{Mi} \cdot M_i - \sum_i p_{Xi} \cdot X_i - (OT_h + OT_f + OT_g)$$

However, contrary to most CGE models, foreign savings $FCAP_m$ or alternatively the exchanged rate can not be freely fixed in the model. Usually in CGE models, either foreign savings are fixed and the exchanged rate adjusts or else the modeler sets an exogenous exchanged rate and foreign savings are endogenous. In fact in IMACLIM-BR foreign savings are already given by Equation 6.3.44 and the specific capital-investment balance (see section 6.3.7.3). We could alternatively free such specification (like Equation 6.3.42 for instance) and set an exogenous trade balance or exchange rate. Eventually capital flows from and to the ROW are not assigned a specific behaviour, adapt to the domestic financing needs but constrain the trade balance and the exchanged rate.

At last, as previously mentioned, other transfers OT (“other current transfers”) and “capital transfers” are defined as a fixed share of GDP. Other transfers include for example interests payments.

$$\frac{OT}{GDP} = \frac{OT_0}{GDP_0} \quad (6.3.45)$$

6.3.4 Growth engine

As introduced earlier, IMACLIM-BR projects the Brazilian economy in the medium to long run in a single step projection and relies on the method of comparative statics.

In IMACLIM-BR the growth engine is basically exogenous and technical progress is implemented through factor augmenting coefficients.

The growth engine is the combination of several drivers:

- The total population and active population growth:

$$N = (1 + \delta_N)^t \cdot N_0 \quad (6.3.46)$$

$$NS = (1 + \delta_{NS})^t \cdot N_0 \quad (6.3.47)$$

- The implicit capital accumulation computed through a proportional link between

total fixed capital consumption and the current level of total investment in capital good (see eq. (6.3.60))

- A Harrod neutral exogenous technical progress on labor, implemented by means of a factor augmenting coefficient (see section 6.3.5.2)

6.3.5 Production and final consumption trade-offs

6.3.5.1 Final consumption trade-offs

Final demand is derived from a utility function of the Stone-Geary form (or Linear expenditure system - LES):

$$U = \prod_i (C_i - C_{i_{min}})^{\bar{\alpha}_i} \quad (6.3.48)$$

With a LES utility system, only the consumption of goods and services above the basic need level $C_{i_{min}}$ provides utility so that it represents a minimum of consumption that should be satisfied. The marshallian demand of goods and services derived from the maximisation of utility under expensed income constraint R_{CONS} is given by the following equation:

$$\forall i \quad C_i = C_{i_{min}} + \frac{\bar{\alpha}_i}{p_{Ci}} \cdot \left(R_{CONS} - \sum_j p_{Cj} \cdot C_{j_{min}} \right) \quad (6.3.49)$$

The basic needs are described as volumes per capita multiplied by population and are calibrated at base year with the exogenous parameters sh_i :

$$C_{i_{min}} = sh_i \cdot C_{i_0} \cdot \frac{N}{N_0}$$

$\bar{\alpha}_i$ is the share of income (basic needs excluded) devoted to consumption of good i beyond basic need. This constant parameter is calibrated at base year.

6.3.5.2 Production trade-offs

The structure of production trade-offs are inspired from [Gherzi et al. \(2011\)](#) and the idea that these trade-offs are limited by technical asymptotes that constrain the unit consumptions of factors above some floor values. The assumption is made that the *variable* shares of the unit consumptions of production inputs and factors are substitutable according to a CES specification. The existence of a fix share of each of these consumptions implies that the elasticities of substitution of *total* unit consumptions

(sum of the fix and variable shares) are not fixed, but decrease as the consumptions approach their asymptotes. In the meantime, asymptotes make it possible to calibrate specific elasticities of substitution for the different inputs and factors. This provides a convenient way to create simple reduced-forms of bottom-up models.

Under these assumptions and constraints, the formulation of the unitary consumptions of secondary factors α_{ij} , of labour l_j and of capital k_j can be written as the sum of the floor value and a consumption above this value. The latter corresponds to the familiar expression of conditional factor demands of a CES production function with an elasticity of σ_j (the coefficients of which are calibrated at base year).

$$\alpha_{ij} = \frac{1}{(1 + \psi_{ij})^t} \cdot \left[\beta_{ij} \cdot \alpha_{ij0} + \left(\frac{\bar{\lambda}_{ij}}{p_{Cij}} \right)^{\sigma_j} \cdot \left(\sum_{i=1}^n \bar{\lambda}_{ij}^{\sigma_j} \cdot p_{Cij}^{1-\sigma_j} + \bar{\lambda}_{Lj}^{\sigma_j} \cdot \frac{p_{Lj}}{(1 + \phi_{Lj})^t}^{1-\sigma_j} + \bar{\lambda}_{Kj}^{\sigma_j} \cdot p_K^{1-\sigma_j} + \bar{\lambda}_{LDj}^{\sigma_j} \cdot p_{LDj}^{1-\sigma_j} \right)^{\frac{\sigma_j}{1-\sigma_j}} \right] \quad (6.3.50)$$

$$l_j = \frac{1}{(1 + \phi_{Lj})^t} \cdot \left[\beta_{Lj} \cdot l_{j0} + \left(\frac{\bar{\lambda}_{Lj}}{p_{Lj}} \right)^{\sigma_j} \cdot \left(\sum_{i=1}^n \bar{\lambda}_{ij}^{\sigma_j} \cdot p_{Cij}^{1-\sigma_j} + \bar{\lambda}_{Lj}^{\sigma_j} \cdot \frac{p_{Lj}}{(1 + \phi_{Lj})^t}^{1-\sigma_j} + \bar{\lambda}_{Kj}^{\sigma_j} \cdot p_K^{1-\sigma_j} + \bar{\lambda}_{LDj}^{\sigma_j} \cdot p_{LDj}^{1-\sigma_j} \right)^{\frac{\sigma_j}{1-\sigma_j}} \right] \quad (6.3.51)$$

$$k_j = \frac{1}{(1 + \psi_{Kj})^t} \cdot \left[\beta_{Kj} \cdot k_{j0} + \left(\frac{\bar{\lambda}_{Kj}}{p_K} \right)^{\sigma_j} \cdot \left(\sum_{i=1}^n \bar{\lambda}_{ij}^{\sigma_j} \cdot p_{Cij}^{1-\sigma_j} + \bar{\lambda}_{Lj}^{\sigma_j} \cdot \frac{p_{Lj}}{(1 + \phi_{Lj})^t}^{1-\sigma_j} + \bar{\lambda}_{Kj}^{\sigma_j} \cdot p_K^{1-\sigma_j} + \bar{\lambda}_{LDj}^{\sigma_j} \cdot p_{LDj}^{1-\sigma_j} \right)^{\frac{\sigma_j}{1-\sigma_j}} \right] \quad (6.3.52)$$

$$ld_j = \frac{1}{(1 + \psi_{LDj})^t} \cdot \left[\beta_{LDj} \cdot ld_{j0} + \left(\frac{\bar{\lambda}_{LDj}}{p_{LDj}} \right)^{\sigma_j} \cdot \left(\sum_{i=1}^n \bar{\lambda}_{ij}^{-\sigma_j} \cdot p_{Clij}^{1-\sigma_j} + \bar{\lambda}_{Lj}^{-\sigma_j} \cdot \frac{p_{Lj}}{(1 + \phi_{Lj})^t}^{1-\sigma_j} + \bar{\lambda}_{Kj}^{-\sigma_j} \cdot p_K^{1-\sigma_j} + \bar{\lambda}_{LDj}^{-\sigma_j} \cdot p_{LDj}^{1-\sigma_j} \right)^{\frac{\sigma_j}{1-\sigma_j}} \right] \quad (6.3.53)$$

This sum is however modified to take into account the combination of exogenous labor productivity improvements ϕ_{Lj} - implemented as factor augmenting productivity gains - and structural changes for input and factor consumption, implemented as simple multipliers $\frac{1}{(1+\psi_{ij})^t}$ or $\frac{1}{(1+\psi_{Kj})^t}$. These multipliers makes it possible to drive changes in production patterns in order to mimic specific energy and economic scenarios in terms of trend energy intensity of production, fuel mixes, capital intensity, etc.

In addition, let us emphasize again that the “cost of capital” p_K entering the production trade-offs is *stricto sensu* the price of “machine capital”, i.e. equal to a simple weighted sum of the investment prices of immobilized goods (eq. (6.3.19)), which is not directly related to the actual return on capital. It is possible to track returns on capital *ex post* based on investments levels and gross operating surplus.

6.3.6 Trade

The competition on international markets relies first of all on relative prices. The ratio of imports to domestic production on the one hand, and the “absolute” exported quantities on the other hand, are elastic to the terms of trade, according to constant, product-specific elasticities. Three specifics are added to this standard framework. Energy imports are treated specifically and imports trends outside terms of trade are driven by sh_{Mi} multipliers to mimic given energy scenarios. Second, non-energy imports are treated as “income elastic” beyond terms of trade, which is implemented with constant elasticities to GDP level. This feature reflects the trend towards increasing shares of imports as GDP grows, which has been observed in Brazil in the last decades (dos Santos et al., 2011). Eventually, exports are impacted by global economic growth, independently of terms of trade variations. This is captured by assuming an exogenous rate of growth of exports δ_{Xi} .

Energy goods:

$$\frac{M_i}{Y_i} = sh_{Mi} \cdot \frac{M_{i_0}}{Y_{i_0}} \cdot \left(\frac{p_{Mi_0} \cdot p_{Yi}}{p_{Yi_0} \cdot p_{Mi}} \right)^{\sigma_{Mi}} \quad (6.3.54)$$

Non energy goods:

$$\frac{M_i}{Y_i} = \frac{M_{i_0}}{Y_{i_0}} \cdot \left(\frac{p_{Mi_0} \cdot p_{Yi}}{p_{Yi_0} \cdot p_{Mi}} \right)^{\sigma_{Mi}} \cdot \left(\frac{GDP}{GDP_0} \right)^{(\sigma_{MYi}-1)} \quad (6.3.55)$$

All goods:

$$\frac{X_i}{X_{i_0}} = \left(\frac{p_{Mi_0} \cdot p_{Xi}}{p_{Xi_0} \cdot p_{Mi}} \right)^{\sigma_{Xi}} \cdot (1 + \delta_{Xi})^t \quad (6.3.56)$$

6.3.7 Market and accounting balances

6.3.7.1 Goods markets

Goods market clearing is a simple accounting balance between resources (production and imports) and uses (households and public administrations' consumption, investment, exports). Thanks to the process of hybridization, this equation is written in Mtoe for energy goods and consistent with the 2005 Brazilian energy balance (notwithstanding that the G and I of energy goods are nil by definition).

$$\forall i \in \{1, \dots, n\} \quad Y_i + M_i = \sum_{j=1}^n \alpha_{ij} \cdot Y_j + C_i + G_i + I_i + X_i \quad (6.3.57)$$

6.3.7.2 Labor market

The labor market conditions, results from the interplay between labor demand from the production systems, equal to the sum of their factor demands $l_i \cdot Y_i$, and of labor supply from households. As part of key structural assumptions, the model allows for a strictly positive unemployment rate u and the market balance writes:

$$\sum_{i=1}^n l_i \cdot Y_i = (1 - u) \cdot NS \quad (6.3.58)$$

The unemployment level depends on a so-called “wage curve” (Blanchflower and Oswald, 1995) which synthesizes the forces that drive average wage formation. Such an empirical curve can be interpreted as the result of wage bargain between employers and employees or as an aggregate labor supply curve. Within the wage curve, indexation can vary from pure nominal to pure real wage indexation according to the coefficient sh_r .

$$\frac{w}{(1 + \phi_{Lj}) \cdot (sh_r \cdot CPI + (1 - sh_r)) \cdot w_0} = \left(\frac{u}{u_{ref}} \right)^{\sigma_u} \quad (6.3.59)$$

This makes it possible to test alternative visions of labor markets and their consequences on policy analysis. As studied by [Thubin \(2012\)](#), using a wage curve enables to cover the key debatable issues about labor markets and their consequences on carbon tax policy assessment. Our wage curve depends on two key parameters: the elasticity σ_u and the coefficient of indexation sh_r . Within the labor supply interpretation of the wage curve, the case where $\sigma_u = -\infty$ implies a fixed level of employment, which can be interpreted as a fixed level of labor supply. In this case the average wage is perfectly flexible and labor market behaves as a perfect market. σ_u further enables to test variant levels of wage rigidity in the long run. In addition, the wage curve can be more or less indexed on nominal or real wages. The indexation on real wages reflects a force centered on the purchasing power of labor income. Conversely, nominal wage indexation reflects a higher international competition between national and foreign workers, so that wages are compared to the international price index (the *numéraire* of the model).

Let us remind that a real metric of labor is used in the model - full time equivalent jobs - and sector specific wages. We make the assumption that in the long run workers are substitutable independently from the sector and the respective labor productivity.

6.3.7.3 Investment and capital flows

Contrary to standard CGE models, IMACLIM-BR does not represent explicit capital markets and the capital-investment balance is “demand-driven”. As previously highlighted, productive sectors arbitrate capital consumption according to prices of equipment. Then total capital consumption translates into a demand for investment at time t through the β vector within the implicit formulation of smooth capital accumulation.

$$\frac{I_i}{\sum_{j=1}^n k_j \cdot Y_j} = \bar{\beta}_i = \frac{I_{i_0}}{\sum_{j=1}^n k_{j_0} \cdot Y_{j_0}} \quad (6.3.60)$$

In the meantime the assumption is made of a single investment good in the economy as a weighted sum of different goods calibrated at base year (β vector).

Furthermore, the supply for investment adapts to the demand and capital formation from firms complete households and public contribution to satisfy that demand and balance investment flows.

$$GFCF_h + GFCF_f + GFCF_g = \sum_{i=1}^n p_{Li} \cdot I_i \quad (6.3.61)$$

Eventually, the investment balance, together with households saving rate and public expenses, imposes the external or trade balance which is endogenous in the model.

6.3.7.4 Land market

In this version of the model, the price of land is exogenous and follows the exogenous increase of land productivity:

$$p_{LDi} = p_{LDi_0} \cdot (1 + \phi_{LDi}) \quad (6.3.62)$$

In others versions of IMACLIM-BR, specific constraints on land allocation are implemented to study land-use issues.

6.3.8 Carbon tax policies

The model is specifically designed to study carbon tax policies in the medium to long run by generating policy-constrained projections. In the model, implementing a carbon tax amounts to adding a shock on fossil fuels prices proportional to their carbon content at the time horizon studied. Within our one-step projection framework, the underlying assumption is that a phase-in carbon tax is applied in the economy starting, say in 2015, with a small level to reach the ultimate carbon tax level at the time t studied. Accordingly, the model represents the result of technico-economic adjustments and market interactions at t as the end of a smooth pathway which undergoes a rising carbon tax.

The policy constrained price system is the following - with t_{Carb} the carbon price and $\overline{\gamma}_{ij}$ the emission factor of energy good i for sector j :

$$p_{ICij} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSCij}}) \cdot (1 + \overline{\tau_{CONSi}}) + t_{Carbj} \cdot \overline{\gamma}_{ij} \quad (6.3.63)$$

$$p_{Ci} = p_i \cdot (1 + \tau_{BMi} + \tau_{TMi} + \overline{\tau_{MSCi}}) \cdot (1 + \overline{\tau_{CONSi}}) + t_{Carbh} \cdot \overline{\gamma}_{ih} \quad (6.3.64)$$

This framework can accommodate sector specific carbon prices.

Total carbon revenues are the sum of carbon taxes levied on the different sectors:

$$T_{Carb} = \sum_i \left(\sum_j t_{Carbj} \cdot \overline{\gamma_{ij}} \cdot \alpha_{ij} \cdot Y_j \right) + \sum_i t_{Carbh} \cdot \overline{\gamma_{ih}} \cdot C_i \quad (6.3.65)$$

In the present model version, IMACLIM-BR can simulate four different carbon tax policies based on four different carbon revenues recycling options:

- No recycling (NR): carbon revenues feed public budget
- Reduction of sales taxes (RST): this recycling option consists in reducing the sector specific rates of sales taxes $\overline{\tau_{CONSi}}$ by the same coefficient δ_{CONS} for all sectors while maintaining neutral policy budget:

$$\forall i \in \{1, \dots, n\} \quad \tau_{CONSi} = \overline{\tau_{CONSi}} \cdot (1 - \delta_{CONS}) \quad (6.3.66)$$

$$T_{Carb} = \delta_{CONS} \sum_i \left(\sum_j p_{BTiCij} \cdot \overline{\tau_{CONSi}} \cdot \alpha_{ij} \cdot Y_j \right) + \overline{\tau_{CONSi}} \cdot (p_{BTCi} \cdot C_i + p_{BTGi} \cdot G_i + p_{BTIi} \cdot I_i) \quad (6.3.67)$$

- Reduction of payroll taxes (RPT): this recycling option consists in reducing the sector specific rates of payroll taxes $\overline{\tau_{Lgi}}$ by the same coefficient δ_{Lg} for all sectors while maintaining neutral policy budget:

$$\forall i \in \{1, \dots, n\} \quad \tau_{Lgi} = \overline{\tau_{Lgi}} \cdot (1 - \delta_{Lg}) \quad (6.3.68)$$

$$T_{Carb} = \delta_{Lg} \cdot \left(\sum_i \overline{\tau_{Lgi}} \cdot w_i \cdot l_i \cdot Y_i \right) \quad (6.3.69)$$

- Lump sum transfer to households (LS): total carbon revenues are directly transferred to households while maintaining neutral policy budget:

$$R_{gh} = \rho_g \cdot N + Lump \quad (6.3.70)$$

$$T_{Carb} = Lump \quad (6.3.71)$$

6.4 Two expanded model versions

6.4.1 A 6-sectors version with 6 households groups - IMACLIM-BR 6-6

The IMACLIM-BR 6-6 version contemplates the desegregation of the *Households* institutional sector in six sub-groups defined by income brackets at base year. The behavior of each group or class is synthesized by means of a representative households of that group. In this version of the model, a few equations are modified: the equation of households accounts and the final consumption trade-off. The gross primary income of class h is:

$$RBT_h = \overline{\omega_{Lh}} \cdot \left(\sum_{i=1}^n w_i \cdot l_i \cdot Y_i \right) + \overline{\omega_{Kh}} \cdot (\overline{\omega_{KH}} \cdot GOS) + \overline{\omega_{LDh}} \cdot (\overline{\omega_{LDH}} \cdot LAND) + \rho_{fh} \cdot N_h + \rho_{gh} \cdot N_h + OT_h \quad (6.4.1)$$

It is constituted of the following elements:

- A share $\overline{\omega_{Lh}}$ of total net income from labor calibrated at base year: $\overline{\omega_{Lh}} \cdot \left(\sum_{i=1}^n w_i \cdot l_i \cdot Y_i \right)$. For specific scenarios, these shares can be modified to reflect changes in labor income distribution patterns among groups.
- A share $\overline{\omega_{Kh}}$ of total income from capital of households: $\overline{\omega_{Kh}} \cdot (\overline{\omega_{KH}} \cdot GOS)$.
- A share $\overline{\omega_{LDh}}$ of total land rent earned by households as landlords: $\overline{\omega_{LDh}} \cdot (\overline{\omega_{LDH}} \cdot LAND)$.
- Social transfers as the sum of two aggregates: social transfers from private source (like private care insurances) and social transfers from public source. The computation is based on the product of an exogenous level of transfer per capita calibrated at base year and the population of class h . Finally: $R_{fh} + R_{gh} = \rho_{fh} \cdot N_h + \rho_{gh} \cdot N_h$
- A residual level of transfers computed as an exogenous share of a global pool of others transfers to households: $OT_h = \overline{\omega_{OTh}} \cdot OTH$

The structure of expenses is similar to the single class model, including tax rates, saving rates and rates of capital formation class specific and calibrated at base year.

As far as consumption trade-offs are concerned, the 6-6 model version includes class specific LES expenditure systems.

6.4.2 A 12-sectors version with an expanded demand system and a specific oil sector - IMACLIM-BR 12-ext

6.4.2.1 An expanded demand system

Sectors		
Production	HH consumption	Production factors
Energy		
Bioenergy (BIO)	Biofuels (BIOTRA) Firewood (BIORES)	Labor Capital Land
Coal (COAL)		
Crude Oil (OIL)		
Natural Gas (GAS)	-	
Refined Oil (ROIL)	Oil fuels (ROILTRA) LPG (ROILRES)	
Electricity (ELEC)	-	
Non-Energy		
Load Transportation (LOAD)	-	
Pass. Transportation (PASS)	-	
Livestock (CATT)	-	
Agro-industry (AGRI)	-	
Industry (INDUS)	Transport vehicles (INDVHC) Others manufactured goods (INDOTH)	
Services (COMP)	-	

Table 6.3: Sectors, consumption goods and factors in IMACLIM-BR 12-ext version

In the IMACLIM-BR 12-ext version, the utility of households depends on four types of goods and services. These four goods and services are (i) *food goods (FD)*, (ii) *transport services (TRA)*, (iii) *residential energy services (RES)* and (iv) a composite nest of *others goods and services (OTH)*, which correspond to the rest of manufactured goods and services. The first layer of the utility function is a LES utility:

$$U = (C_{FD} - C_{FD_{min}})^{\bar{\alpha}_{FD}} \cdot (C_{TRA} - C_{TRA_{min}})^{\bar{\alpha}_{TRA}} \cdot (C_{RES} - C_{RES_{min}})^{\bar{\alpha}_{RES}} \cdot (C_{OTH} - C_{OTH_{min}})^{\bar{\alpha}_{OTH}} \quad (6.4.2)$$

The marshallian demands of goods and services derived from this utility system, are:

$$\forall i \in [FD, TRA, RES, OTH] \quad C_i = C_{i_{min}} + \frac{\bar{\alpha}_i}{p_{Ci}} \cdot \left(R_{CONS} - \sum_j p_{Cj} \cdot \bar{C}_j \right) \quad (6.4.3)$$

The basic needs are described as volumes per capita multiplied by population and

are calibrated at base year with the exogenous parameters sh_i :

$$C_{i_{min}} = sh_i \cdot C_{i_0} \cdot \frac{N}{N_0}$$

The strength of such a demand system is to base households utility on the goods and services that really are at play in preferences trade-offs. This further makes it possible to detail the chain of underlying goods and services consumption that ultimately serve to satisfy these services demands. Basically, the purchase of private vehicles and fuel consumption can only be thought as combined to satisfy transportation needs. The expanded demand system contemplated is represented in figure 6.3.

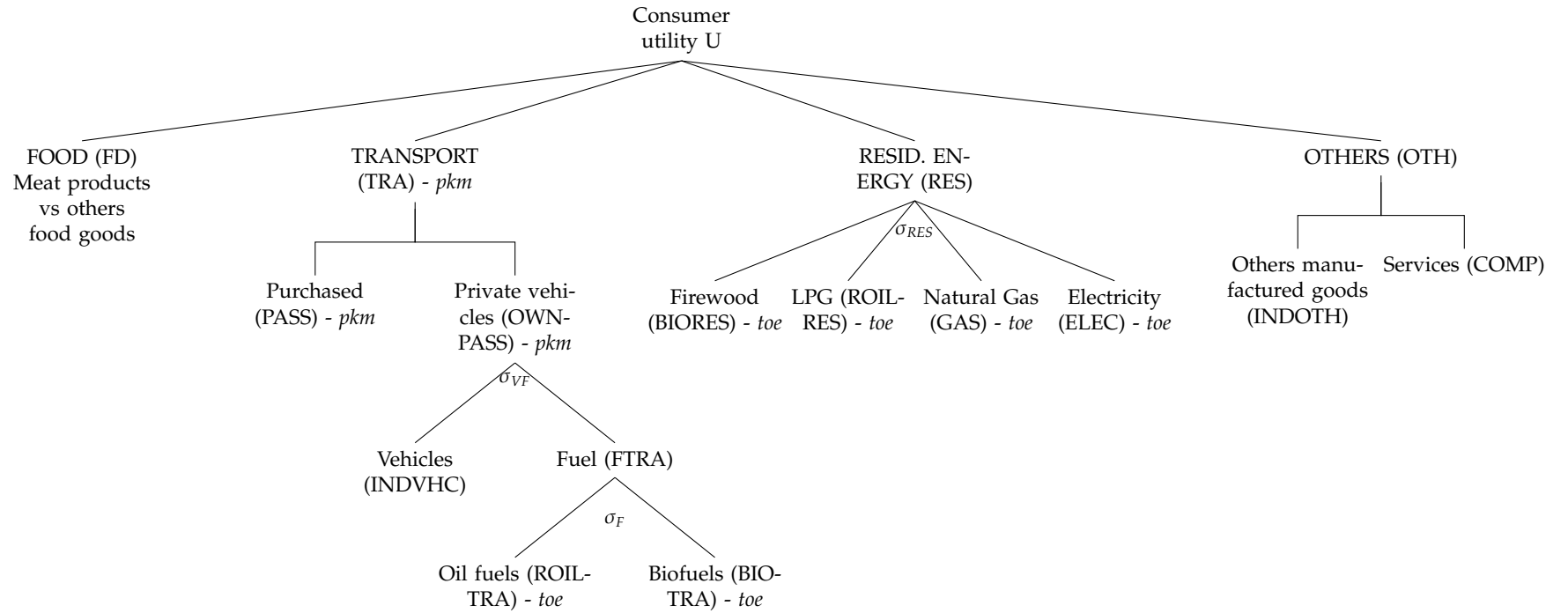


Figure 6.3: IMACLIM-BR 12-ext demand system

Down-stream nests correspond to either CES or Leontief specifications calibrated at base year.

Food is constituted of beef products (Cattle) and other food goods that substitute with the elasticity σ_{MR} . This elasticity controls the diet changes according to price levels. Residential energy sources substitutions are controlled by σ_{HOUS} . The dual accounting structure of the model and the accounting of energy flows in physical units offers room to fine-tune the projection of energy demand structure. In particular we choose to implement exogenous trends in residential energy use structure to stick to bottom-up projections by means of exogenous evolution rates of energy sources shares outside relative prices change. This is a simple and convenient way to compensate for the expense-share conservative properties of CES nests in order to implement structural changes in energy consumption⁴. This is especially important to generate long run projections for emerging economies. The dual accounting schemes makes it possible to ground these structural changes on bottom-up projections. To give just one example for Brazil, as average income grows, households are expected to massively get rid of traditional biomass to turn to modern energy sources like gas and grid electricity.

Demand levels linked to Residential energy bundle are given as follows:

$$\forall i \in [BIORES, ROILRES, GAS, ELEC] \quad C_i = \frac{C_{RES}}{1 + \delta_{RESi}} \cdot \bar{\lambda}_i^{-\sigma_{RES}} \cdot \left(\frac{p_{C_{RES}}}{p_{C_i}} \right)^{\sigma_{RES}} \quad (6.4.4)$$

$$p_{C_{RES}} = \left(\sum_i \bar{\lambda}_i^{-\sigma_{RES}} \cdot \frac{p_{C_i}}{1 + \delta_{RESi}} \right)^{\frac{1}{1-\sigma_{RES}}} \quad (6.4.5)$$

The transportation bundle is more expanded. It starts with the breakdown between purchased transportation services (public transportation, taxis, etc.) and own transportation supplied by private light duty vehicles. In the model the breakdown is Leontief, which implies it is a structural feature of future paths:

$$\forall i \in [PASS, OWNPASS] \quad C_i = C_{TRA} \cdot \left(\frac{C_{i_0}}{C_{TRA_0}} \right) \quad (6.4.6)$$

The own transportation bundle is a CES nest of private vehicles purchase and fuel

⁴It is to be noted that these coefficients are not AEEI (Autonomous energy efficiency index) coefficients and do not incur so-called "rebound effect". They are just multipliers to implement specific trend structural changes in energy consumption

consumption:

$$C_{INDVHC} = C_{OWNPASS} \cdot \overline{\lambda_{INDVHC}}^{\sigma_{VF}} \cdot \left(\frac{p_{C_{OWNPASS}}}{p_{C_{INDUS}}} \right)^{\sigma_{VF}} \quad (6.4.7)$$

$$C_{FTRA} = \frac{C_{OWNPASS}}{1 + \delta_{EffFuel_t}} \cdot \overline{\lambda_{FTRA}}^{\sigma_{VF}} \cdot \left(\frac{p_{C_{OWNPASS}}}{\frac{p_{C_{FTRA}}}{1 + \delta_{EffFuel_t}}} \right)^{\sigma_{VF}} \quad (6.4.8)$$

$$p_{C_{OWNPASS}} = \left(\overline{\lambda_{INDVHC}}^{\sigma_{VF}} \cdot p_{C_{INDUS}}^{1 - \sigma_{VF}} + \overline{\lambda_{FTRA}}^{\sigma_{VF}} \cdot \frac{p_{C_{FTRA}}}{1 + \delta_{EffFuel_t}}^{1 - \sigma_{VF}} \right)^{\frac{1}{1 - \sigma_{VF}}} \quad (6.4.9)$$

$\delta_{EffFuel_t}$ is a coefficient of autonomous efficiency gains (AEEI) of private vehicles (light duty vehicles mainly).

The fuel bundle is a CES nest of biofuels (ethanol) and oil fuels (gasoline mainly and diesel):

$$C_{BIOTRA} = C_{FTRA} \cdot \overline{\lambda_{BIOTRA}}^{\sigma_F} \cdot \left(\frac{p_{C_{FTRA}}}{p_{C_{BIOTRA}}} \right)^{\sigma_F} \quad (6.4.10)$$

$$C_{ROILTRA} = C_{FTRA} \cdot \overline{\lambda_{ROILTRA}}^{\sigma_F} \cdot \left(\frac{p_{C_{FTRA}}}{p_{C_{ROILTRA}}} \right)^{\sigma_F} \quad (6.4.11)$$

$$p_{C_{FTRA}} = \left(\overline{\lambda_{BIOTRA}}^{\sigma_F} \cdot p_{C_{BIOTRA}}^{1 - \sigma_F} + \overline{\lambda_{ROILTRA}}^{\sigma_F} \cdot p_{C_{ROILTRA}}^{1 - \sigma_F} \right)^{\frac{1}{1 - \sigma_F}} \quad (6.4.12)$$

Eventually, the bundle for Others goods is Leontief:

$$\forall i \in [INDOTH, COMP] \quad C_i = C_{OTH} \cdot \left(\frac{C_{i_0}}{C_{OTH_0}} \right) \quad (6.4.13)$$

6.4.3 Oil and liquid fuels sectors

The 12-ext model version makes it possible to assess the articulation between oil and climate policies. In particular, the models enables to test various targets of crude oil production in the medium run in order to assess its impacts on the economy and growth. Accordingly, this model version sets the level of domestic crude oil production as an exogenous parameter whereas it is endogenous in the reference version. Domestic oil consumption is endogenous and depends on market mechanisms so that oil exports represent the reminder of oil production. Such a framework makes it possible to endogenize the breakdown of oil production (between domestic consumption and exports) according to market conditions - on liquid fuels especially - for a given level production. In practice the equation for crude oil exports is replaced by the following

equation which sets the level of domestic production at time t :

$$Y_{OIL} = Y_{OIL_0} \cdot (1 + \delta_{YOIL})^t \quad (6.4.14)$$

Let us remind, that already in the reference version, the oil price of exports follows the world oil price:

$$p_{X_{OIL}} = \frac{p_{X_{OIL_0}}}{p_{M_{OIL_0}}} \cdot p_{M_{OIL}} \quad (6.4.15)$$

Finally, alternative tax conditions about liquid fuels can be tested by playing with the system of sales tax τ_{CONS} . This makes it possible to assess alternative fuel price policies and the competition between biofuels and oil fuels for transportation especially.

6.4.4 Miscellaneous specifics

6.4.4.1 Transport margins

Business margins τ_{BMi} and transport margins τ_{TMi} , identical for all intermediate and final consumptions of good i , are calibrated at base year and kept constant - except those on *LOAD* sector and trade activities aggregated within the *COMP* sector, which are simply adjusted, to have the two types of margins sum up to zero :

$$\forall i \notin [COMP, LOAD] \quad \begin{cases} \tau_{BMi} = \overline{\tau_{BMi}} \\ \tau_{TMi} = \overline{\tau_{TMi}} \end{cases} \quad (6.4.16)$$

$$\begin{aligned} & \sum_{j=1}^n \tau_{BM_{COMP}} \cdot p_{COMP} \cdot \alpha_{COMPj} \cdot Y_j + \tau_{BM_{COMP}} \cdot p_{COMP} \cdot (C_{COMP} + G_{COMP} + I_{COMP} + X_{COMP}) \\ & + \sum_{i \neq COMP} \sum_j \overline{\tau_{BMi}} \cdot p_i \cdot \alpha_{ij} \cdot Y_j + \sum_{i \neq COMP} \overline{\tau_{BMi}} \cdot p_i \cdot (C_i + G_i + I_i + X_i) = 0 \quad (6.4.17) \end{aligned}$$

$$\begin{aligned} & \sum_{j=1}^n \tau_{BM_{LOAD}} \cdot p_{LOAD} \cdot \alpha_{LOADj} \cdot Y_j + \tau_{BM_{LOAD}} \cdot p_{LOAD} \cdot (C_{LOAD} + G_{LOAD} + I_{LOAD} + X_{LOAD}) \\ & + \sum_{i \neq LOAD} \sum_j \overline{\tau_{BMi}} \cdot p_i \cdot \alpha_{ij} \cdot Y_j + \sum_{i \neq LOAD} \overline{\tau_{BMi}} \cdot p_i \cdot (C_i + G_i + I_i + X_i) = 0 \quad (6.4.18) \end{aligned}$$

6.4.4.2 Agriculture sectors

The sectors that use the specific land factor (*BIO*, *CATT* and *AGRI*) generate a total available land income:

$$LAND = \sum_{i=1}^n p_{LDi} \cdot ld_i \cdot Y_i \text{ with } ld_i = 0 \text{ for sectors outside } BIO, CATT \text{ and } AGRI \quad (6.4.19)$$

6.5 Conclusion

This chapter has presented at length the IMACLIM-BR modeling platform. To conclude, we can characterize the modeling approach in light of the model guide developed in chapter 2 to create the “identity card” of the model along the three axes: interdependence, transformations drivers and transition dynamics.

- The **interdependence** scheme is that of a SAM-based multi-sector model which singles out energy and non-energy sectors at an intermediary level of aggregation (a dozen of economic sectors). The accounting framework builds on an I-O structure and the dual accounting of flows both in physical units and money value when relevant (energy, transport services, land areas, etc.). In addition the model details end-use energy sectors with explicit activity levels about transport services (in passenger.km and ton.km) and industry productions. IMACLIM-BR accounting framework is also expanded towards the representation of the secondary income distribution with specific taxes and transfers and the interaction between four institutional sectors and possibly six households income groups. Finally, the representation of technical systems do not include technology explicitness but partly relies on sector-level reduced forms of engineering models.
- As for the **transformation drivers**, the model includes an exogenous growth engine with Harrod’s neutral technical change based on labor productivity gains and implicit capital accumulation. The model also includes exogenous features of energy technical change at sector level through AEEI specifications and price-induced technical change embedded in the functional forms retained at the time horizon studied. Because it generates one-step projections, IMACLIM-BR does not capture explicit capital inertia but can capture implicit pathway of technical change through innovation possibility curves. Eventually, the model embarks specific exogenous drivers of structural changes to generate contrasted energy-economy futures at the time horizon studied. It includes specific investment patterns, trade pattern for energy goods, structural trends of energy demand

linked to the structure of end-use sectors (transport sectors for instance). Goods specific income elasticities of household consumption also contribute to structural changes inducement.

- Finally **transition dynamics** are pretty specific in the model due to the one-step projection which does not make it possible to distinguish inter-temporal and intra-temporal dynamics. Implicitly though, the model somehow assumes perfect foresight until the time horizon studied (because the prices taken into account for production/consumption trade-offs coincide with the effective prices) but myopic expectations beyond. In addition a trend gap to the production frontier (implicit) is modeled through specific second-best mechanisms: imperfect market of goods, rigidities on labor markets with involuntary unemployment, imperfect capital allocation, sub-optimum techno-economic choices embedded in functional forms, etc. In a word IMACLIM-BR computes implicit sub-optimum but smooth pathways in the medium run.

Chapter 7

Macroeconomic and distributive implications of carbon tax policies in Brazil until 2030

7.1 Introduction

This chapter develops a first application of the IMACLIM-BR framework to the assessment of the macroeconomic and distributive implications of carbon tax policies in Brazil until 2030. The first goal is methodological in nature. It aims at highlighting how IMACLIM-BR as a tool, can generate consistent energy-economy projections by crossing expert and stakeholders views about future energy and economic systems. It also enhances how the modeling platform makes it possible to perform uncertainty analysis at the intersection between alternative policy packages and contrasted structural assumptions about the economic system. The second objective is to contribute to the up-to-date policy debates in Brazil around the implementation of carbon tax policies to articulate mitigation goals with other economic and social objectives.

The chapter includes four more sections. Section 7.2 uses IMACLIM-BR 6 version to generate a reference energy-economy projection based on the up-to-date energy plans and macroeconomic prospects. Then section 7.3, which is the central section, explores with IMACLIM-BR 6 the macroeconomic implications of alternative carbon tax policies until 2030. It performs a methodical uncertainty analysis at the interface between recycling options of carbon revenues, technical constraints of mitigation and structural mechanisms of the economic system. This makes it possible to map the synergies and trade-offs to reach simultaneous mitigation and economic goals and

to highlight the main determinants of the macroeconomic implications of carbon tax policies. Section 7.4 uses IMACLIM-BR 6-6 version to expand the analysis to the distributive implications of carbon tax policies between a set of households income groups. Section 7.5 concludes.

7.2 Generating consistent energy-economy projections with Imaclim-BR: a reference scenario

This section simulates a central reference scenario at time horizon 2030 that is based on the most recent national energy plan (EPE, 2014a, PNE 2050) and up-to-date social and macroeconomic prospects. The objective is to integrate energy and socio-economic visions to generate a new consistent energy-economy projection. To do so, we implement in the model a set of exogenous parameters taken from the energy plan and macro-economic scenarios as trend drivers, and the model endogenizes the energy-economy relationships to generate a consistent scenario. The final output slightly departs from both initial energy and macroeconomic scenarios to yield a new consistent picture. A sensitivity analysis of the results to labor and trade mechanisms sharpens the understanding of the main projection drivers.

7.2.1 Reference scenario narrative, assumptions and implementation

Our reference scenario (named REF 2030 hereafter) is intended to embody PNE 2050 projections and PNE 2050 provides the narrative and the exogenous assumptions of the scenario. In particular, it includes the climate objectives of the PNMC until 2020¹. Therefore REF 2030 scenario is not actually a *business as usual* (BAU) scenario but more a governmental scenario including a set of specific energy and climate plans. The rest of this subsection details the narrative and the main exogenous assumptions of REF 2030 scenario.

To begin with, REF 2030 assumes that Brazil's population increases by 0.75% per year on average during the 2005-2030 period and reaches 223 million people in 2030². During the same period, structural changes of demographics yield a 1.2% per

¹As described in chapter 5, PNE 2050 details the up-to-date government projections and plans for the energy system until 2050 and *a fortiori* includes the current policies in place (including climate policies). Part of PNE 2050 was released in 2014 and included the macroeconomic and final demand studies (EPE, 2014b,a). The energy supply study is still in a review process. In addition, PNE 2050 may be re-published with new figures in a close future, especially with lower economic growth assumptions to take into account the recent economic stall. Our study is based on the "future former" version and its optimistic levels of economic growth as it is the most recent published prospects.

²<http://www.ibge.gov.br/apps/populacao/projecao/>

year increase of active population to reach 133 million workers in 2030. The scenario further assumes that economic growth is higher in Brazil than in the rest of the world on average during the period. Such a domestic economic growth is especially made possible by an increase of productivity resulting from investments in infrastructures and machinery, better education and better global efficiency (and reduction of the *custo Brasil*³). This trend implies a significant increase of the investment ratio of the economy. At the same time, the positive trade balance drops slightly, which reflects a significant rise of imports despite the increase of oil and commodities exports. Until 2030, world oil price stays around US\$85/barrel which is consistent with IEA projections.

The structure of the energy system follows PNE 2050 in 2030 and the general prospects described in chapter 5. It includes first an increase of bioenergy and natural gas shares in the fuel mix compared to 2005. Bioenergy expands with added biomass-fired power generation capacities, a higher usage of bioenergy in industry and a higher penetration of biofuels for transportation. Natural gas expands in power generation and industry. The share of hydro power slightly drops in electricity generation and the share of renewable technologies (wind power, bioenergy) and fossil fuel thermal (coal and natural gas) capacities increase and enable to meet the growing demand: shares of natural gas and bioenergy triple in power generation mix compared to 2005, the share of coal almost doubles. Eventually, pre-salt oil fields enable a boom of total fossil fuels net exports until 2030.

To generate a consistent quantitative projection of this narrative, we use the IMACLIM-BR 6 model which distinguishes three energy sectors (bioenergy, fossil fuels and electricity) and three non-energy sectors (agro-industry, rest of industry and services). Technically, implementing REF scenario consists in assigning values to the set of “scenarios parameters” (see section C.2.1 in appendix) based on PNE 2050 and others sources. Then the model simulates a new consistent projection that integrates macroeconomic and energy visions.

A first part of scenarios parameters concerns structural exogenous **macroeconomic assumptions** (cf table 7.1). Within the “Harrod neutral” exogenous growth engine of IMACLIM-BR - based on labor productivity gains - and given the level of active population and structural unemployment of 7%, we estimate the necessary exogenous labor productivity gains of 2.5% (common to all economic sectors) to reach the average “natural” GDP growth rate of 3.85% per year. Effective GDP is endogenous in the model. In addition, we input a 1% per year increase of trend capital intensity of production (ψ_K). This both reflects an autonomous catch-up in capital intensity of

³The *custo Brasil* refers to the increased operational costs associated with doing business in Brazil, making Brazilian goods and services more expensive compared to other countries.

Parameter	Description	Value
δ_N	0.75	Annual rate of population growth (%)
δ_{NS}	1.16	Annual rate of active population growth (%)
u_{ref}	7	Reference rate of unemployment (%)
ϕ_L	2.5	Annual rate of labor productivity growth (%)
ψ_K	1	Annual rate of growth of trend capital intensity of production (%)
δ_{Xi}	3.5	Annual structural rate of increase of exports (non-energy sectors)
τ_S	7	Households saving rate (%)
δ_{PMOIL}	1.5	Annual growth rate of world fossil fuels price (%)

Table 7.1: Main macroeconomic parameters of REF scenario

production and a pro-active policy towards investing in new infrastructures which actually results in increasing the capital content of production. Non-energy sectors exports are assumed to rise in trend like rest of the world growth - outside terms of trade - at a +3.5% per year growth rate (δ_{Xi}). Households saving rate increases from 6.4% in 2005 to 7% in 2030 of disposable income and reflects a slight increase of households participation to domestic investment efforts. Eventually, world fossil fuel prices grow 1.5% per year compared to international composite good which is the *numéraire* of the model.

Beyond macroeconomic trends, IMACLIM-BR makes it possible to embark technical assumptions about energy sectors due to the dual accounting framework of energy flows in both physical and money value units. In particular it enables to **embark information about structural changes in the energy system**. In REF 2030, we inform these changes through the preliminary construction of an energy balance - in physical units - for 2030 based on PNE 2050 and others assumptions. This energy balance reflects the structural changes of the energy system described in the scenario narrative. We then use this energy balance to inform (i) the trend structure of power generation fuel mix, (ii) the trend fuel structure of energy end-use sectors and residential energy consumption and (iii) the trends for energy commodities exports and imports levels. Such structural changes are implemented through ψ_{ij} , sh_{Mi} and δ_{Xi} scenarios parameters (see section C.2.1) calibrated with the preliminary energy balance. Let us remind that ψ_{ij} parameters are simple scalars applying to energy technical coefficients - in physical units - of the Input-Output table outside relative price changes. Technical coefficients can further vary around these trends according to relative price changes as specified by production functions⁴. Therefore the ultimate energy technical coefficients slightly

⁴It is to be noted that these scalars are not factor augmenting coefficients like AEEI coefficients. AEEI coefficients correspond to real productivity gains which trigger a reaction of productive systems towards

depart from the exogenous trends due to the changes of relative prices.

7.2.2 Results

To properly understand the outcomes of REF 2030 energy-economy projection, it is very useful to compare it to a “homothetic growth” scenario (HG 2030 scenario). In this HG scenario, effective GDP growth is directly derived from working population growth and labor productivity gains. It somehow corresponds to a Solow’s stabilized growth pathway. All extensive variables (investment, household consumption, imports, exports, all transfers, etc) increase like GDP and all intensive variables (technical coefficients, etc.) and relative prices remain constant. The sole average wage increases and exactly captures the labor productivity gains as in Solow’s model. Thus the shares of labor and capital income in GDP remain constant. There are no structural changes (i) in the energy system, (ii) the investment pattern nor (iii) in trade flows. **Eventually the HG scenario provides an anchor to understand how specific exogenous structural trends induce deviations from this benchmark to yield a specific economic picture.** Macroeconomic outcomes of base year (BY 2005), HG 2030 and REF 2030 are compared in table 7.2. Figure 7.1 shows a focus on net exports per sector in the three scenarios.

	BY 2005	REF 2030	HG 2030
Real GDP (10 ¹² R\$2005)	2.143	5.577	5.391
Average growth rate per year (%)	-	3.90	3.76
GDP per capita(10 ³ R\$2005)	11.8	25.0	24.2
Investments / GDP ratio (%)	16.0	19.9	16.0
HH final consumption / GDP ratio (%)	67.0	66.0	67.0
Trade balance / GDP ratio (%)	3.68	0.75	3.68
GDP deflator (compared to base year)	-	1.202	1.000
Unemployment rate (%)	8.56	5.36	7.00
Variation of average real wage (outside productivity effects)	-	1.009	1.000
Share of net labor income in GDP (%)	37.6	36.7	37.6

Table 7.2: Macroeconomic outputs of REF scenario

In a nutshell, REF scenario first implies higher GDP and employment than HG scenario. Second, deviations in GDP structure happen, in accordance with the exogenous structural trends implemented. Main deviations include higher investment

higher remuneration of energy. Rather, we use simple scalars to drive an exogenous trend for the energy system structure.

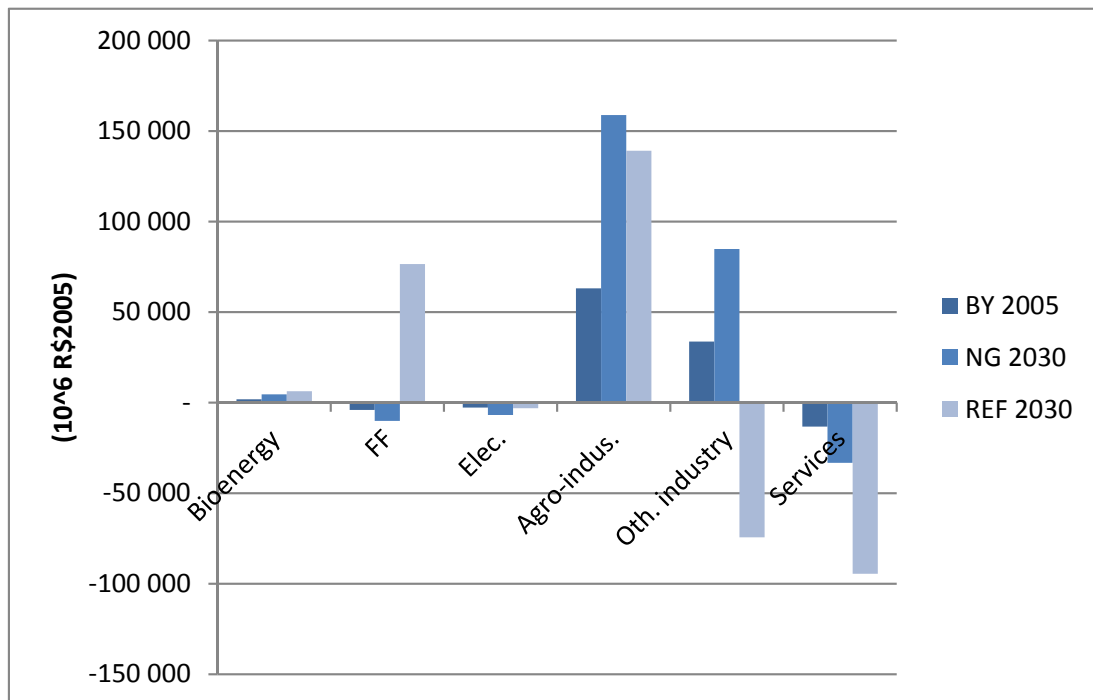


Figure 7.1: Net exports in BY 2005, REF 2030 and HG 2030

ratio (20.0% of GDP), lower trade balance (0.7% of GDP), and significantly higher GDP deflator (1.21).

REF picture is the result of interacting forces, which can be disentangled to understand the main drivers of the projection. As in the HG case, the main drivers of economic growth are working population growth and labor productivity gains. The deviations from the HG case are driven by the specific exogenous trends on (i) energy system structure, (ii) investment and saving patterns and (iii) trade flows. The ultimate balance of the system happens through the adjustment of the terms of trade and nominal wages. Therefore, the macroeconomic consistency of the scenario mainly happens through trade and labor market mechanisms.

Let us analyze in more detail the mechanisms at play. The pattern of investment is the starting point. Increasing the capital content of production mechanically drives a structural increase of the investment ratio of the economy. This is related to the rule of implicit capital accumulation in the model, which proportionally links fixed capital consumption (as a proxy of capital stock) and investment. As demand for capital by productive sectors depends on the price of investment goods, the investment ratio is more or less imposed to the system in the absence of significant change of relative prices. In addition, a slightly higher saving rate of households implies a lower

households consumption ratio, which is more or less fixed in the absence of important distributive changes of national income. All in all the constraints on investment and final consumption ratios mechanically impose the trade balance - GDP ratio which is driven down due to the increase of the investment ratio. From the capital balance point of view, the additional investments (compared to HG scenario) are mainly financed by the rest of the world and a small contribution of domestic private savings. As for trade flows, the strong exogenous shock on fossil fuels exports more than compensates for the slower growth - compared to domestic natural growth - of non-energy export markets. Non-energy imports are elastic to real GDP in the model⁵ so that imports increase faster than domestic production. All in all, trade balance ultimately adjusts to the macroeconomic constraints through the terms of trade and the increase of the domestic price index. Concerning the domestic price structure, increasing capital intensity of production already yields a trend increase of domestic prices despite the slight decrease of average energy costs. Finally, the system requires a sharper increase of domestic prices to reach balance, which is necessarily provided by the upward adjustment of nominal wages. Ultimately, employment is driven up through the wage curve - partially indexed on nominal wages - which boosts domestic production significantly above the HG level.

To put things short, the structural rise of the investment ratio is the main driver of the deviation from the homothetic growth scenario. The trend evolution of investment and final consumption ratios mechanically drive the trade balance ratio down. The system finally reaches balance through the upward adjustment of the terms of trade and of the average nominal wage. The ultimate GDP level depends on the level of employment and is related to the nominal wage through the wage curve. The reaction of trade flows to the terms of trade and of the employment level to nominal wages are the two main adjustment mechanisms of the reference projection.

Energy and emissions structure of REF 2030 are reported in table 7.3.

Globally, the decrease of energy intensity in end-use sectors and the changes of fuel mixes towards more bioenergy, renewables and natural gas, lead to a global 4% decrease of energy-related CO₂ emissions intensity of GDP in REF 2030 compared to BY and NG to reach 0.145 t CO₂ / 1000 R\$.

⁵This is a specific of our model that reflects observed trends for Brazil (dos Santos et al., 2011). This feature departs from usual Armington hypothesis which assumes a homothetic evolution of the demands for domestic and imported goods outside terms of trade variations.

	Bioenergy	Fossil fuels	Elec.	Agro-indus.	Industry	Composite	HH
Bioenergy	77.120	0.	30.866	35.649	38.597	16.899	12.665
Fossil fuels	839	332.013	44.847	12.150	77.697	81.532	45.501
Electricity	561	2.073	10.900	7.473	34.852	19.468	18.900
Y	215.517	649.112	90.430				
X	3.721	132.530	11				
M	0	77.998	3808				
Fossil emissions CO ₂	0	79.271	132.049	37.181	184.854	246.791	122.652
Fossil emissions increase	0	x 3.2	x 5.1	x 2.1	x 1.9	x 2.3	
Total emissions (MtCO ₂ eq /year)	808.504	(x 2.5)					

Table 7.3: Energy and Emissions in REF scenario

7.2.3 Sensitivity analysis

We carry out a short sensitivity analysis of the reference projection to the exogenous parameters governing key adjustment mechanisms, about (i) labor markets with the flexibility of wages and (ii) trade with the reaction of trade flows to the terms of trade and the GDP level.

In IMACLIM-BR, the flexibility of wages is embodied by a wage curve (see section 6.3.7.2) which depends on two parameters: (i) the elasticity of the average wage to unemployment σ_u and the type of wage indexation embodied by sh_r . We first test the sensitivity of the macroeconomic outcomes to the flexibility of wages between full flexibility ($\sigma_u = -\infty$) and higher rigidity ($\sigma_u = -0.17$) for the reference state of wage indexation ($sh_r = 0.5$). Key results include a small sensitivity of the domestic price index (or the terms of trade), wages, no sensitivity of final consumption, investment and trade balance ratios and a significant sensitivity of employment, domestic production and real GDP levels. These results can be explained as follows: the structural constraint on consumption, investment and then trade balance ratios constrain the terms of trade and the level of nominal wages whatever the wage flexibility. The limited freedom to adjust in price impose an adjustment in volumes to the system through the wage curve and thus employment and domestic production are very sensible to wage flexibility. In addition, more flexible wages need to increase more to sustain the level of employment, and conversely for higher wage rigidity. But wages are constrained so

that higher wage flexibility leads to lower employment and lower economic growth.

We also analyze the sensitivity of the economic projection to the wage indexation in the wage curve between the two polar indexations on nominal ($sh_r = 0$) or real ($sh_r = 1$) wages⁶. We can note that the pattern of sensitivity is close to the previous one. In fact in the case where the price index rises, nominal wages increase faster than real wages so that indexing the wage curve “less” on real wages and “more” on nominal wages amounts to decrease wage flexibility for a given initial level of indexation on real wages.

In conclusion, **labor markets conditions are important determinants of the level of employment and economic growth** in the projections. However these conditions have little effect on the price system, the exchange rate and the structure of GDP.

Trade mechanisms are also key determinants of the projection. σ_{MYi} , σ_{Mi} and σ_{Xi} are the exogenous parameters governing trade mechanisms. Let us recall that a specific feature of IMACLIM-BR is that imports of non-energy goods are elastic to real GDP in the reference model setting ($\sigma_{MYi} = 1.1$). The reference setting also includes median elasticities to the terms of trade in the long run in a context of high uncertainty about such parameters. We then study the sensitivity of economic outcomes to the beliefs about trade elasticities in the long run. Some recent econometric studies ([dos Santos et al., 2011](#)) reflect that trade is more sensitive to income (GDP) and less to the terms of trade in the long run. Then twice lower price elasticities and a 1.3 elasticity to real GDP of imports lead to a similar macroeconomic situation than the reference case: the higher income elasticity of imports compensates for smaller price elasticities so that similar terms of trade are required to balance the system. The same kind of results happen if we stick to the Armington assumption with a one-elasticity of imports to GDP and high elasticities (x2) of imports to the terms of trade which is customary in Armington empirical implementation: higher price elasticities compensate for the inelasticity to income. Finally we show the very high sensitivity of results to trade elasticities when testing the extreme situations: simultaneous low and high price and income elasticities. In the low elasticity case, the GDP deflator increases 120% compared to base year to balance the system. The related hike of nominal wages leads to a boom of employment and economic growth all the higher than wages are rigid. Conversely for the high price and income elasticities case, the GDP deflator required is slightly lower than the structural increase of domestic prices - due to trend higher capital intensity - so that labor efficient wages undergo a very small downward adjustment (less than

⁶When $sh_r = 0$, the wage curve links the average *nominal* wage to the unemployment level and the average *real* wage when $sh_r = 1$. The average real wage corresponds to the average nominal wage deflated by the consumption price index.

1%) compared to the HG pathway. In this case the macroeconomic outcomes are not significantly sensitive to wage flexibility any more and employment stays close to 7% in the range of wage flexibility considered.

What insights stand out from this first exercise? We have shown how IMACLIM-BR can be first used as a long term energy-economy consistency modeling tool. From a macroeconomic point of view, we have demonstrated that in the case where specific investment, savings patterns and capital flows - as deviations from the natural growth pathway - are imposed to the economic system, the **macroeconomic outcomes are very sensitive to labor markets and trade conditions**. Said differently, generating a consistent macro-economic projection requires to explicit labor market and trade mechanisms. In particular, in the case of average trade elasticities, the constrained wage moderation required to balance the system, implies that global economic output mostly depends on the upward adjustment of employment in volume which is all the higher than wages are rigid. We can further conclude that implementing in Brazil an economic growth plan based on investment and improved infrastructures of production mostly financed by foreign savings, may be successful in providing higher productivity, employment and growth in the long run. **Critical determinants for this success may be (i) the way foreign capital inflows impact the terms of trade through trade mechanisms and (ii) how labor markets adapt to the rise of domestic prices through wage flexibility.**

7.3 Assessing the macroeconomic implications of carbon tax policies

Section 7.2 has explained how IMACLIM-BR can generate consistent reference energy-economy projections for Brazil. Such reference scenarios provide an anchor to study the implications of implementing deeper decarbonization beyond already adopted climate goals. Generating precise reference energy-economy projection is important to specifically appraise the implications of new mitigation goals. This framework could for instance make it possible to assess the implications of the INDCs recently adopted by Brazilian government compared to prior plans. In this study we do not analyze the specific implications of given mitigation packages⁷ but rather the issue of implementing a carbon tax policy as a key macroeconomic tool to reach energy mitigation targets eventually similar to those included in Brazilian INDCs

⁷The *IES Brasil* study (Wills et al., 2015), also conducted with IMACLIM-BR, aims precisely at studying the macroeconomic and social implications of identified mitigation packages at time horizon 2030.

until 2030. By the way Brazilian government has been recently working on a project of carbon tax as part of a larger carbon fiscal reform. Pricing CO₂ emissions is indeed considered the best macroeconomic tool to reach economic-efficient climate objectives, whether it is implemented by means of carbon markets or carbon taxes. However, as already discussed, carbon-pricing alone may not be the silver bullet to manage the transition towards low carbon development. More complex policy packages should be considered such as specific sector “command and control” policies or investment plans in long-lived infrastructures. On the whole, introducing a carbon tax policy as the basic policy tool to foster low carbon development has at least two major interests: (i) establishing a crucial long term signal to guide efficient economic choices towards low carbon activities and (ii) generating tax revenues that can be used to reconcile abatement objectives with others economic development goals along a low carbon transition.

In this section we study with IMACLIM-BR the macroeconomic implications of implementing a carbon tax policy until 2030 in Brazil in order to curb energy-related CO₂ emissions beyond existing targets. AFOLU emissions are especially not included in the present assessment. We focus here on the specific challenge to curb energy-related emissions which are expected to be the main source of emissions beyond 2020 as detailed in chapter 5. In addition, our study fits within the old debates about mitigation costs estimation and the effect of carbon taxes. At the macroeconomic level, the “double dividend” hypothesis has been substantively discussed from a theoretical point of view (Goulder, 1995). The goal has been to understand in what circumstances the recycling of carbon revenues in reducing existing tax distortions can provide an economic dividend beyond the environmental dividend. This question has not been entirely solved and some scholars have advocated that this issue should be empirically studied according to specific contexts. Here we carry out a pure empirical evaluation of carbon tax implications in Brazil. Our endeavor aims at disentangling the key mechanisms of the interplay between possible **carbon tax policies**, **technical constraints** to mitigation and **macroeconomic mechanisms** in the specific Brazilian context until 2030. To do so, we conduct a variant analysis on policy options about carbon revenues recycling crossing a variant analysis on mitigation potentials informed by bottom-up analysis and macroeconomic mechanisms including labor markets and trade effects. The results show that if technical constraints certainly play a role in the macroeconomic and sectoral implications of tax policies, they may not be the main determinants of the macroeconomic outcomes considering the range of technical options available. Rather, the type of recycling scheme of carbon revenues and the macroeconomic context such as specific functioning and distortions of labor markets, trade openness are crucial

determinants of the macroeconomic outcomes of carbon tax policies in Brazil.

7.3.1 Macroeconomic implications of a carbon tax with no recycling of carbon revenues

Starting from REF 2030 scenario generated in section 7.2, we first contemplate the introduction of a unilateral domestic carbon tax applying to all domestic energy-related emissions, which reaches US\$100/tCO₂ in 2030. In this CLIM-NR 2030 scenario, carbon revenues are not recycled and accrue to public budget to decrease public debt. In addition Brazil alone implements a carbon taxation. This feature may not be completely realistic because Brazil may actually not adopt more ambitious climate policies if others countries do not act the same. Nonetheless, this extreme case provides an interesting benchmark to pinpoint the crucial issues and trade-off with the implementation of deeper decarbonization of the energy system in Brazil. Table 7.4 shows the macroeconomic outcomes of CLIM-NR 2030.

	BY 2005	REF 2030	CLIM-NR 2030	Δ CLIM-NR - REF
CO ₂ energy emissions	324	808	565	-30%
Real GDP (10 ¹² R\$2005)	2.143	5.577	5.277	-5.38%
Average real GDP growth per year (%)	-	3.90	3.67	-0.23 p.
Unemployment rate (%)	8.56	5.36	6.76	+1.40 p.
GDP deflator	1	1.202	1.199	-0.3%
Services exports (index)	1	1.97	2.00	+2.0%
Industry exports (index)	1	2.09	2.06	-1.4%
HH real expended income	1.435	3.745	3.481	-7.0%
Labor intensity of composite sector	-	0.533	0.549	+3.1%
Variation of average real wage (outside productivity effects)	-	1.010	0.934	-7.4%

Table 7.4: Macroeconomic results of CLIM-NR 2030

Introducing a progressive carbon tax on energy emissions to reach US\$100/tCO₂ in 2030 without recycling carbon revenues implies 30% lower energy-related CO₂ emissions compared to REF 2030. Industry emits 42% less CO₂ and transportation around 30% (emissions from transportation represents the bulk of emissions in composite and households sectors). Power generation only contributes around 11% to global energy-related mitigation effort. Such an abatement framework is consistent with bottom-up studies. In addition, lower emissions are reached to the detriment of most macroeconomic indicators: real GDP is 5.4% lower compared to REF 2030, unemployment

reaches 6.8% and households consumption is 7% lower. Therefore, **without recycling carbon revenues, the carbon tax significantly hits the economy and implies sizable economic costs** (around 1,5 year delay of economic growth compared to REF 2030).

This first policy case is actually more illustrative than realist and helps to understand the main macroeconomic mechanisms involved in the gross introduction of a carbon tax in the long run. Moreover, part of macroeconomic outcomes are not intuitive: introducing the carbon tax ultimately leads a slight *decrease* of domestic price index compared to the reference. This further favors competitiveness for some economic sectors like services. Such outcomes are related to the significant decrease of the average real “efficient wage”, which is a key variable to reach system balance.

To understand the chain of mechanisms, it is possible to split between *direct* and *indirect* effects. Applied on producing sectors, the carbon tax first drives prices of production up through the rise of energy costs despite substitution between fossil energy and others production factors, including labor. The general rise of prices, which is amplified by the multiplier effect of inter-industry relationships, further lowers final demand. Households actually face differentiated higher prices amplified by the carbon tax on final fossil fuel consumption. This in turn changes the structure and volume of final demand towards a global decrease of that demand. Meanwhile the general increase of prices alters competitiveness through terms of trade degradation, which results in lower net exports. This direct depressive effect is amplified by two indirect effects: (i) the drop of households income linked to the decrease of production and (ii) the decrease of investment. Eventually a mechanism of **wage moderation** does make it possible for the system to balance. The global decrease of activity, partially offset by the increase of labor content of production, actually drives employment down, which in turn drives wages down through the wage curve. Finally the decrease of wages alleviates or even offsets the loss of competitiveness, which eventually stabilizes the level of activity of the economy. This mechanism of wage moderation is thus crucial to assess the ultimate effect of introducing a carbon tax in the economy.

To better understand the mechanisms at play, we perform a sensitivity analysis of the results to alternative visions about labor markets and trade mechanisms (similar to section 7.2.3).

Table 7.5 presents the sensitivity of the relative impacts of the carbon tax compared to the reference to the degree of wage flexibility. Results show that **the higher the flexibility of wages, the lower the relative impact of carbon taxation on the economy**. Such results can be understood by analyzing the mechanism of wage moderation through the flexibility of wages and the wage curve. The higher the wage flexibility, the higher the capacity of the system to transfer the rise of prices into a decrease of

wage flexibility	full	REF	-50%
Emissions	-29%	-30%	-31%
Real GDP	-3.9%	-5.4%	-6.3%
Unemployment rate	+0	+ 1.4 p	+2.3 p
Consumption price index	-1.3%	+0.1%	+1.0%
Nominal wages	-8.6%	-7.4%	-6.1%
HH real consumption	-5.8%	-7.0%	-7.9%
Exports industry	-0.2%	-1.3%	-2.0%
Emissions (absolute)	565	564	566
Real GDP (absolute)	5263	5277	5287
Unemployment rate (absolute)	7%	6.8%	6.6%

Table 7.5: Sensitivity of results to wage flexibility

wages while maintaining the level of employment. In the case of low wage flexibility, the depressive effect of the carbon tax drives employment down and wages moderation hardly offsets the loss of competitiveness. On the contrary, when wages are perfectly flexible, the depressive effect on employment is totally absorbed by wage moderation. On the whole it ends up with better competitiveness and higher households real income despite lower nominal wages. This mechanism of “spring” played by the wage curve here over the long run, is similar to that highlighted in [Guivarch \(2010\)](#) for the short run.

Table 7.6 shows the sensitivity of the relative impacts of the carbon tax to terms of trade elasticities. We have demonstrated in section 7.2.3 that the economic projection

trade elasticities	/2	REF	x2
Emissions	-26%	-30%	-32%
Real GDP	-4.0%	-5.4%	-6.4%
Unemployment rate	+0.8	+ 1.4 p	+1.9 p
Labor intensity of composite	+2.5%	+3.1	+3.4%
Consumption price index	-3.3%	+0.1%	-0.1%
Nominal wages	-9.7%	-7.4%	-8.1%
Real wages	-6.6%	-7.4%	-8.2%
HH real consumption	-5.8%	-7.0%	-8.1%
Exports industry	+0.8%	-1.3%	-2.6%
Emissions (absolute)	671	564	528
Real GDP (absolute)	5617	5277	5120
Unemployment rate (absolute)	3.6%	6.8%	8.4%

Table 7.6: Sensitivity of results to trade elasticities

is very sensitive to trade elasticities and economic outcomes are all the higher than trade elasticities are low. The analysis of the relative impacts of the carbon tax should take into account this fact. In a relative perspective, one can figure out that higher trade elasticities amplify the depressive effect of the carbon tax on domestic activity through a larger decrease of net exports with the same price shock. Consequently wage moderation should be higher and drive unemployment and GDP down. The sensitivity of GDP and employment losses are consistent with this analysis and **relative GDP losses are all the higher than trade elasticities are high**. Real wage moderation follows the same hierarchy and moderation is higher in the high elasticity case. However nominal wage moderation and domestic price index follow a different hierarchy. This has actually to do with the heterogeneity of the counter-factual baselines. “Starting” from a high unemployment rate in the reference highly opened economy, a relatively low nominal wage moderation implies high employment losses. In the end, GDP losses are the resultant of employment losses and the increase of labor content of production.

To conclude this section, let’s mention that *relative* results can hide a different hierarchy of *absolute* outcomes. Because alternative functioning of the economic system also applies to baselines and relative results to changing baselines may not be good proxies for absolute results. By the way, the higher the flexibility of wages the lower the relative GDP losses due to the carbon tax compared to the baseline but the lower the absolute GDP level. In this case, the absolute depressive effect in the baseline actually more than offsets the positive relative mechanism. For trade elasticities, additive effects appears and relative impacts amplify baseline divergences.

7.3.2 A central tax policy scenario - taxing fossil CO₂ , reducing sales taxes - and role of technical systems

7.3.2.1 Macroeconomic and sectoral results

In this subsection, we contemplate a more realistic reference tax policy scenario of the same US\$100/tCO₂ in 2030 but including the recycling of carbon revenues through reducing sales taxes (CLIM-RST 2030). The technical features of the scenario are detailed in section 6.3.8. Reducing sales tax is *a priori* a rather neutral recycling scheme in terms of distributive impacts between households and productive sectors because it directly alleviates the carbon tax burden for both institutional sectors: it has a direct impact on households purchasing power through final consumption and on production costs through intermediary consumption. Globally, implementing RST tax policy makes it possible to reduce CO₂ emissions of 25% while limiting GDP loss to 2.8% compared to REF 2030.

Figure 7.2 shows the breakdown of emissions among economic sectors. The bulk

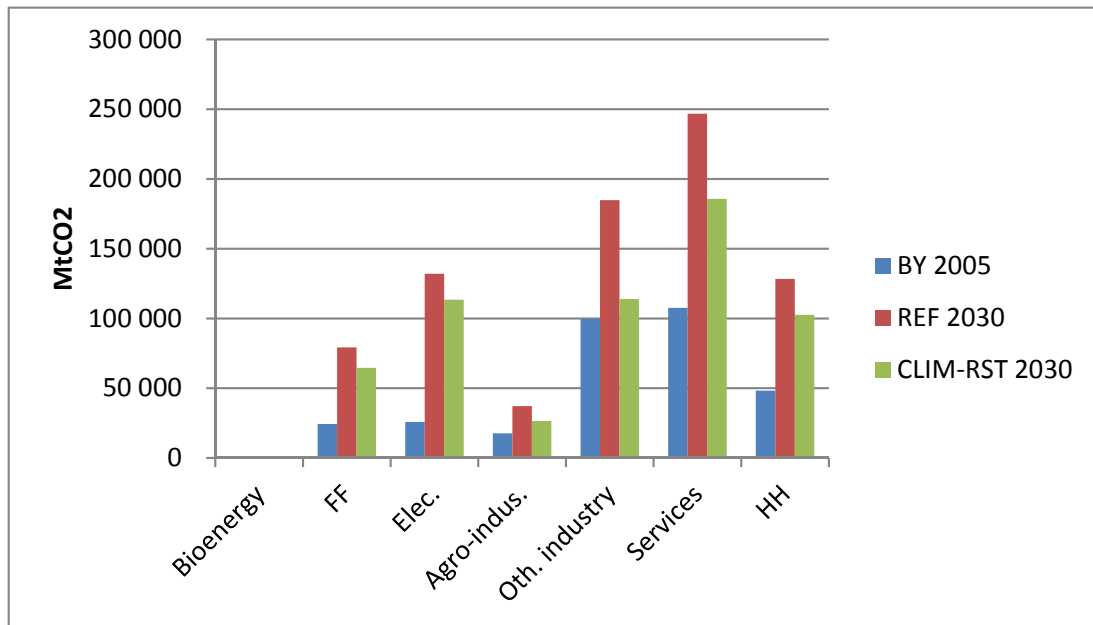


Figure 7.2: CO₂ emissions by sector in BY 2005, REF 2030 and CLIM-RST 2030

of emissions abatement comes from industry (35% of abatement), composite (30%) and households (13%) sectors - that is energy end-use sectors. Most of the abatement - as well as emissions - from composite and households sectors comes from transportation. In this scenario energy sectors - including power sector - contribute little to emissions abatement (16.5%). This is consistent with bottom-up studies.

Figure 7.3 shows the impact of RST tax policy on sectors outputs. As could be expected, fossil fuels production drops to the benefit of bioenergy. Furthermore, power generation is significantly impacted because it is limited in terms of technical flexibility. Industry and services outputs drops almost like GDP with services a bit better off owing to lower carbon content.

Finally, Figure 7.4 shows net exports for the different sectors. We observe a drop of net exports for most sectors, except fossil fuels. The carbon tax reform does reduce the competitiveness of most domestic productions with the highest impact on industry. The decrease of fossil fuel imports enables net exports to increase.

Table 7.7 shows the macroeconomic outcomes of CLIM-RST. As expected, **recycling carbon revenues makes it possible to offset part of the direct burden of the carbon tax** on GDP, employment and household consumption (see section 7.3.1). It operates

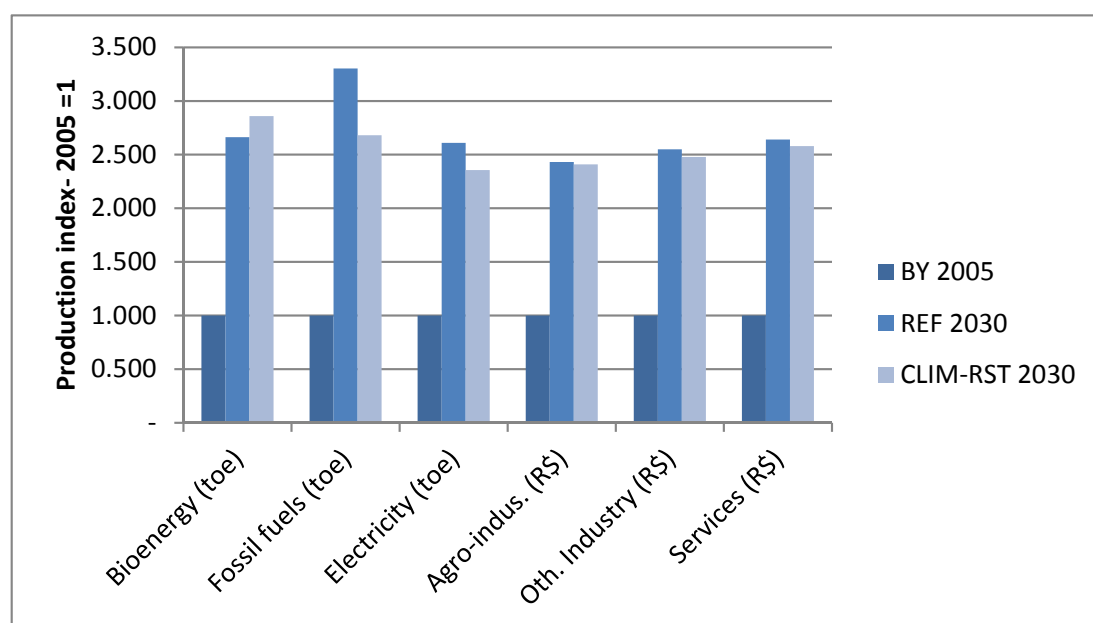


Figure 7.3: Domestic production by sector in BY 2005, REF 2030 and CLIM-RST 2030

	BY 2005	REF 2030	CLIM-RST 2030	Δ CLIM-RST - REF
CO ₂ energy emissions	324	808	607	-25%
Real GDP (10 ¹² R\$2005)	2.143	5.577	5.423	-2.76%
Average real GDP growth per year (%)	-	3.90	3.78	-0.12 p.
Unemployment rate (%)	8.56	5.36	5.50	+0.14 p.
GDP deflator	1	1.202	1.242	+3.3%
Services exports (index)	1	1.97	1.90	-3.3%
Industry exports (index)	1	2.09	2.02	-3.3%
HH real expended income	1.435	3.745	3.651	-2.5%
Labor intensity of composite sector	-	0.533	0.541	+1.6%
Consumption price index	1	1.182	1.220	+3.2%
Variation of average real wage (outside productivity effects)	-	1.01	0.99	-2.2%
Variation of nominal wages (outside productivity effects)	-	1.18	1.20	+1.4%

Table 7.7: Macroeconomic results of CLIM-RST 2030

through several channels as follows. First, reducing sales taxes offsets part of the propagation of increased fossil fuels costs in the I-O matrix and thus limits the increase

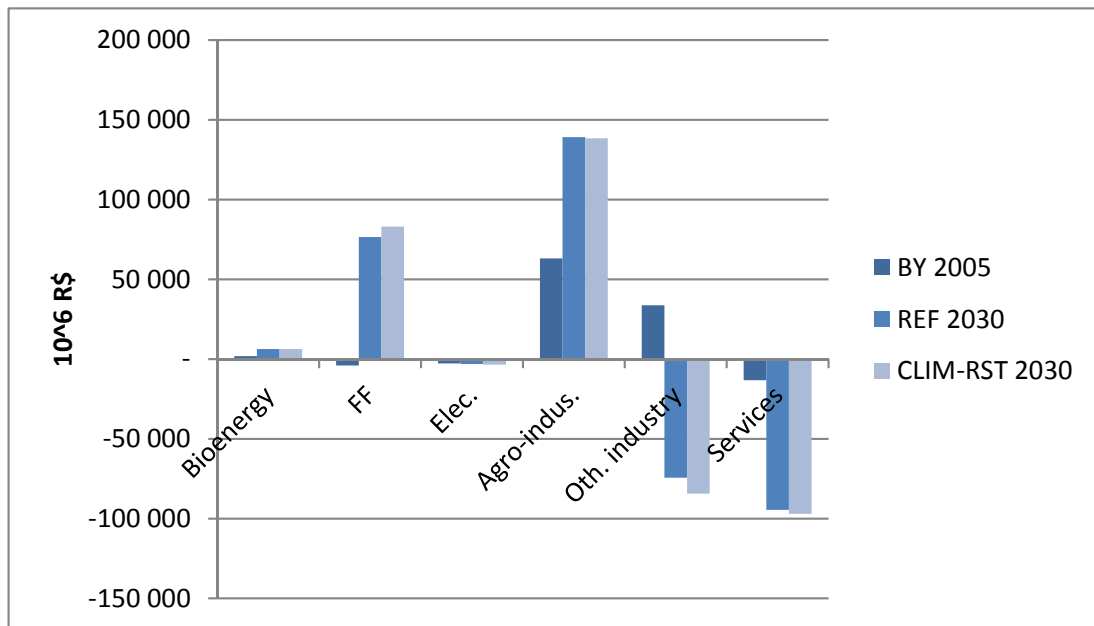


Figure 7.4: Net exports by sector in BY 2005, REF 2030 and CLIM-RST 2030

of domestic production costs. Second it reduces the loss of purchasing power of households by reducing the gap between consumers' and producers' prices. Therefore the resulting depressive effects on households final demand, net exports and indirectly on investments are more limited compared to NR scenario. On the production side of the economy, the increase of energy costs and average prices tends both to decrease real wages (if one reasons with constant nominal wages) and to increase labor intensity of production through factor substitution towards relative cheaper labor. This trend drives employment and potential domestic production to a lower level than the direct loss of final demand. Eventually an upward offset of the level of employment is needed to reach system balance. In the meantime, such an adjustment rises nominal wages through the wage curve. It is worth noting that this upward adjustment of nominal wages works here the other way around compared to the case where carbon revenues are not recycled (see section 7.3.1).

7.3.2.2 Sensitivity of the results to the flexibility of technical systems

In this subsection we study the impact of technical systems flexibility on macroeconomic outcomes. Doing this, we provide new empirical material to feed the debate

about the importance to rightly represent technical flexibilities in general equilibrium models to perform relevant economy-wide climate and energy policy assessment. We have already highlighted that improving bottom-up - top-down hybridization is relevant for several reasons including: (i) to guarantee the coherence of economic and technical projections, (ii) to improve the dialog between engineers and economists and (iii) because technical constraints impact economic pathways. Numerical simulations of this subsection contributes to the discussion on the last point especially.

We contemplate two alternative scenarios to the central CLIM-RST scenario: (i) one scenario with higher general substitution possibilities for end-use energy sectors and power generation (RES-GEN) and (ii) one scenario specifically targeting higher flexibility of power generation only (RES-ELEC). The implementation of higher flexibility of end-use sectors simply consists in increasing general elasticity of substitution by 50% ($\sigma = 1.8$).

For power generation, we try to embark part of available bottom-up information and scenarios. Several studies contemplate a low potential of abatement from power sector beyond reference policies until 2030. Studies reckon on only 100-150 MtCO₂ abatement from power generation for the 2010-2030 period based on the expansion of hydro, wind power and biomass co-generation capacities. Our reference CLIM-RST policy is consistent with such low flexibility of power sector. Other studies like [Lucena et al. \(2015\)](#) contemplates much higher flexibility of power generation and a deep decarbonization of power generation at time horizon 2030 with a US\$50/t CO₂ price. To reflect alternative possible flexibility of power generation we calibrate power sector substitution possibilities to mimic an average scenario estimated from [Lucena et al. \(2015\)](#). In practice we adjust the technical asymptote of fossil fuels inputs and sector elasticity of substitution so that fossil fuel-based electricity is reduced to 10% of power generation mix in 2030 with a US\$100/t CO₂ price.

The results about the macroeconomic sensitivity to technical flexibilities of productive sectors is shown in table 7.8. As RST-GEN results first show, **higher flexibility of technical systems yields significantly higher emissions abatement and alleviates slightly the carbon tax burden with lower GDP losses**. However, aggregated GDP losses hide contrasted distributions of the economic burden with less intuitive outcomes: **the higher flexibility of productive systems ultimately benefits to employment and households to the detriment of productive sectors competitiveness**. More precisely, higher flexibility increases total net employment compared to both RST an NR scenarios but worsen competitiveness.

These outcomes are linked to the counter-intuitive evolution of the system towards an increase of domestic prices, which results from indirect effects as follows. First,

Flexibility of technical systems	CLIM-RST	General +50%	ELEC +50%
Emissions	-24.9%	-39.7%	-32.6%
Real GDP	-2.76%	-2.64%	-2.17%
Unemployment rate	+0.14 p	-0.1 p	+0.03 p
Labor intensity of composite	+1.6%	+1.8%	+1.3%
GDP deflator	+3.3%	+5.6%	+3.6%
Nominal wages	+1.4%	+4.0%	+2.1%
HH real consumption	-2.5%	-2.0%	-1.8%
Exports industry	-3.3%	-4.4%	-3.3%
Exports composite	-3.3%	-5.4%	-3.7%
Electricity production price	+21%	+8%	+6%
Share of emissions abatement from power generation	9.2%	21.8%	27.7%

Table 7.8: Sensitivity of impacts of RST tax policy to flexibility of production system

higher flexibility does induce higher decarbonization and alleviate the direct rise of production costs, which directly alleviates the burden on final demand. However, higher flexibility also implies higher factor substitution towards more labor intensive productions. Furthermore employment is driven up to offset labor intensity increase and to sustain production levels and is driven even higher to supply for a less depreciated final demand. Eventually, the rise of employment drives wages up through the wage curve so that wages increase ultimately more than offsets the alleviation of energy costs increase and results in higher domestic prices. Finally, the rise of wages benefits households but worsen competitiveness. It is worth noting that in this case, exports of services (-5.4%) are more impacted than exports of industrial goods (-4.4%) whereas industry undergoes higher direct energy costs.

In addition, fig. 7.5 shows the difference of power generation mix between REF, RST and RST-ELEC scenarios. In RST scenario, the tax policy has actually a very small impact on the power generation mix and most of the abatement in the power sector comes from the drop of electricity production. In RST-ELEC, introducing the carbon price decreases the share of fossil fuels electricity to 10% to the benefit of hydro and wind power mainly. At global level, power generation stands for almost 28% of abatement compared to 9% in the central policy scenario and total abatement of the sector reaches almost 33%. In addition, macroeconomic outcomes are pretty interesting: the flexibility of power generation alone alleviates much more the tax burden than when the whole economy is more flexible - including the same flexibility of power generation.

One can understand such results. First, the higher flexibility of power generation

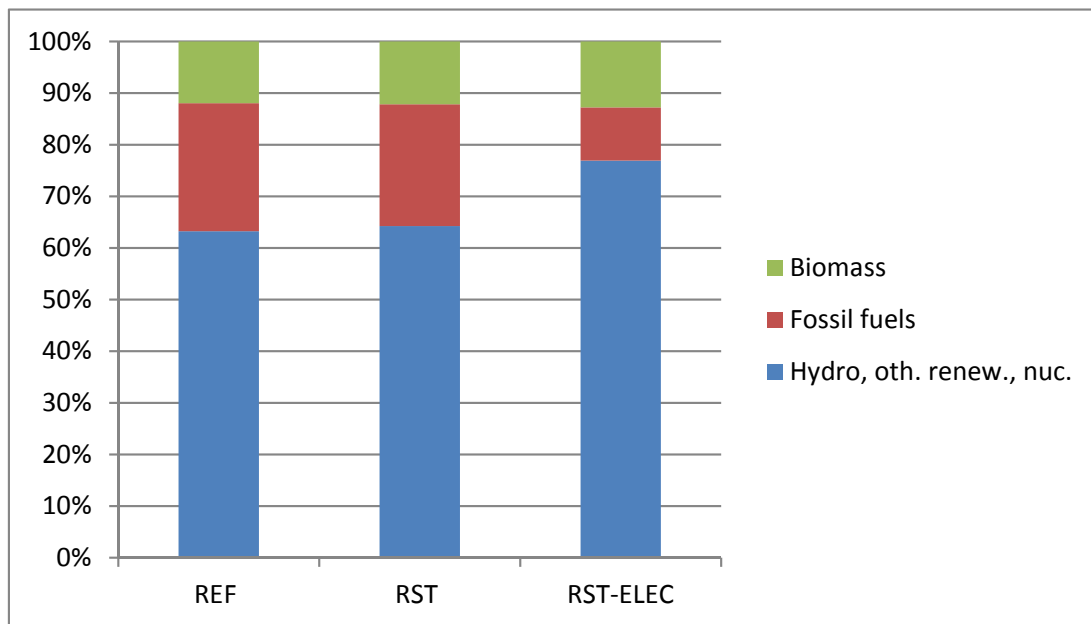


Figure 7.5: Brazil power generation by source for the different scenarios

leads to similar effects on power sector: a strong alleviation of the electricity price increase compared to RST scenario (+6% vs +21%). This positive effect spreads in the economy and restore part of final demand exactly as in RST-GEN. The main difference is that adding flexibility in power generation incurs lower average labor intensity of production compared to CLIM-RST scenario: the positive effect on the price of goods through the I-O matrix leads to a lower relative increase of factor prices compared to the price of labor. Therefore employment and further wages do not need to be driven as drastically up to offset the increase of labor intensity. In the end, the rise of wages and domestic prices is more limited which limits the impacts on competitiveness. In short, the positive effect of the limited electricity price increase on final demand added to the limited increase of domestic prices, eventually limit the losses of competitiveness and households purchasing power.

This section has shown that **the effect of the flexibility of technical systems on net mitigation costs can be ambiguous and involve counter-intuitive mechanisms that can offset direct impacts and leads to close GDP losses**. However, the power sector could play a significant role in alleviating the cost burden of a carbon tax if the whole technical potential was exploited⁸.

⁸Let's mention that imposing a carbon tax on a pretty rigid energy supply system (refining and power

7.3.3 Uncertainty analysis: the interplay between carbon revenues recycling options and labor and trade structural mechanisms

7.3.3.1 Alternative recycling options: what trade-offs between policy objectives?

The goal of this section is to assess the implications of alternative carbon tax policies - characterized by alternative carbon revenues recycling options - and their interplay with alternative visions of the economic system around two key components: labor markets and trade mechanisms.

To do so, we consider two additional recycling options aside the reduction of sales taxes: (i) the reduction of payroll taxes (CLIM-RPT) and (ii) lump-sum transfers to households (CLIM-LS). In the CLIM-RPT scenario, carbon revenues - still levied on both households and productive sectors - are used to decrease sector specific rates of payroll taxes by the same proportion for all sectors while maintaining neutral budget. In the CLIM-LS scenario, carbon revenues are entirely transferred to households as a scaling up of social transfers. These schematic options are an illustration of possible policy packages.

Table 7.9 shows the comparative results of NR, RST, RPT and LS policies for the same US\$100/t CO₂ carbon tax in 2030 with the reference model setting. The first thing to note is that every recycling options make it possible to alleviate the economic burden of the carbon tax to reach similar GDP losses (2.8-2.9 %) with close CO₂ emissions abatement (25-26%). However, interestingly, the underlying breakdown of economic burden is pretty contrasted. Figure 7.6 shows a **trade-off between households consumption, international competitiveness and employment** in the long run, according to the recycling option chosen. No option is superior for all indicators.

Furthermore, part of the results are consistent with expected trade-offs and direct effects: (i) transferring total carbon revenues to households, does alleviate the loss of purchasing power the most (to yield only -0.4% consumption loss), to the detriment of competitiveness (+11% of the price index); (ii) reducing payroll taxes does lower the relative cost of labor the most and favor employment (+0.3%).

However, others outcomes are less intuitive. Taking RPT and RST options, it is clear that the shift of fiscal burden from productive sectors to households is higher with RPT than RST. In the RPT case, carbon revenues levied on households are used to decrease production costs only, whereas with RST, part of carbon revenues are used to alleviate the sales tax burden borne by households specifically. However, modeling

generation) may not be the best policy to implement. In case of possible reduced mitigation options in the energy supply system, we can show that it is better to leave it outside the carbon tax perimeter to get similar emissions abatement with pretty lower GDP losses.

Recycling scenario	CLIM-NR	CLIM-RST	CLIM-RPT	CLIM-LS
Emissions	-30%	-25%	-26%	- 25%
Real GDP	-5.4%	-2.8%	-2.9%	-2.8%
Employment	-1.5%	-0.1%	+0.3%	+0.1%
GDP deflator	+0.3%	+3.3%	+6.7%	+11.7%
Consumption price index	+0.1%	3.2%	+6.4%	10.8%
Labor intensity of services	+3.1%	+1.6%	+2.3%	+1.9%
Average real wage	-7.4%	-2.2%	-1.1%	-3.9%
Average nominal wage	-7.4%	+0.9%	+5.2%	+6.5%
HH real consumption	-7.0%	-2.5%	-2.0%	-0.4%
Services exports	+1.9%	-3.3%	-5.0%	-9.2%
Industry exports	-1.3%	-3.3%	-5.4%	-8.3%
pComp	-1.8%	+4.2%	+7.0%	+10.0%
pIndus	+1.6%	+3.4%	5.2%	+11.3%
Trade balance	+0.8 p.	-0.1 p.	-0.4 p.	-0.2 p.
Real investment	-4.7%	-1.7%	-2.1%	-1.8%

Table 7.9: Sensitivity of macroeconomic outcomes to carbon revenues recycling scenarios

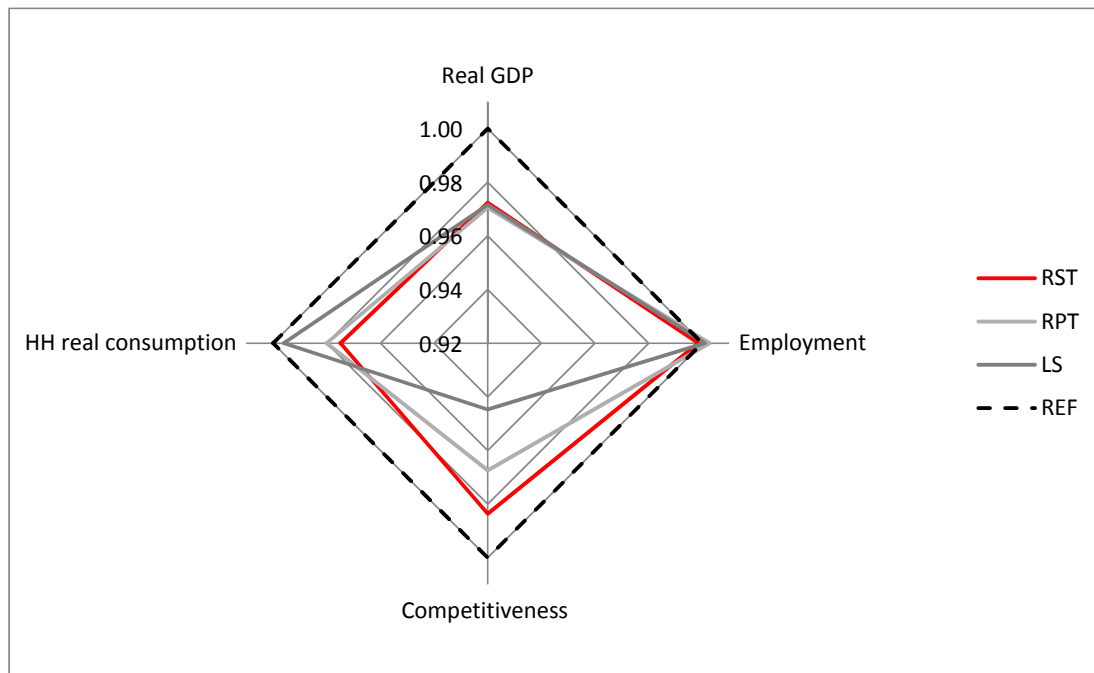


Figure 7.6: Comparison of recycling options

results in the long run show that households are not worse off and competitiveness is not more preserved with RPT than with RST and the reverse situation even happens. The key of this result is the feed-back effect from labor markets, which more than offsets the switch of fiscal burden in the RPT case as follows: the relative decrease of labor costs raises labor intensity of production which drives employment up. But at the same time, employment pulls wages up through the wage curve to a point where part of households purchasing power is finally restored but where the net increase of domestic prices degrades competitiveness. In the RST case, the employment effect is lower because reducing sales tax does not decrease relative labor costs and furthermore wages increase is lower. Finally competitiveness is less impacted but the relative lower increase of employment and wages dimly restores households purchasing power.

In addition, it is worth noting that the feed-back effect from labor markets also plays an important role in the LS case. The strong direct rise of domestic prices - not offset by any tax alleviation in this case - implies a significant relative decrease of labor price which drives labor intensity of production (+1.9%) and employment up. Employment, which is half indexed on nominal and real wages in the reference model setting, drives nominal wages to a even higher point than the RPT case. One

Labor market configuration	Description
Full WF	Full wage flexibility
Low WF real	Low real wage flexibility
Low WF nom	Low nominal wage flexibility

Table 7.10: Labor markets scenarios

understand at the same time, that reaching such resulting high domestic price index (+11.7%) is consistent with limited GDP losses only if the impact on trade is limited and thus only where trade openness is small.

From the former explanations, we can expect that the hierarchy of the different recycling options about their relative effects in the long run on GDP, households consumption, competitiveness or employment may depend upon two key aspects of the economic system: labor markets and trade mechanisms. Therefore we explore in the following, the interplay between carbon revenues recycling options and alternative visions of the Brazilian economy about labor markets and trade.

7.3.3.2 Sensitivity of the results to labor markets and trade conditions

To begin with, we study the sensitivity of previous results to labor market conditions. Usual CGE models in the energy-climate field suppose that wages are perfectly flexible in the long run, which in our framework corresponds to the $\sigma_u = -\infty$ situation. In addition, the wage curve formulation makes it possible to depart from this assumption and to study the implications of partial wage flexibility in Brazil on carbon tax policy assessment. Some econometric studies claim the existence of a wage curve for Brazil with an elasticity of -0.2/-0.1 for real wage in the medium run. Therefore we contemplate three different patterns of labor markets (see table 7.11). The Full WF configuration supposes that nominal and real wages are fully flexible and the unemployment rate remains constant ($\sigma_u = -\infty$). The Low WF real configuration supposes that real wages are partially rigid and the unemployment rate is indexed on average real wage within the wage curve ($\sigma_u = -0.17$ and $sh_r = 1$). Finally the Low WF nom configuration supposes that the unemployment rate is indexed on the average nominal wage within the wage curve ($\sigma_u = -0.17$ and $sh_r = 0$). A wage curve indexed on real wages characterizes a low opened economy where domestic employees focus on their purchasing power. Alternatively, a wage curve indexed on nominal wages is the sign of an opened economy where domestic employees are in competition with foreign workers. As in section 7.3.1, we make the assumption that these contrasted formulations of labor markets are valid outside climate policies. As shown in section 7.2,

contrasted formulations of labor markets yield very contrasted no-policy baselines, which should be taken into account in the analysis.

The results of the sensitivity of *relative* impacts of alternative tax policies to the functioning of labor markets are shown in table 7.11.

Usage of carbon revenues	Full WF			Low WF real			Low WF nom		
	RST	RPT	LS	RST	RPT	LS	RST	RPT	LS
Real GDP	-2.6%	-3.2%	-2.9%	-3.5%	-3.6%	-4.5%	-2.6%	-2.6%	-2.2%
Employment	+0%	+0%	+0%	-0.9%	-0.4%	-1.7%	+0.1%	+0.7%	+0.8%
GDP deflator	+3.1%	+6.9%	+11.7%	+4.1%	+7.4%	+13.6%	+3.1%	+6.4%	+11.1%
Labor intensity of Services	+1.5%	+2.2%	+1.9%	+1.6%	+2.2%	+1.9%	+1.6%	+2.3%	+2.0%
Average real wage	-2.2%	-1.0%	-3.7%	-2.1%	-1.0%	-3.5%	-2.4%	-1.2%	-4.1%
Average nominal wage	+0.7%	+5.5%	+6.6%	+1.8%	+6.0%	+8.5%	+0.6%	+4.8%	+5.7%
HH real consumption	-2.3%	-2.2%	-0.4%	-3.2%	-2.5%	-1.9%	-2.4%	-1.7%	-0.2%
Real investment	-1.5%	-2.3%	-1.9%	-2.4%	-2.7%	-3.4%	-1.5%	-1.8%	-1.3%
Trade balance (% nom. GDP)	-0.1 p.	-0.4 p.	-0.9 p.	-0.1 p.	-0.4 p.	-0.9 p.	-0.1 p.	-0.4 p.	-0.9 p.

Table 7.11: Sensitivity of tax policies impacts to the functioning of labor markets - relative impacts

As expected, **labor market conditions significantly impact the economic costs of tax policy scenarios**. It is possible to understand the effects of labor markets conditions on *relative* costs via the intensity of the feed-back effect. First of all, Full WF scenarios yield similar outcomes than with the reference setting of the model except for the RPT case maybe, where the higher flexibility of wages worsen the loss of competitiveness. Low WF scenarios show more contrasted results. **Real wages indexation worsens macroeconomic losses** for all tax scenarios. It comes from the fact that, offsetting the higher labor intensity of production through employment variation, implies a much higher increase of average nominal wage to catch up purchasing power. This stronger rise of nominal wages stabilize the economy at a lower GDP level through higher losses of competitiveness and lower employment. This effect is stronger for the LS case because a stronger increase of nominal wages is required to offset the direct burden of the carbon tax on prices. The contrary occurs when unemployment is indexed on nominal wages: increasing employment implies a softer rise of nominal wages so that lower losses of purchasing power and competitiveness can be reached. As a result, all three tax policies yield a net gains of jobs - a so-called "double dividend" for employment - compared to the baseline with nominal wage indexation.

In addition, the hierarchy of policy options along main economic indicators (as shown in fig. 7.6) is globally robust to alternative flexibility of both real and nominal wages. Nevertheless, labor market conditions have a significant impacts on the ranking of options regarding GDP losses and employment.

Let's now analyze the sensitivity of results to two contrasted levels of openness to international trade. In the first case, elasticities to terms of trade are twice lower than in the reference setting ($\sigma_{Mi} = 0.5$ and $\sigma_{Xi} = 0.6$) whereas in the high openness case, elasticities of exports are increased of 50% ($\sigma_{Xi} = 1.8$) and elasticities of imports are double the reference ($\sigma_{Mi} = 2$). The very contrasted results shown in table 7.12 confirm that trade openness is a key element in the long run answer of the Brazilian economy to carbon tax policies.

When trade openness is limited, the relative GDP losses of tax policies are small and even negative for LS case with net positive effects on employment for all recycling options, despite much lower abatement levels. The explanation is simple: increasing production costs through the rise of energy costs and nominal wages, incurs too small trade losses to offset the positive effect of employment and real wages gains. This effect is all the stronger so as the recycling option tends to degrade competitiveness. The effect is exactly reversed for higher trade openness, including about the hierarchy of recycling options.

Usage of carbon revenues	limited trade openness			high trade openness		
	RST	RPT	LS	RST	RPT	LS
Emissions	-17.0%	-17.2%	-12.9%	-27.4%	-29.5%	-29.4%
Real GDP	-1.1%	-0.8%	+0.3%	-3.6%	-4.1%	-4.7%
Employment	+0.3%	+0.7%	+0.9%	-0.6%	-0.2%	-0.9%
GDP deflator	+10.5%	+19.8%	+35.5%	+1.0%	+2.9%	+5.3%
Labor intensity of Services	+0.6%	+0.7%	-0.1%	+1.9%	+2.8%	+2.7%
Average real wage	+0.2%	+2.4%	+2.7%	-3.1%	-2.4%	-6.2%
Average nominal wage	+9.8%	+20.9%	+35.5%	-2.0%	+0.5%	-1.5%
HH real consumption	-0.0%	+1.5%	+4.9%	-3.6%	-3.6%	-3.0%
Real investment	-0.1%	+0.2%	+1.6%	-2.6%	-3.5%	-4.0%
Services exports	-4.9%	-8.1%	-13.5%	-1.7%	-2.0%	-5.3%
Industry exports	-3.9%	-6.5%	-10.5%	-2.8%	-4.5%	-6.9%
Trade balance (% nom. GDP)	-0.1 p.	-0.2 p.	-0.5 p.	-0.1 p.	-0.4 p.	-1.0 p.

Table 7.12: Sensitivity of tax policies impacts to trade openness

7.3.3.3 Conclusion

To sum up, labor markets conditions and trade openness play decisive roles in the relative impacts of carbon tax policies in the long run. For all recycling options, the indexation on nominal wages ultimately leads to lower GDP and purchasing power losses, all the lower than wages are rigid. In addition, higher trade openness leads to higher losses through a loss of competitiveness. As far as the hierarchy of recycling options is concerned, robust elements to labor markets and trade conditions stand-out: (i) RST incurs the lowest loss of competitiveness, before RPT and LS; (ii) LS incurs the lowest loss of households consumption and more interestingly, RPT induces lower loss than RST. The hierarchy of options in terms of GDP and employment depends on labor and trade conditions.

7.3.4 A short comparison with France

Previous section has highlighted that different possible carbon tax policies could lead to similar GDP losses with contrasted breakdown of aggregate costs. In this subsection we want to go further in understanding these results, in order to sharpen the diagnosis about carbon tax policies in Brazil in relation to its very specific energy and economic characteristics. Doing so, we justify the empirical approach and the need to carry out region specific analysis of tax policies, with economic models embarking detailed characteristics of the regional context under study. This approach is all the more relevant for policy making as there is no general theory about the impacts of alternative carbon tax policies. In order to understand the specific situation of Brazil, we draw a comparison with the implications of similar tax policies in France. The goal is to understand the role of the specific initial or trend structure of Brazilian economy in the answer to the different carbon tax policies.

An extensive analysis of carbon tax policies in France has been carried out by [Combet \(2013\)](#) with a very similar modeling tool - regarding labor market and trade mechanisms especially. The main difference is that the study explores counter-factual deviations compared to the historic France in 2004, as if tax policies had been implemented say 20 years before. As a consequence, relative implications of tax policies match absolute outcomes. The results of implementing RPT (*Baisse des cotisations*) and LS (*Redistribution forfaitaire intégrale*) tax policies in France with a 300€/tCO₂ carbon tax are reported in fig. 7.7.

In order to isolate the role of trend economic structures in the answer to tax policies, we simulate RPT and LS tax policies - with a US\$100/tCO₂ carbon tax - in IMACLIM-BR with similar model parameters than the French study for labor markets and trade.

Neutralité budgétaire Modalité d'usage des recettes	RDPC*		
	Aucune Remboursement de la dette	Redistribution forfaitaire intégrale	Baisse des cotisations
Emissions totales de CO ₂	-38,5%	-34,8%	-34,1%
Produit intérieur brut réel	-6,5%**	-0,7%	+1,9%
Emploi total (éq. temps plein)	-5,7%***	+0,3%	+3,5%
Prix de production composite****	-0,6%	+3,7%	-1,0%
Intensité en travail du bien composite	+0,8%	+0,8%	+1,4%
Consommation composite des ménages	-10,8%	+0,5%	+1,6%
Volume des exportations de bien composite	+0,4%	-1,9%	+0,6%
Proportion de bien composite importée	-0,5%	+3,2%	-0,9%
Consommation publique réelle	-3,1%	+3,7%	+5,4%
Investissement réel	-6,9%	-0,7%	+1,9%
Ratio de la dette publique au PIB	-92,0%	id.	id.

* RDPC : ratio de la dette publique au PIB constant.

** Une baisse de 6,5% du PIB correspond à une variation de 0,34 point du taux de croissance annuel sur 20 ans. En supposant que ce taux est de 2% sans réforme, cela représente un retard de croissance d'environ quatre ans.

*** La baisse de 5,7% de l'emploi correspond à un écart de 1,4 millions d'emplois par rapport à la situation historique, ou encore, à un chômage supérieur de 5,2 points (de 9,6% à 14,8%).

****Relativement au prix mondial de la production composite.

Figure 7.7: Implications of a 300€ /tCO₂ carbon tax with NR, RPT and LS recycling options applied to France in 2004

Source: [Combet \(2013\)](#)

Compared to our central policy case, it means lower wage flexibility with unemployment indexation on nominal wages plus lower trade elasticity. We choose not to align elasticities of substitution on the french model not to loose the specifics of Brazilian technical and structural flexibilities. The results for Brazil shown in table 7.13 are consistent with previous analysis.

Two elements stand-out in the comparison of results. First, recycling carbon revenues by either LS or RPT option alleviates much less the average economic burden in Brazil than in France. Second, RPT tax policy is much favorable than LS in France for all economic indicators (including household purchasing power) whereas, LS provides higher average alleviation of tax burden in Brazil. However, it is difficult to compare the average economic costs between the two cases because the level of carbon tax and the level of abatement are very different. In addition, technical flexibilities are higher in Brazil than France which partly explains the high level of carbon tax required to decarbonize the French economy. At the same time, a higher carbon tax generates

	LS	RPT
Emissions	-21.9%	-24.2%
Real GDP	-1.3%	-2.0%
Employment	+1.0%	+0.7%
GDP deflator	+17.2%	+10.0%
Labor intensity of Services	+1.3%	+1.9%
Average real wage	-2.1%	+0.0%
Average nominal wage	+13.3%	+9.2%
HH real consumption	+1.7%	-0.7%
Real investment	-0.3%	-1.2%
Services exports	-8.3%	-4.8%

Table 7.13: Implications of LS and RST policies for Brazil in 2030 with similar labor and trade parameters than in the French study

higher carbon revenues and further provides a higher lever to alleviate the carbon tax burden.

Aside from this, comparing benchmark energy-economy structures of Brazil and France provides crucial keys to understanding the results. Table 7.14 shows key comparative energy-economy indicators for historic France 2004 and Brazil REF 2030. Part of the higher economic burden of mitigation in Brazil than in France can be first explained by the higher CO₂ content of GDP in Brazil and a much higher energy cost-share in domestic production compared to France 2004. In addition, some elements of Brazilian baseline helps to understand why Brazil may be a worse candidate for “double dividend” compared to France. In the literature, the possibility to get an economic dividend beyond the environmental dividend with a carbon tax policy, appears when the carbon tax does not eventually fall on revenues from labor or productive capital. Such a situation may be triggered by using carbon revenues to decrease existing tax distortion and is all the likelier to happen as imperfections are high in the no-policy economy. A classic case is when part of the carbon tax burden is transferred abroad via the decrease of fossil fuel imports triggered by the domestic carbon tax which acts as an implicit tax on imports. Such a lever works for France which imports in 2004 65% of fossil fuels consumed. As a contrast, Brazil will be an important fossil fuel net

Indicators	Brazil REF 2030	France 2004
Emissions / real GDP (tCO ₂ / 10 ³ US\$)	0.30	0.19
Energy costs / Production	7.8%	2.1%
Share of HH emissions in total	16%	37%
L cost / EN cost	3	15
Fossil fuels M / domestic cons.	13%	65%
Trade flows / GDP	24%	51%
HH consumption / GDP	66 %	55%
unemployment rate	1.8%	9.6%

Table 7.14: Comparative indicators of Brazil REF 2030 and France 2004

exporter in 2030 and such a tax transfer would not happen: carbon tax would strike domestic fossil fuel producers in the first place. A second element of differentiation is the no-policy level of unemployment which is much lower in Brazil than in France. Such a situation reduces the opportunity to offset the carbon tax burden by increasing employment and thus GDP with appropriate tax policy. These considerations are consistent with our results and the absence of strong double dividend for GDP with any tax policy in Brazil 2030, whereas reducing payroll taxes in France leads to a net strong economic dividend with the improvement of all economic indicators.

We now reach the question of the very contrasted relative implications of RPT and LS tax policies between France 2004 and Brazil 2030. Indeed, results show that in Brazil 2030, LS tax policy alleviates more the carbon tax burden than RPT options and leads to lower GDP loss, higher employment, higher purchasing power despite a stronger degradation of trade balance. Conversely for France, LS option does not lead similar net economic dividend than RPT does. The main ingredients for these contrasted results are taken from table 7.14: a much lower share of households emissions in total baseline emissions in Brazil, (a much lower carbon tax), a much lower labor - energy costs ratio, a much lower unemployment rate and a twice lower share of trade flows in GDP. These indicators make it possible to understand why the same virtuous circle as in France can not be reached in Brazil by lowering payroll taxes with carbon revenues. Low relative household's emissions and a low carbon tax actually lead to a weak transfer of fiscal burden from productive sectors to households. Consequently, the domestic price index does not decrease like in France to trigger the virtuous circle. Furthermore, lower labor - energy costs ratio implies a higher increase of labor content of production. This drives employment up which fast reaches upper labor supply because of low no-policy unemployment. On the whole, the slight increase of employment and wages does not offset higher labor intensity of

production and the degradation of terms of trade. Conversely in the French case, the high transfer of fiscal burden leads to lower domestic prices which boosts foreign trade all the more than trade activities are initially high. High initial labor costs and unemployment lead to higher employment and production without harming competitiveness through a moderate rise of wages. As far as the LS case is concerned, the significant increase of domestic prices induces relatively small trade losses in Brazil because of low trade openness. Carbon revenues are in fact better used to feed the domestic market through households consumption. In the meantime employment and wages can increase significantly without too much impacting final demand with trade losses. Conversely for France, the loss of competitiveness induced by domestic prices hike can not be offset by the rise of employment and wages.

As a conclusion we may claim that France and Brazil does not have the same levers to induce a virtuous circle through carbon revenues recycling and the alleviation of existing labor taxes. It partly comes from the low ratio of labor and energy costs (around 3) in Brazil compared to France where labor costs are fifteen times higher than energy costs. However, even if lump-sum transfers look a promising policy to minimize net economic costs in Brazil, it may be hazardous to implement it as such. It could actually weaken trade policies in the long run and in any case it would not be accepted by domestic industries without others compensations. All the more so as we have demonstrated that LS implications was pretty sensitive to alternative functioning of Brazilian economy. Finally, we venture to assert that reducing sales taxes may be the most reasonable option for Brazil amongst the three options studied. RST tax policy leads to a small and shared economic burden between households and productive sectors and it is the less sensitive option to alternative economic visions.

7.4 Distributive issues of climate policy and articulation of objectives

In this last section, we explore a few elements about the distributional implications of carbon tax policies in Brazil at time horizon 2030. From the economic analysis point of view, this topic becomes all the more important than it is not independent from the study of aggregated macroeconomic implications. This situation happens in second best economies where the conditions of “separability” between economic efficiency and income distribution are not met. Furthermore, specific trade-offs between economic efficiency and equity issues may happen according to different tax policy frameworks and recycling options especially. From the policy viewpoint, such trade-offs are key in

the articulation between decarbonization targets and various economic development objectives such as economic growth, employment, inequality decrease and poverty alleviation.

To contribute to this debate in Brazil, we analyze the distributional implications of the four carbon tax policies studied in section 7.3.3: NR, RST, RPT and LS. To do so, we use the specific *IMACLIM-BR 6-6* model version which desegregates the representative household into 6 subgroups defined by income brackets observed at base year (see chapter 6). In *IMACLIM-BR 6-6*, groups mainly differ by the saving rate (exogenous) and the structure of both income and expenses. The structure of expenses varies across groups upon expenses shares of consumed goods. In addition, the contrasted income structures across groups result from an exogenous sharing between groups of different income sources (labor, productive capital, social transfers, etc.).

We start by simulating a reference scenario similar to REF 2030. The saving rates of the two lowest classes are slightly increased until 2030 to reach an average 7% saving rate of households to stick to REF 2030 assumptions. In addition, we choose not to implement any trend about inequality reduction between groups in the reference case until 2030, whereas it seems a consensual assumption. The reason is we want to avoid implementing arbitrary forces of inequality resorption in the reference scenario and focus on the specific distributional effects triggered by tax policies. The dynamics of income inequality is a highly debated issue and further research will help implementing more realistic reference inequality dynamics. In practice, we assume that the share of each income source received by each group remains constant until 2030 as calibrated at base year.

Figure 7.8 shows the income structure of households groups in 2030 in the reference scenario, starting from lowest class (HH1) to highest class (HH6). Interestingly, one can notice that the share of labor income in total income is almost homogeneous across groups. Main differences come from the high share of social transfers in lowest groups which are replaced by income from productive capital and land rent in higher income groups.

The results about the implications of the four carbon tax policies (NR, RST, RPT and LS⁹) until 2030 in terms of real expended income variations per household group are shown in fig. 7.9.

What stands out is that most tax policy have little distributional effects except LS policy. In the LS case, lowest income group consumption increases 17% compared to reference whereas highest group consumption drops 1%. The universal “green check”

⁹In the LS policy, each households group receive a share of total carbon revenues proportional to the number of households in the group.



Figure 7.8: Shares of income sources by household group in 2030

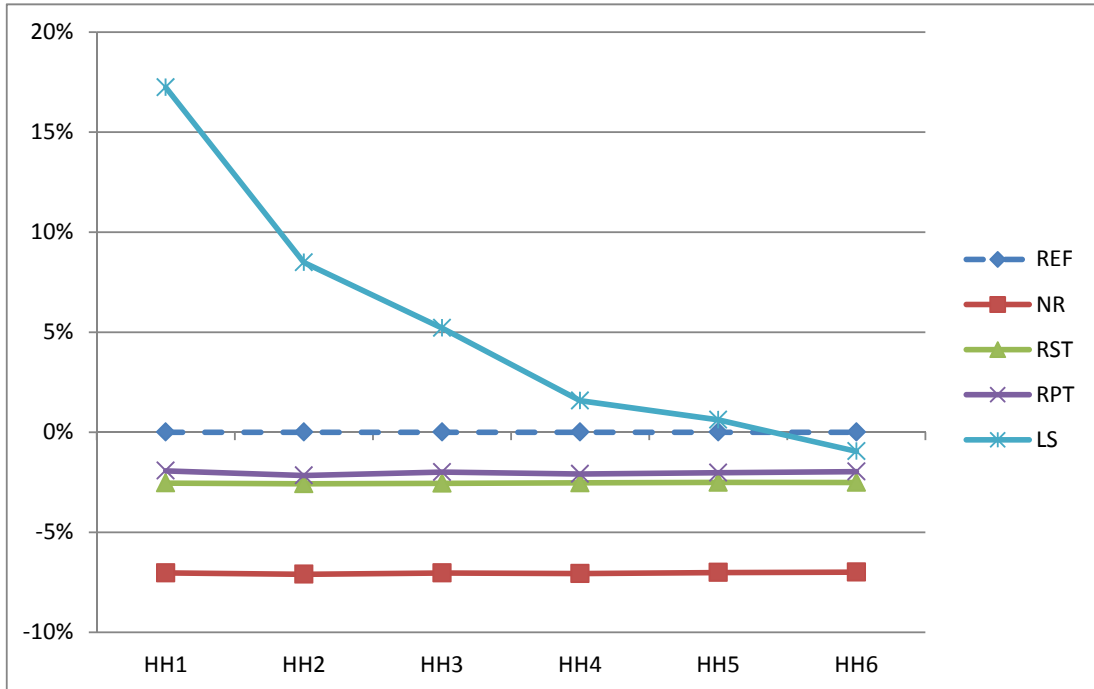


Figure 7.9: Variation of real expended income compared to reference according to tax policy option and household group

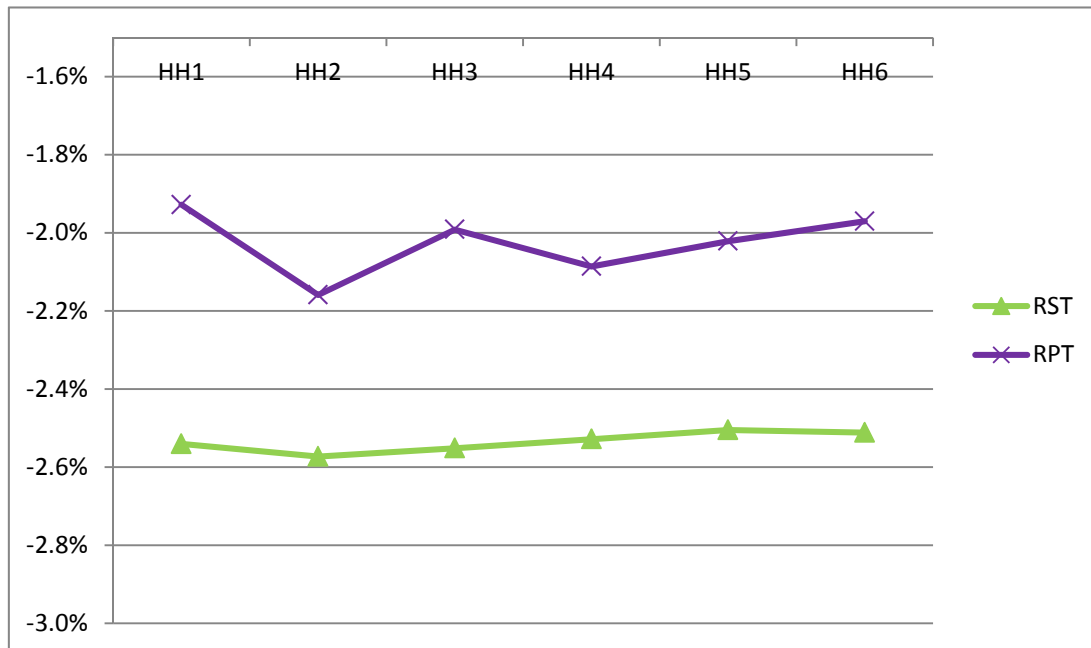


Figure 7.10: Variation of real expended income: zoom on RST and RPT

received by households actually represents 20% of total reference income of HH1 and only 0.7 % of HH6's in our scenario. The distributional effect of a universal "green check" is all the higher than reference inequality are high. A more realistic reference GINI index would lead to lower distributional effects but would not change qualitative results¹⁰.

Looking closer at RST and RPT results as shown in fig. 7.10, one can notice a distributional pattern in the RPT case compared to RST. The superposition of trends of consumption variation and of share of labor income in total income across households group, helps to understand the small distributional effect. RPT option actually favors employment and wages so that it finally favors households with high share of labor income. RST option is almost neutral in our model in terms of income distribution.

Eventually it is possible to consolidate results and compare tax policies performance along environmental, economic, social and distributive dimensions to identify key synergies and trade-offs. Figure 7.11 shows the performance of NR, RST, RPT and LS carbon tax policies in 2030 compared to the reference scenario, along five indicators: (i) decarbonization level (inverse of emissions abatement), (ii) real GDP, (iii) employment,

¹⁰In our reference scenario, the GINI index is kept constant to 0.57 until 2030. A more realistic GINI index of say 0.44 would lead a 9% increased of HH1 consumption for instance

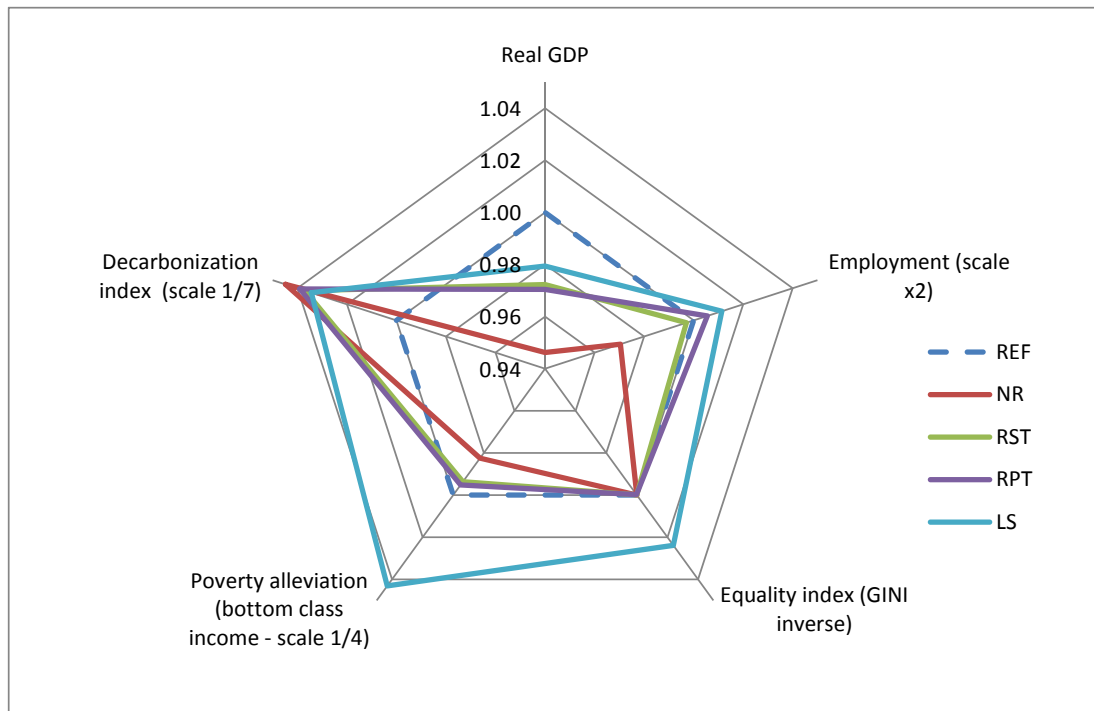


Figure 7.11: Comparison of carbon tax policies performance

(iv) GINI inverse and lowest group income. Without surprise, NR option triggers highest decarbonization to the detriment of economic and social indicators (except inequality). In addition RST and RPT options lead to close results along the different indicators. Small trade-offs can be detected between employment, GDP and household consumption. Eventually LS policy is the most performing policy for most indicators. The positive effect of lump sum transfers identified in section 7.3.4 is enhanced by households desegregation and the consideration of differentiated saving rates. Indeed, the green check promotes the lowest income groups which have lower saving rates in the model. Among others effects, this boosts final consumption even more than when the saving rate is fixed. To conclude, it seems there is room for an inclusive low carbon development pathway in Brazil until 2030 if carefully designed carbon tax policies include transfers towards the lowest income groups.

7.5 Conclusion

This chapter shows how the IMACLIM-BR framework can be used to explore the implications of carbon tax policies in Brazil in the medium to long run and the articulation of policy objectives. The scope of analysis is pretty large and the chapter attempts to

provide methodological, economic and policy insights.

On the methodological side, we have shown how *IMACLIM-BR* makes it possible to generate consistent energy-economy projections in the long run in a single step owing to its general equilibrium backbone, energy-economy dual accounting and an implicit growth engine. Practically, technical coefficients, in physical units when appropriate, are the entry points to implement structural macroeconomic and energy trends. The consistency of projections is guaranteed by the general equilibrium interdependence and the dual accounting of energy flows. In addition, using *IMACLIM-BR* simulation tool fits into a specific forward-looking approach based on the exploration of consistent energy-economy futures. The forward-looking analysis is based on a variant analysis on both policy packages and alternative visions of structural mechanisms of the economic system. It broadens the uncertainty analysis towards the functioning of the economy itself by considering second-best structural mechanisms of the economic system.

Beyond methodological issues, this chapter attempts to contribute to the economic debate about climate policies and the specific carbon tax policy debate in Brazil at time horizon 2030. Climate policies are often assessed under a technological and sectoral angle based on abatement cost curves or the articulation between sector contributions to mitigation in CGE models. Climate policy costs are abatement costs, sector costs or aggregated GDP costs. Uncertainty analysis often targets the availability of technologies and technical progress. Eventually, most often climate policy takes the form of a carbon price reflecting marginal abatement costs. Such analysis is key to understand the mitigation challenges but is today only one part of the problem. In a new context of nationally determined mitigation plans, this type of analysis is not sufficient to design practical climate policies and the articulation of different policy objectives beyond decarbonization. For instance, introducing a carbon price is not only a question of marginal costs but also an issue of income transfers between economic agents. Implementing a carbon tax generates revenues that can be redistributed. Such economic transfers have in practice major impacts on both aggregated mitigation costs but also on the breakdown of costs and dividends among economic sectors and economic agents. From this last point arises the issue of the articulation of policies because carbon tax policies can have very contrasted impacts on key social and economic indicators like employment, competitiveness, public budget, income inequality, etc. In addition, structural specifics of the economic system pertaining to labor markets or trade for instance, can have important implications for the long run effects of carbon tax policies and the articulation of objectives. This chapter aimed at contributing to the debate about carbon tax policies in Brazil to reach ambitious energy-related emissions

target and the articulation with other social and economic objectives.

First off all, results show that recycling carbon revenues makes it possible to reduce GDP costs of a 25% emissions reduction by a factor two until 2030 (compared to the case of no redistribution of revenues) to yield around 2.8% GDP losses compared to a government scenario. This result is consistent with the weak double dividend hypothesis. In addition, according to the recycling option chosen, trade-offs appear between different economic objectives for similar GDP costs. For instance, the lump-sum transfer option provides more than 2% more households consumption than the sales tax reduction but yields 5-6% less exports due to losses of competitiveness. Interestingly, reducing payroll taxes is certainly the best option regarding employment but may not be the best option to offset losses of competitiveness in the long run. This comes for the peculiarity of Brazil regarding the trend small labor - energy cost ratio and the low trend unemployment rate, which implies the appropriation of carbon revenues recycling through an increase of nominal wages and thus on domestic prices. As a fossil fuel producer and exporter, Brazil has a smaller general potential for double dividend compared to France for instance. In addition, the lever of distorsive labor taxes is much smaller. The weak transfer of fiscal burden to households prevent to get the same virtuous circle as in France and the decrease of domestic prices. Advantageous labor conditions only yield more labor intensive productions and higher domestic prices through the rise of nominal wages. However, it seems relevant for Brazil to target poorest households through carbon revenues recycling. Because it makes first it possible to reach the companion objective to decrease income inequality. At the same time, favoring global households consumption may be an interesting macroeconomic option in a country with comparative low trade flows and an important domestic market. Nevertheless, it may not be reasonable to sacrifice trade competitiveness. Eventually, a policy mix targeting low income groups and specific sectors exposed to trade competitiveness may be the best option for Brazil.

Chapter 8

Oil and climate policy in Brazil: how to manage the paradox?

8.1 Introduction

The golden image of the Brazilian oil sector in the end 2000's has been significantly tarnished in the last two years with the serious crisis that has been hitting the giant Petrobras and the general economy. The present context of very low oil prices weakens further the oil industry. However, the oil sector, with the development of pre-salt resources, is expected to remain a pillar of Brazil economic development in the decades to come and its ripple effect on the rest of the economy may play a significant role in growth recovery in the short to medium run. In addition, significant expected revenues from excess production exports in a more favorable price environment ([Goldemberg et al., 2014](#)) are planned to be reinvested in education and health in order to boost productivity in the long run, a key structural handicap of present Brazilian economy. Globally, according to most recent 10-year energy plan [EPE \(2015\)](#), after a relative stagnation in the short run until 2017 (around 2.7 mb/d), domestic oil production is expected to grow steadily to exceed 5 mb/d in 2024 in a reference scenario, the half of which is planned to be exported. These figures are actually consistent with others estimations ([Goldemberg et al., 2014](#); [IEA, 2013](#)).

If the arguments for the positive effect of pre-salt oil development on Brazilian economy in the medium run seem indisputable, concerns have been expressed about the risk of "Dutch disease" ([Bresser-Pereira, 2008](#); [Ismail, 2010](#)). In this logic the strong increase of oil exports implies currency overvaluation, "*low rates of growth of the manufacturing industry, artificially high real wages, and unemployment*" ([Bresser-Pereira, 2008](#)). Subsequently, a careful balanced management across time of economic sectors between

commodity-based sectors and manufacturing industry may be required to avoid major macroeconomic risks. The current severe difficulties experienced by oil exporting countries in the present context of low oil prices (Venezuela, Algeria, etc.) also illustrate the possible weakness of the dependence to commodity prices volatility.

At the same moment, the world has just adopted the first universal climate agreement in COP21, which claims the beginning of the end of the oil and fossil fuels era. Within the climate governance, Brazil has been taking its competitive advantage and historic leading role in low carbon economy by displaying ambitious intended commitments (INDCs). The INDCs released in september 2015 (FCCC-UN, 2015b) include to reduce total GHG emissions by 43% compared to 2005 level by improving energy efficiency and up-scaling the sustainable use of bioenergy and the penetration of renewable technologies in energy supply, beyond the drastic reduction of deforestation . Meeting such a global target actually requires to significantly moderate the growth of energy related emissions as these emissions will continue to increase in the next 15 years at least and will become the first GHG emissions source in Brazil beyond 2020, ahead land-use and agriculture (La Rovere et al., 2013).

Furthermore, one clearly understands the paradox of Brazil situation which ambitions to become a major oil province on the one hand, and to strengthen its position as a leader in climate governance on the other, with the intended commitment to decarbonize deeper its energy system. What is thus the consistency of the official discourse? In a context of severe economic doldrums and considering its sizable remaining development gap, Brazil does not intend to renounce the economic manna of pre-salt oil. The official plan is thus to supply the growth of domestic energy demand with bioenergy and renewable energy sources and direct additional oil production to exports. This would make it further possible to both maximize oil revenues and contribute to meet domestic emissions target.

The success of the global energy-climate plan strongly depends on the level of further expansion of biomass and natural gas in industry and more critically of further expansion of biofuels in the transport sector. Oil fuels represent the bulk of total final demand of fossil fuels (78% in 2013). In addition the transport sector currently accounts for 70% of oil fuel domestic consumption and half total energy related emissions. Liquid fuels represent the quasi totality of transport energy demand with a heavy reliance on roads for both passengers and freight. Heavy vehicles (buses, trucks) rely on diesel oil and the further penetration of biodiesel is constrained by the future blending mandate which is now 7% in volume. Ethanol is in fact the real forte of biofuel's sector and already represents more than 35% of liquid fuels demand for light duty vehicles (LDV). With the bulk of LDVs being "flex fuel" in a close future, there is a high potential

to increase ethanol market share with hydrated ethanol. Eventually, the ethanol market share for LDVs is a key adjustment variable of total domestic oil consumption else very sensitive to relative prices of gasoline and ethanol. Consequently, the success of the fuel plan will depend on the consistency of government policies over the next decades towards *“removing subsidies for fossil fuels and using the added revenues to promote similar fiscal policies for biofuels. Adhering to a strict implementation of such policies is a precondition for reaching deeper decarbonization with Brazil’s current fuel strategy”* (La Rovere et al., 2015). In addition, diverting cheap newfound oil resources to domestic use would further weaken the efforts to develop energy efficiency.

However, one can observe in recent years a reverse trend in contradiction with expressed intentions, with an increase of gasoline demand by more than 40% from 2010 to 2014 while hydrated ethanol sales slumped. This is the consequences of a taxation policy favoring cheap oil fuels to curb inflation down and improve households purchasing power in the short run. *“A sharp trend reversal must happen if a Deep Decarbonization Pathway is to be pursued, and this reversal can only be achieved with adequate taxation rules. The government should also adhere to its plans to export the extra crude oil produced in the next few years and resist the temptation to divert it to the internal market when international prices drop”* (La Rovere et al., 2015).

One can thus observe that the domestic low carbon pathway, even with the perspective of stronger biofuel industries, a more energy efficient production system and maximum oil revenues, may not be the easiest route, politically and economically, considering the apparent short term temptation to subsidize oil fuels. Looking further in time, one key issue is to understand the ultimate economic implications in the long run of two possible contrasted pathways: (i) a low carbon pathway and (ii) an intensive domestic oil pathway based on continuing subsidizing oil fuels to favor purchasing power and divert part of the newfound oil to domestic market. This paper seeks to provide answers to these questions by simulating the macroeconomic implications of different contrasted oil-climate scenarios until 2030 with a novel energy-economy model for Brazil. 2030 is a key time horizon because it both corresponds to the horizon for most recent climate commitments and to approximately reach the plateau of pre-salt oil production. Four scenarios are compared:

- A reference scenario (*REF*) which corresponds to government energy and climate plans prior COP21 including the full development of oil production.
- An alternative scenario (*Low OIL*) in which Brazil decides not to increase oil production until 2030 to be consistent with global climate action.

- An oil intensive scenario (*OIL int*) based on full oil production and subsidy to favor domestic oil consumption.
- A first low carbon scenario (*LC*) based on implementing a carbon tax policy to meet more ambitious climate targets.
- A second low carbon scenario (*LC+eff*) expanding *LC* with further energy efficiency policies in the transport sector.

The results show that renouncing to expand oil production in the medium run to be consistent with global climate action may not be an option because oil exploration may actually significantly boost GDP and households welfare until 2030. Under the assumption of full oil production until 2030, we show that Brazil may face a divide between two contrasted routes that yield similar GDP levels: the oil intensive pathways and the low carbon energy efficient pathways. We conclude that the low carbon pathway, which is the official government plan for the long run, seems to be the best way-out to the Brazilian oil-climate paradox not only for environmental reasons. The reminder of the paper is composed of three sections: section 8.2 details the scenario design and the modeling approach of the present work. Section 8.3 discusses the results about the energy-economy implications of the scenarios. Section 8.4 concludes.

8.2 Methodology

8.2.1 Model and data

The analysis in this paper is conducted with the *IMACLIM-BR* model. *IMACLIM-BR* is a hybrid energy-economy CGE model specifically designed to build consistent energy-economy projections for Brazil in the medium to long run. The model generates integrated projections of the energy-economy system in a single step computation and is further used in comparative statics. In practice the model generates various projections as alternative counterfactuals driven by different sets of parameters and policy packages. The insights provided are valid under the assumption that the policy-induced transition from base year economic balance to a given policy-constrained future, is completed, after a series of technical and economic adjustments whose duration and scope are embedded in the behavioral functions retained for the time horizon under consideration. The transition process itself is however not described, but implicitly supposed to be smooth enough to prevent e.g. multiple equilibria, hysteresis effects, etc. *IMACLIM-BR* further departs from the standard neo-classical CGE framework in several key features (see chapter 6). In addition, the description of the consumers' and

producers' trade-offs, and the underlying technical systems, are specifically designed to facilitate calibration on bottom-up expertise in the energy field, with a view to guaranteeing technical realism to the simulations of even large departures from base year point.

The IMACLIM-BR version used for this study details 12 economic sectors including 6 energy sectors (bioenergy, coal, crude oil, gas, oil fuels and electricity) and 6 non-energy sectors (freight transportation, passenger purchased transportation, livestock production, rest of agro-industry, rest of industry, composite). The representation of household's final consumption singles out the main final service types in a first layer within a standard LES demand system: food, mobility and housing. Basic needs are calibrated to represent service specific income elasticities. Demand for mobility is further detailed with a nested-CES framework and can be satisfied by either purchased transportation (plane, bus, taxi, etc.) or own transportation based on LDVs. Own transportation further combines fuel and an aggregate of vehicle purchase and services. Eventually, the fuel aggregate is a combination of ethanol and gasoline. The substitution elasticity between ethanol and gasoline is calibrated to reflect empirical behaviors in the long run, taking into account the 25% blending mandate of anhydrous ethanol in gasoline C and considering that 85% of LDV's will be "flex-fuel" in 2030 (EPE, 2014a).

Furthermore, the oil sector is attached with a specific behavior in the model as total domestic production is a scenario parameter reflecting a production objective to be reached in 2030. Subsequently, domestic crude oil consumption is endogenous and depends on the domestic demand level for oil fuels, the level of imports of final oil fuels and of domestic refining capacities. The level of crude oil exports is the endogenous balance of total production. The price of exported oil is indexed on world price based on its specific average quality (Goldemberg et al., 2014) and domestic oil production price reflects production costs. Capital costs of oil production are also adjusted to reflect capital-intensive pre-salt extraction¹. It is to be noted that the representation of the oil sector departs from standard CGE models where fossil fuel production usually depends on a fixed resource factor substitutable with others factors, the endowment of which decreases as production happens. Such a representation implies decreasing return in production.

IMACLIM-BR captures a detailed taxation system including payroll taxes, production taxes and sales tax on final consumption. The model also includes indirect taxation on income and profits. Furthermore, tax rates parameters are the main policy variables

¹Average oil capital costs are assumed 30% higher in 2030 than 2005: US\$17/bbl vs US\$13/bbl.

to generate alternative policy scenarios.

Eventually, IMACLIM-BR is calibrated on a 2005 hybrid SAM crossing economic and physical accounts (see chapter 6 and chapter 4). Energy volume flows are expressed in toe and transportation services in ton.km (t.km) and passenger.km (p.km). IMACLIM-BR further preserves dual accounting in simulation to generate macroeconomic and energy scenarios.

8.2.2 Study design

In a first stage, we build and simulate a reference scenario until 2030 with IMACLIM-BR, which aims at reflecting government energy and climate plans prior COP21. IMACLIM-BR makes it possible to generate our own consistent energy-economy reference picture based on a set of energy and macroeconomic exogenous parameters calibrated on existing government plans. The reference scenario provides an anchor to study the energy, climate and macroeconomic implications of alternative oil and climate policies. The key policy variables to generate alternative scenarios include the objective of oil production, oil fuels and biofuels taxation, general carbon tax and specific energy efficiency measures targeting the transport sector.

8.2.2.1 A reference energy-economy scenario

The narrative of the reference scenario (*REF*) is that from the National Energy Plan (PNE 2050) (EPE, 2014a) until 2030 combined with several others sources. It especially includes the mitigation objectives of the National Climate Change Plan (PNMC) extended to 2030. Our reference scenario thus aims at mimicking key energy-economy trends of the existing government plans, while generating our own projection based on IMACLIM-BR own energy-economy consistency.

In practice, we first assume a trend economic growth of Brazil of 3.9% per year and an average 3.5% per year for the rest of the world. These assumptions translate into the calibration of exogenous population and active population growth rates, labor productivity gains and levels of exports outside changes in terms of trade. GDP and exports are endogenous in the model and vary around these trends. The investment-GDP ratio is assumed to reach around 20% reflecting the development of modern infrastructures. This trend is implemented in the model through an exogenous increase of the capital intensity of production. In addition, the exogenous world oil price reaches 85\$/ton in 2030 as a reference oil price in 2030.

In *REF* scenario, oil production reaches 5.5 bM/d in 2030 as an exogenous target, which is a median value of different reference projections (EPE, 2015; Goldemberg

et al., 2014; IEA, 2013). Our reference scenario also aims at mimicking the energy matrix embodied in PNE 2050 in 2030. To do so we build a preliminary energy balance based on PNE 2050 which enables us to determine trend structural changes about fuels mixes and energy intensity for energy supply, conversion and end-use sectors. These trends are implemented by exogenous scalar adjustments of energy technical coefficients in the Input-Output matrix. Direct translation of physical information is possible in IMACLIM-BR owing to the accounting of energy flows in physical units. Effective energy technical coefficients are further endogenous in the model and vary around the trends according to relative prices. These trends about the energy system first include a global increase of bioenergy and natural gas shares in the fuel mix compared to 2005. Bioenergy expands with added power generation capacities from biomass, a higher usage of bioenergy in industry and a higher penetration of biofuels for transportation. Natural gas expands in power generation and industry. The share of hydro power drops (65% in 2030) in electricity generation and the share of renewables (wind power, bioenergy) and fossil fuel thermal (coal and natural gas) capacities increase and enable to meet the growing demand: shares of natural gas and bioenergy triple in power generation mix compared to 2005, the share of coal almost doubles. The energy efficiency of LDVs - implementing as factor augmenting - increases of 0.7% per year during the 2005-2030 period. Finally, oil fuel and biofuel taxation is fine-tuned to reach around 57 billion liters ethanol demand (anhydrous and hydrated) in 2030. In practice it means increasing biofuel subsidy on the one hand and increasing oil fuels tax on the other to maintain neutral budget.

8.2.2.2 Alternative oil and climate scenarios

The first alternative scenario labeled *Low OIL* assumes that Brazil does not increase its yearly oil production between 2015 and 2030 and maintains it to 2.5 mb/d. In practice, it means to exploit only a reduced fraction of Santos basin potential until 2030 and roughly stick to proven reserves (end-2012). Even if the *Low OIL* scenario represents a rather unrealistic scenario for Brazil *per se*, it makes it possible to estimate the macroeconomic effects of pre-salt reference exploration until 2030 by comparison to the reference scenario. A few studies already provide assessment of the macroeconomic implications of pre-salt oil exploration (Valladares, 2013; Magalhães and Domingues, 2014).

Under the assumption that Brazil explores the pre-salt resource in accordance with government plans, we build three alternative scenarios to the reference.

The oil intensive scenario (*OIL int*) goes in an opposite direction from official

government plans but embodies what could be an extension in the long run of the policy of low oil fuels prices which has been applied during latest years. In this scenario, the recently observed policy of subsidizing oil fuels is extended until 2030 and part of the increase of oil fuels demand is supplied by domestic oil fuels produced with domestic oil in new refining capacities. In the meantime, ethanol demand remains constant between 2015 and 2030 around 30 billion liters per year. To run this scenario we implement taxation rules in 2030 to yield the plateau of ethanol demand at 32 billion liters per year according to market conditions. In practice, the taxation conditions of biofuels remain those from based year and we implement an added subsidy across oil fuels financed by public budget. Therefore such a taxation policy aggravates the public deficit in the model (or the deficit of a state-owned company like Petrobras) and reflects the long run trend deficit of Petrobras recently observed. Lower oil fuels prices else weaken the efforts to upscale energy efficiency so that the transport sector is 8% less efficient than in the *REF* scenario in 2030.

The first low carbon scenario (*LC*) aims at strengthening reference climate action to get close to the newly adopted emissions targets with recent INDC. To do so, we maintain the reference base tax policy of oil fuels and biofuels and we add a 70\$/tCO₂ carbon tax targeting emissions linked to final energy consumption only (transport, agriculture, industry, services and households). Carbon revenues are further recycled into general sales tax reduction. This first *LC* scenario is extended towards a *LC+eff* scenario which adds to the *LC* scenario a set of complementary policies targeting a better efficiency of the transport sector. The energy efficiency of LDVs increases of 40% compared to *REF* scenarios to reach the European standards of energy efficiency of vehicles. Heavy vehicles energy efficiency - for both passengers and load transportation - increases 9% compared to *REF*. In addition, freight transport optimization allows to reduce the needs for freight services. A trend decrease of 8% compared to *REF* of the technical coefficient of load transportation in agriculture, industry and composite sectors is added to the set of complementary policies.

8.3 Results and discussion

8.3.1 Reference scenario outcomes

The macroeconomic outcomes of *REF* scenario are shown in table 8.1. GDP growth averages 3.92% per year during the 2005-2030 period and the employment rate drops to around 5%. *REF* scenario reflects a structural change of GDP along the economic development path: the trade balance and final households consumption decrease in

	BY 2005	REF 2030
CO ₂ energy emissions	324	826
Real GDP (bR\$2005)	2.143	5.608
Average real GDP growth per year (%)	-	3.92
Unemployment rate (%)	8.56	5.22
GDP deflator	1	1.26
Investment rate (% GDP)	16.0	20.0
Trade balance (% GDP)	3.7	1.0
HH real expended income (% GDP)	67.0	65.7
Agro-industry exports (index)	1	1.97
General industry exports (index)	1	2.04
Services exports (index)	1	1.88
Average real wage (outside productivity effects - index)	-	1.00

Table 8.1: Macroeconomic results of REF scenario

share to the benefit of investment. Domestic price index also increases of 26% during the period. The underlying macroeconomic consistency mechanism is the following. First the trend increase of capital intensity of production mechanically pulls the growth of the investment ratio. Then, part of additional investments is supplied by the slight increase of households saving rate, hence the decrease of final consumption ratio. Subsequently, the remainder of the needed investment is supplied by foreign capital flows which mechanically drives the trade balance down. Finally, the drop of the trade balance ratio increases the terms of trade and the GDP deflator which finally adjusts through the rise of average nominal wages. Let's note that trade mechanisms play a crucial role in reaching system balance and macroeconomic consistency. Beyond GDP structural change, REF scenario embodies sector structural change through the interplay between inter-industry relationships, final consumption and trade patterns. Without going into the details, the GDP share of industry decreases to the benefit of services and transport services especially, due to an income elasticity higher than 1. Consequently, the total demand for passengers.km increases of 4.2% per year between 2005 and 2030.

Turning to the energy and environmental aspects of the reference projection, fig. 8.1 shows the levels of energy CO₂ emissions and final energy demand and the sector breakdown thereof. If the transport sector is only the second final energy consumer, it is the first contributor to CO₂ emissions with 44% of fossil emissions ahead the wider industry. Energy supply and conversion and buildings generate only one quarter of

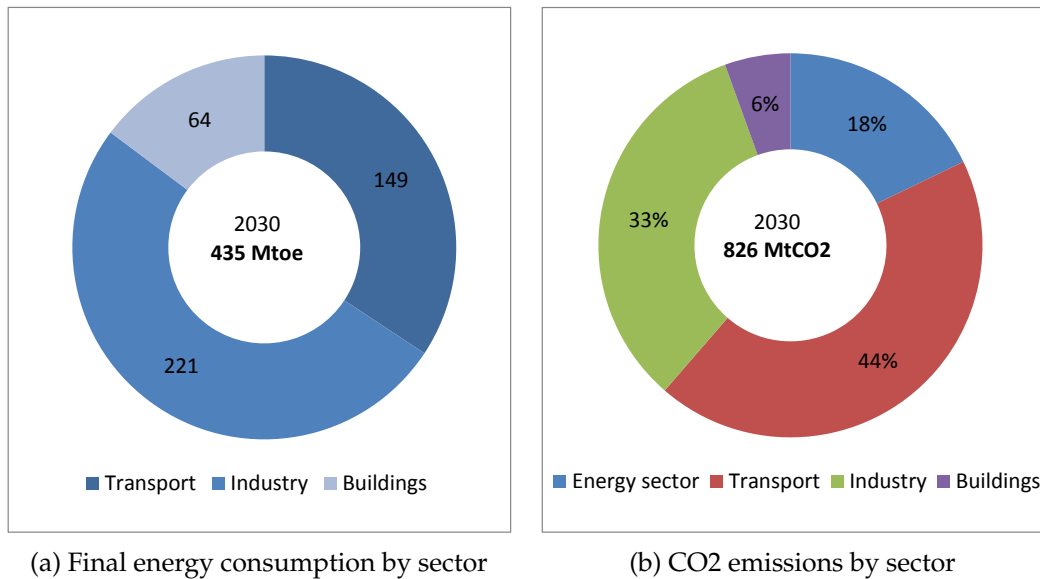


Figure 8.1: Final energy and energy CO2 emissions by sector

emissions. The total level of energy related CO2 emissions is consistent with others existing scenarios (La Rovere et al., 2013). The details of final energy demand by source (fig. 8.2) shows several structural changes. The share of electricity increases mainly due to the increase of grid-electricity demand in buildings to supply for more appliances. The share of natural gas is pulled up with the strong expansion of pipeline gas in industry sectors to the detriment of coal. The global share of bioenergy slightly drops with the fall of traditional biomass consumption despite the additional penetration of solid biomass in industry and the significant up-scaling of biofuels in transportation. Finally the share of oil fuels decreases significantly due to the substitution towards others fuels in industry and transport in particular. Figure 8.3 details the expansion of biofuels in the transport sector. The favorable tax conditions beyond 2015 boost the final demand for ethanol (hydrated ethanol mainly) for LDVs to reach 57 billion liters in 2030 (14 bl in 2005). The 7% blending mandate of biodiesel makes it possible to sell 6.5 billion liters for heavy vehicles. Overall, with 34 Mtoe, biofuels stand for 23% of total transport final energy and ethanol represents a 44% market share of light duty vehicles. Eventually, the model computes the oil balance (fig. 8.4) which reveals that on the 5.5 mb/d of crude oil produced, 2.9 are used to feed the domestic and 2.6 mb/d can be exported.

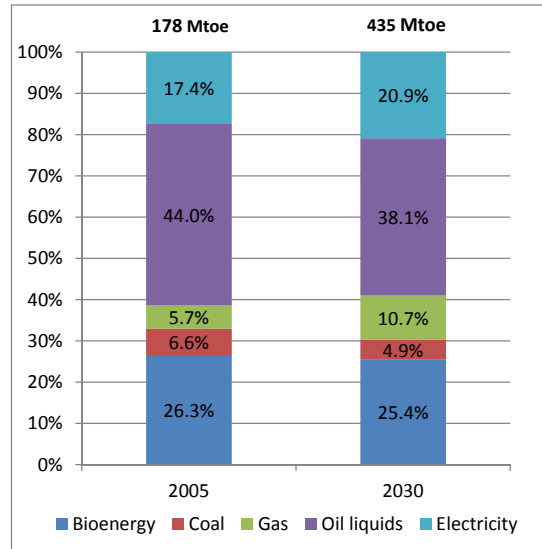
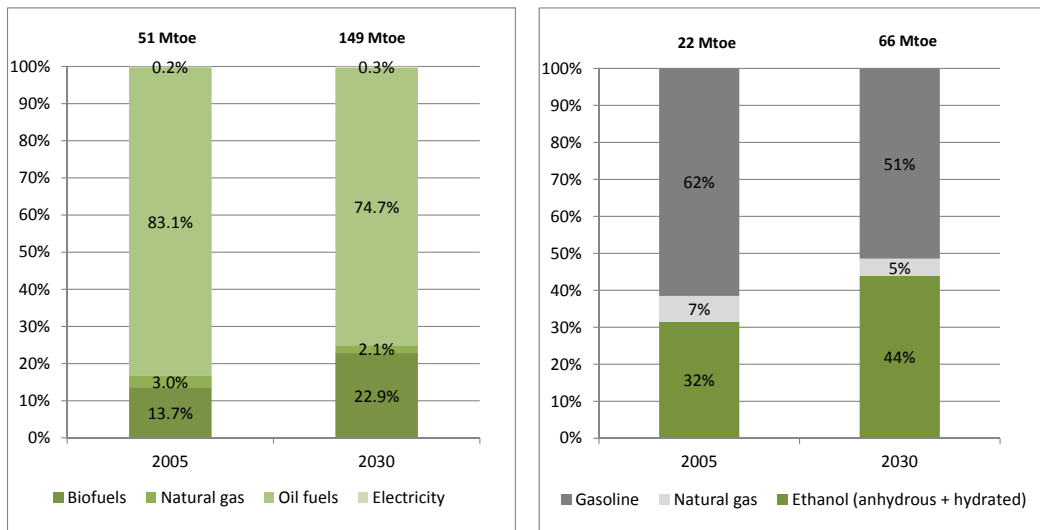


Figure 8.2: Final energy by source



(a) Final energy mix - total transport sector

(b) Fuel mix - Light duty vehicles

Figure 8.3: Final energy mix - transport sector

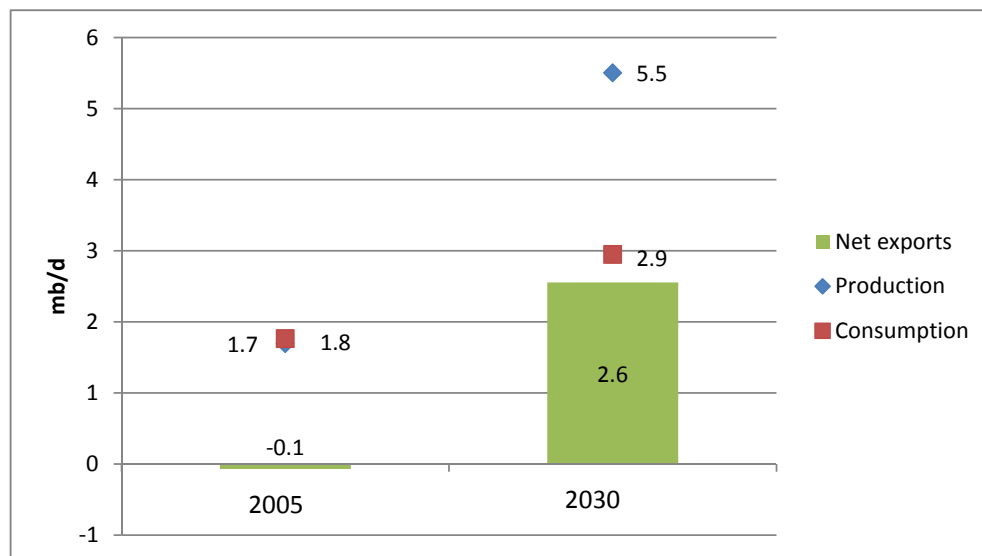


Figure 8.4: Oil balance

8.3.2 Implications of leaving oil under the ground

With 826 MtCO₂ of energy related emissions, less than 4 tCO₂/cap and a 2.5% decrease of carbon intensity of GDP between 2005 and 2030, the reference scenario already makes Brazil a model student in climate performance. However, the rating can be slightly lowered if one take into account in the analysis the emissions generated abroad via oil exports. In the reference scenario, exporting 2.6 mb/d of oil would generate around 450 MtCO₂ in 2030, which is roughly the current level of energy emissions in Brazil. In this view, Brazil's GDP "generates" not 826 MtCO₂ but almost 1300 MtCO₂. An interesting question is thus what would be the macroeconomic consequences of maintaining oil production to present level until 2030 and thus contributing to global climate action. Viewed differently the question targets the macroeconomic impacts of exploring further oil resources until 2030.

Comparing the macroeconomic outcomes of *Low OIL* and *REF* scenarios, provides an estimation of the economic implications until 2030 of increasing oil production from current 2.5 mb/d to 5.5 mb/d. We also compute a *High OIL* scenario to have the complete range of plausible futures². The comparative macroeconomic outcomes of *REF*, *Low OIL* and *High OIL* scenarios are shown in table 8.2. Results show that the macroeconomic implications of up-scaling oil production between *Low OIL* and

²The *High OIL* scenario supposes that oil production reaches 6.9 mb/d which is the high assumption taken from IEA (2013).

	<i>Low OIL</i>	<i>REF</i>	<i>High OIL</i>	Δ <i>Low OIL-REF</i>
Oil production (mb/d)	2.5	5.5	6.9	
Domestic oil consumption (mb/d)	2.7	2.9	3.0	
Net oil exports (mb/d)	-0.2	2.6	3.9	
Oil export revenue (% GDP)	-0.1	2.9	4.3	+171 bR\$
real GDP (bR\$)	5311	5608	5719	+5.6%
Investment rate (% GDP)	19.4	20.0	20.2	+0.6 pts
GDP deflator	1.00	1.26	1.40	+26%
Agro-industry exports (index - 2005)	2.40	1.97	1.79	-18%
Industry exports (index - 2005)	2.38	2.04	1.91	-14%
Services exports (index - 2005)	2.37	1.88	1.69	-21%
Agro-industry production (index - 2005)	2.41	2.47	2.49	+2.2%
Industry production (index - 2005)	2.51	2.53	2.52	+0.9%
Services production (index - 2005)	2.48	2.64	2.70	+6.6%
Trade balance (% GDP)	1.8	1.0	0.6	
HH real expended income (index - 2005)	2.40	2.62	2.72	+9.3%
Average real wage (outside productivity effects)	0.93	1.00	1.03	
Unemployment rate	8.5%	5.2%	4.2%	

Table 8.2: Impacts of oil production level in 2030

REF are twofold: (i) a global *output effect* with a significant increase of GDP (+5.6%), households welfare (+9.3%) and employment (+3.6% jobs); (ii) *structural effects* with an increase of global investment rate, decrease of the trade balance and sector structural changes.

First of all, the order of magnitude of the GDP effect looks consistent with previous studies on Brazil pre-salt oil (Valladares, 2013; Magalhães and Domingues, 2014). However, the underlying mechanisms are different from an approach based on a shock on resources. Magalhães and Domingues (2014) actually simulate the macroeconomic consequences of the *existence* of the pre-salt oil - compared to a baseline with less resources - based on a positive shock on the resource factor endowment of oil and gas sectors between 2010 and 2020. Furthermore, even if the magnitude of the shock is calibrated to mimic a given path of oil production in simulation, such scenarios are different from the present study. In the former case the two scenarios reflect optimal oil production given alternative endowments of resources. In the present study we assume that the implicit same amount of resource is available for both *Low OIL* and *REF* cases and the difference only lies in the choice of the exogenous level of production - as an exogenous policy target - which in both cases may not reflect the “natural” market penetration in perfect economic environment. Subsequently in Magalhães and Domingues (2014) the resource shock trigger a direct productivity effect on the oil sector - the same amount of oil can be produced at lower cost - which spreads in the economy and yields higher oil production and GDP. Our *REF* scenario does not imply a direct positive *shock* on total economic endowment compared to *Low OIL*, but rather a *transfer* of available economic resources to the oil sector.

Furthermore, the ultimate positive effect on GDP in the long run is not guaranteed *a priori*. In our exercise, the positive effect on economic output especially passes through two key channels usually overlooked in the literature: *trade* and *labor markets*. Increasing capital intensive oil production induces a structural change towards higher average capital intensity of production which drives the investment ratio of the economy up (20%). With constrained domestic savings, higher investment is supplied by foreign capital flows, which mechanically drives the trade balance down. The resulting effect on domestic price index appreciation (+26%) is all the stronger than oil exports are higher. At the same time nominal and real wages increase - as the adjustment variables of the price index - which ultimately drives GDP up through two channels: the increase of apparent labor productivity - through substitution away from labor in production - and the increase of employment through the wage curve. Overall, the ultimate average output effect is very sensitive to the wage-employment linkages of the wage curve. In addition, structural effects are more robust to labor markets

uncertainty but stills depend on trade effects. The increase of the domestic price index partially linked to higher oil exports, actually reflects symptoms of “Dutch disease” with significant losses of competitiveness and consequences on exports of non-energy products all the lower as the sector is impacted by average wage increase. The final structural changes depend on the relative importance of domestic and external markets for the different economic sectors. Like this, industry sectors partly oriented to external trade do not really benefit from the global output effect (+0.9%) - the increase of domestic demand hardly offsets the decrease of exports, whereas services output is driven up by GDP and domestic purchasing power (+6.6%).

Our simulations show that the potential average economic benefit of increasing oil production level until 2030 may be significant although the ultimate GDP effect is highly uncertain and depends on key mechanisms about trade and labor markets. Beyond, the structural effects may be substantial with a drop of industry and the increase of services shares in GDP. However the consequences of “Dutch disease” effects are limited by the low dependence of Brazil on external markets³. In practice, the benefits of oil production in the long run may be even higher if the effects of an appropriate recycling of oil revenues were taken into account.

8.3.3 Domestic oil intensive or low carbon pathways: multiple equilibria?

If one consider now that oil production will reach the level of the reference plan, one key question is to assess the implications of alternative strategies of using the oil resource - between domestic use or exports - as part of a broader domestic fuel policy, in order to reach simultaneous macroeconomic, energy and climate objectives. *OIL int*, *LC* and *LC+eff* scenarios illustrate possible alternative pathways to *REF* scenarios based on contrasted tax and energy efficiency policies.

First of all *OIL int* scenario is based on a fined-tuned general oil fuel subsidy, entirely financed by public deficit, which especially leads to maintain ethanol demand (anhydrous and hydrated) to current level in 2030 according to market conditions, that is around 32 billion liters. In this view, from 2015 to 2030, the growth of fuel demand for light duty vehicles is entirely supplied by cheaper gasoline partly imported but mainly produced in new domestic refineries. For heavy vehicles, the blending mandate of biodiesel induces the same biodiesel demand as in *REF* (around 6.5 billion liters). Cheaper oil fuels also expand in others sectors and weaken efforts to improve energy efficiency compared to *REF*, in the transport sector especially. Conversely, a carbon

³Exports only represents less than 13% of GDP in our *REF* scenario compared to more than 26% currently in France for instance

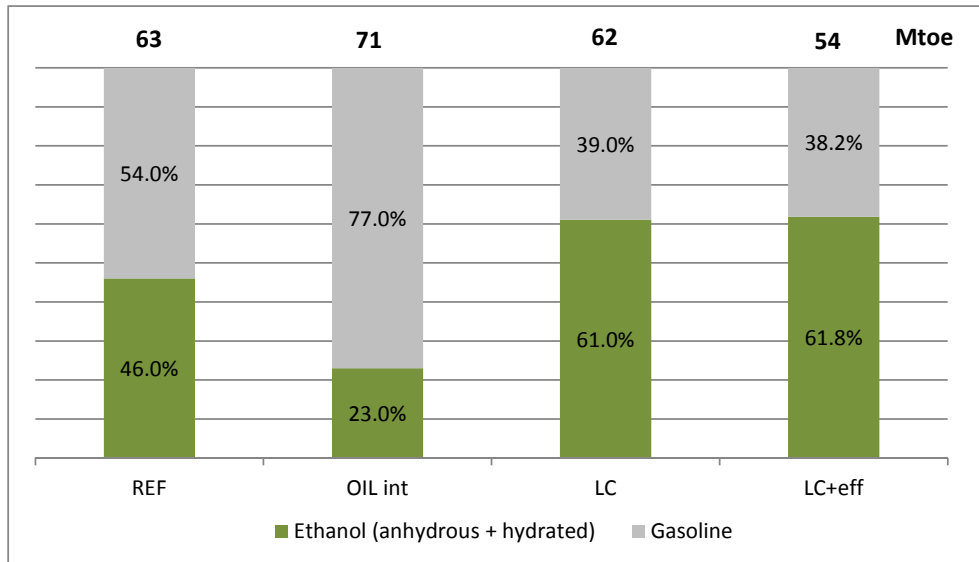
tax is applied on every end-use energy sectors in *LC* and *LC+eff* scenarios on top of the fuel taxation of *REF* scenario in order to reach new climate goals. In *LC* scenario, the carbon tax level of US\$70/tCO₂ is chosen to imply a reverse situation for light duty vehicles compared to *OIL int*: the growth of fuel demand beyond 2015 is supplied by ethanol only (hydrated ethanol mainly) and the demand for gasoline stabilizes at the 2015 level roughly until 2030. Eventually, a 15% biodiesel blending mandate implies a final biodiesel demand of 11 billion liters in 2030 in *LC*.

Figure 8.5a shows the result of the simulations about the level of fuel demand for LDVs and the market shares of gasoline and ethanol in the four scenarios. One can first observe a net opposite evolution of the energy efficiency between *OIL int* and *LC+eff* compared to *REF*. The only slight decrease of fuel demand in *LC* comes from the high substitutability between ethanol and gasoline and the constraints to vehicle efficiency improvement without dedicated policies. As for fuel mixes, stopping ethanol expansion in *OIL int* yields an ethanol market share below 25% in 2030⁴. Conversely, expanding ethanol results in more than 60% market shares of that fuel in *LC* and *LC+eff* scenarios, which would be a new high in Brazil history. Figure 8.5b shows the impact of alternative biofuels stall or higher expansion in the overall transport sector according to the scenario, taking into account the relative expansion of biodiesel beyond ethanol. One can see that the share of biofuels does not exceed one third even in most ambitious scenarios due to the more limited potential of biofuel penetration for heavy vehicles.

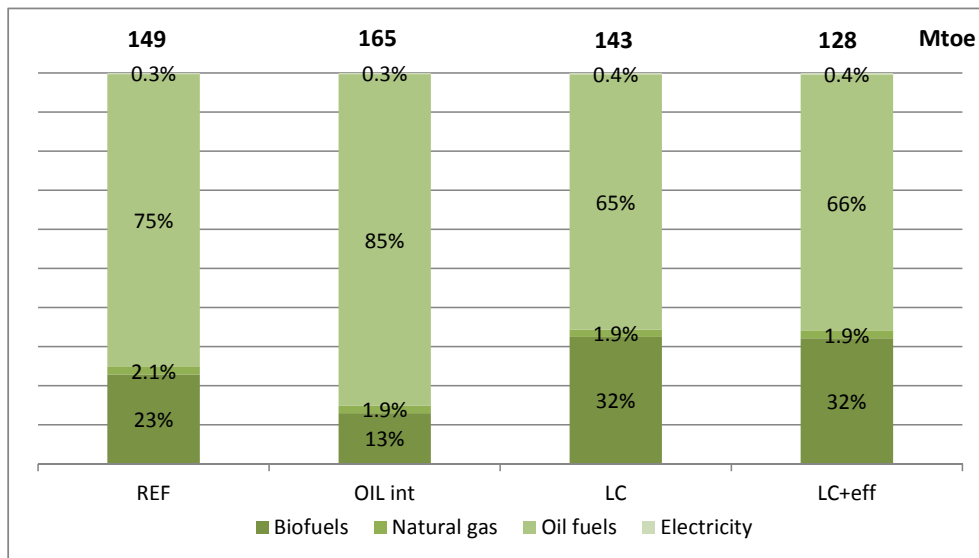
Enlarging the picture to the global energy system, fig. 8.6 shows the results of each scenario about the global final energy mix and demand level. One first thing to note is the higher impact of the carbon tax on the relative decrease of total final energy demand compared to what happens on the transport sector alone. It reflects the fact that efficiency gains in industry are more responsive to carbon price signals than in the transport sector. Concerning energy mixes, results show that the accommodating oil tax policy in the long run in *OIL int* leads the share of oil fuels to roughly return to its 2005 level on the one hand, and a significant fall of global bioenergy demand ratio on the other, below historical records (around 20%)⁵. In *LC* and *LC+eff* scenarios on the contrary, the fall of domestic oil fuels and others fossil fuels shares is accentuated compared to *REF*, to the benefit of low carbon electricity and bioenergy. Energy efficiency gains in transport sector in *LC+eff* intensifies specifically the global fall of oil

⁴The underlying reality could correspond to something between a situation where the largely dominant flex fleet of light vehicles would consume gasoline C only with a 25% blending mandate of anhydrous ethanol and a situation where a sizable part of the fleet remains gasoline cars consuming pure gasoline A.

⁵This is consecutive to abandoning traditional biomass to which adds the stall of biofuels and industrial biomass expansion.



(a) Fuel mix - Light duty vehicles



(b) Fuel mix - total transport sector

Figure 8.5: Fuel mix - transport sector

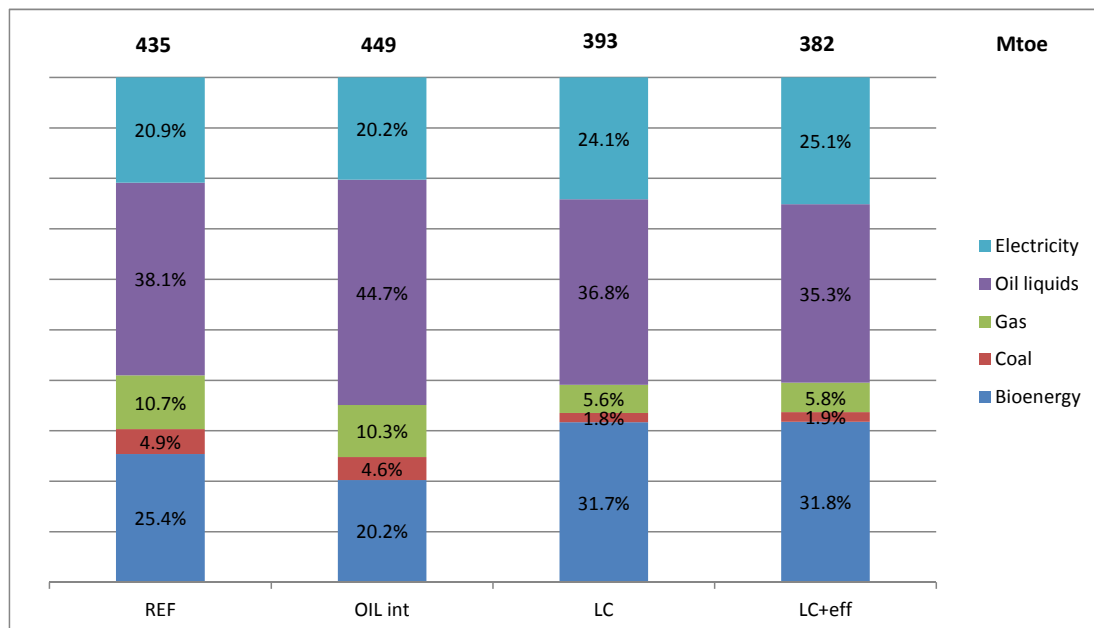


Figure 8.6: Final energy by source

fuels.

Eventually, fig. 8.7 shows the ultimate results of the different scenarios in terms of the endogenous crude oil balance. Starting from the same 5.5 mb/d realized oil production in 2030, scenarios illustrate very contrasted pathways about the usage of the oil resource between domestic and external markets. In the *REF* case almost half the production is exported, whereas 22% less exports are realized in *OIL int* (2 mb/d) and 64% of oil production is directed to domestic markets. Conversely, *LC* and *LC+eff* scenarios significantly increase the share of exported oil to reach 3.1 mb/d in *LC+eff*.

Results thus show that the alternative fuel and carbon tax policies and energy efficiency measures in transport sector yield very different energy profiles in 2030 for the transport sector especially but also for the global energy system and the domestic oil balance. Furthermore it remains to assess the environmental and macroeconomic implications of the different scenarios, which is a central output of the present work. This will make it possible to identify possible synergies and/or trade-offs between domestic climate targets on the one hand, and economic objectives on the other, considering that in any case the oil resource will be explored as planned. One clearly understands the policy issues: if maintaining below market oil fuel prices provides significant economic benefit in the long run and conversely, if low carbon pathways create a major

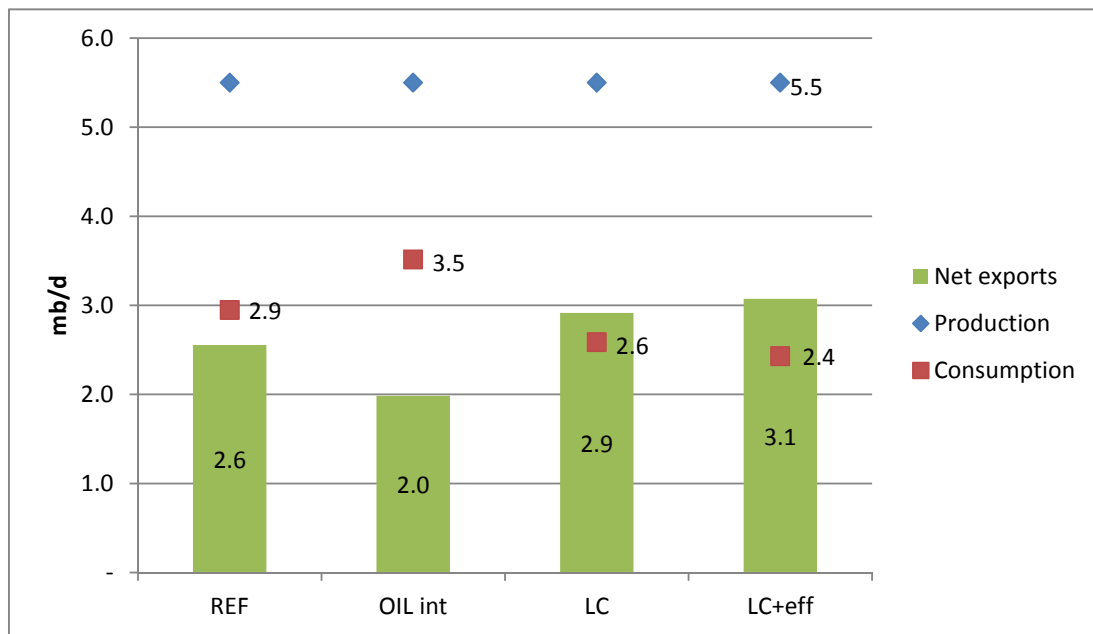


Figure 8.7: Oil balance

economic burden, it could be a serious impediment to further climate action. On the contrary, there could be reasons to prefer a low carbon pathway for economic issues outside climate considerations.

Figure 8.8 shows the result of simulations about the level of total CO₂ energy emissions and the deviation of the real GDP compared to *REF* scenario. First of all, as expected, the levels of emissions are very contrasted between the different scenarios and consistent with the contrasted energy profiles: *OIL int* and *LC+eff* scenarios yield respectively 12.3% more and 26.9% less emissions than *REF* scenarios. However, and this is a critical point, aggregated GDP implications are small. Imposing low oil fuel prices only yields a 0.72% higher GDP compared to the reference in the long run, whereas implementing a US\$70/tCO₂ carbon tax on final energy uses implies a small GDP drop of 0.87%. In addition, complementary energy efficiency policies in the transport sector yields a ultimate 0.57% higher GDP in *LC+eff* scenario compared to the reference. Therefore, these simulations illustrates as such the possibility of “multiple equilibria” characterized by similar GDP levels but with very contrasted energy emissions content (+54% CO₂ emissions in *OIL int* than *LC+eff*).

Beyond the figures, the real insights come from the further understanding of the macroeconomic mechanisms underpinning this phenomenon of multiple equilibria. To do so, we show the detail of the macroeconomic outputs of the different scenarios

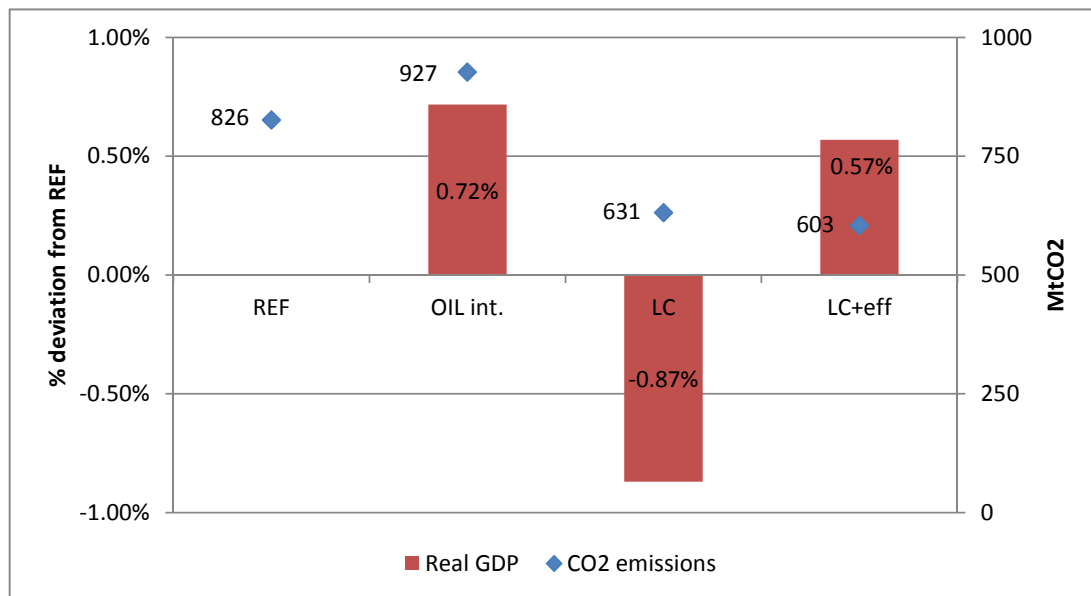


Figure 8.8: CO2 emissions and real GDP deviation from *REF*

in table 8.3. It also enables to highlight the possible diversity of economic structure beyond aggregate GDP. Globally, as for the macroeconomic impact of the oil production level studied in section 8.3.2, the ultimate impact in the long run of the alternative tax and energy efficiency policy packages on GDP, mainly results from the interplay between (i) the domestic economic structure, (ii) the trade constraints and (iii) domestic labor markets. For each alternative scenario, moderation effects do bring the GDP back to *REF* level. Starting with the *OIL int* case, the low fuel oil prices does spread in the economy and drives the general level of prices down, which has a double direct effect: it increases global final demand of goods (households demand through higher purchasing power and net exports through better competitiveness) and real wages. Therefore, the system should ultimately balance with higher employment (consistent with higher real wages in a wage curve formulation of labor markets) and lower labor intensity (substitution away from more expensive labor) of production leading to sizable higher GDP. However, the lower energy efficiency in the transport sector (consecutive to weaker efforts in a low energy price context) is a first moderator of the expansion of low fuel prices. But the key moderating effect comes from the constraints on the trade balance and the level of oil exports. The lower level of oil exports resulting from higher domestic consumption in the *OIL in* case and considering total

	REF	OIL int	LC	LC+eff
CO ₂ energy emissions	826	927	631	603
CO ₂ energy emissions (% REF)	-	+12.3	-23.6	-26.9
Real GDP (% REF)	-	+0.72	-0.87	+0.57
Unemployment rate (%)	5.22	5.23	5.09	4.61
GDP deflator	1.26	1.23	1.31	1.33
Investment rate (% GDP)	20.0	20.0	19.9	19.8
Agro-industry exports (index)	1.97	2.02	1.90	1.87
General industry exports (index)	2.04	2.09	1.97	1.96
Services exports (index)	1.88	1.93	1.82	1.78
Trade balance (% GDP)	1.0	0.7	1.0	0.8
HH real expended income (% REF)	65.7	+0.7	-0.6	+1.7
Average real wage (outside productivity effects - index)	1.00	1.01	0.99	1.02
Oil export revenue (% GDP)	2.3	1.9	2.5	2.6
Public deficit (% GDP)	3.26	3.58	3.29	3.37

Table 8.3: Macroeconomic results of scenarios

oil production as fixed, drives the domestic price down to balance external trade and the domestic price index adjusts with the decrease of average nominal wage. The drop of nominal wages further moderates the employment effect (resulting in no employment improvement with a 5.23 % unemployment rate) and limits the increase of the real wage to 1% compared to *REF*, which also moderates the increase of apparent labor productivity. It ends up with a small higher GDP compared to *REF*. These moderation effects from energy efficiency and trade mechanisms just work the other way around for *LC* and *LC+eff* scenarios. In the *LC* case, the increase of oil exports consecutive to the fall of domestic oil consumption, drives the price index up which pulls nominal wages up and limits the fall of real wages consecutive to the negative shock due to the carbon tax. Increasing nominal wages enables to increase employment (through the constraints of labor markets embodied in the wage curve), and to limit the decrease of apparent labor productivity and finally to limit GDP losses. Eventually, the complementary policies on energy efficiency in the transport sector in *LC+eff* amplify the former mechanisms with even more oil exports (due to even less domestic oil consumption) and a lower carbon tax burden due to better energy efficiency. Finally, this analysis makes it possible to clearly understand the key role of the trade constraints on driving the domestic price index according to different levels of oil exports and the interplay with labor markets through wage-employment relationships and the labor content of production to yield the ultimate level of GDP.

Beyond GDP considerations, the closer comparison of *OIL int* and *LC+eff* outcomes reveals very different underlying economic structures beyond contrasted energy and carbon content for similar GDP levels. It further enables to highlight key synergies and trade-offs about several key components of public policy beyond climate issues: employment, households purchasing power, competitiveness and public finance. First of all, the low carbon pathway seems to be the best route to favor employment with 825 thousands additional jobs in *LC+eff* scenario compared to *OIL int* scenario. In addition workers are more concentrated in more labor intensive and less capital intensive sectors (bioenergy vs oil sectors for instance). Together with slightly higher real wages, it also provides global higher households purchasing power and welfare. This interesting result can be counter-intuitive at first and results from taking into account whole macroeconomic interactions in the long run. The short term idea to maintain low oil fuel prices to maximize households purchasing power may not be the best strategy in the long run to reach that goal if a decrease of nominal wages offsets the initial positive shock on prices. Furthermore, the apparent strength of *LC+eff* scenario in terms of households welfare, is in the meantime significantly detrimental to general competitiveness compared to the *OIL int* case. *LC+eff* scenarios actually yields more than 6% less exports from the global industry with a 8% higher domestic price index. As in section 8.3.2, it illustrates a phenomenon of “Dutch disease” through the debasement of terms of trade which is one downside of up-scaling oil exports. Finally, imposing artificially low oil fuel prices through specific subsidy in *OIL int*, obviously comes at cost and degrades public deficit.

8.4 Conclusion

This chapter analyses the energy, climate and macroeconomic implications of alternative energy and climate policy scenarios in Brazil until 2030. The goal is to feed the debate about the issue to manage the oil-climate paradox in Brazil in the medium run while promoting dynamic economic development.

The results first show that exploring pre-salt oil reserves with the pace indicated by up-to-date energy plans, may yield significantly higher GDP, employment and households welfare than a situation where Brazil would leave the bulk of the resource under the ground. However, the size of the net economic benefit in the medium run (2030) is highly uncertain and depends on key macroeconomic mechanisms including trade and labor markets. The economic benefits of pre-salt exploration may be higher in practice if appropriate recycling of oil revenues is implemented and targets education and health. In addition, significant structural changes may happen together with

“Dutch disease” symptoms and the weakening of global competitiveness impacting the manufacturing industry especially, which is more dependent upon external trade. That’s why complementary policies may be needed to support key exposed industries. On the whole, the economic growth would be more driven by domestic markets (final consumption and investment) with a higher share of services in GDP.

Furthermore, if Brazil does not intend to ignore the possible economic manna of pre-salt, a key issue is to understand what would be the best allocation of oil resources between domestic and external markets to reach simultaneous climate, energy and economic objectives. Our results support the idea that the official plan until 2030 to further decarbonize the domestic energy system and export the bulk of additional crude oil, is by far the best way-out to the oil-climate paradox and makes it possible to reconcile main climate and economic objectives in the medium run. Although recent years illustrate an apparent tension between climate and economic objectives, as shows the short run temptation to subsidy oil fuels to favor purchasing power, our simulations in the medium to long run support the possibility to reconcile climate and economic goals within a low carbon pathway. Concretely, simulations shed light on the possible existence of “multiple equilibria” as alternative pathways with similar GDP levels but contrasted carbon contents. Analyzing the underlying macroeconomic mechanisms highlights key moderation effects linked to energy efficiency and trade effects. In addition, the short term motivation to favor purchasing power with low oil fuel prices may not be the best economic strategy in the longer run because of the adverse effect of lower energy efficiency and lower nominal wages, beyond the degradation of public finance. Conversely, the low carbon pathways based on carbon taxation and specific energy efficiency measures in the transport sector, yields higher employment and households welfare. However, these positive outputs come at the cost of a significant fall of general competitiveness which would have to be carefully managed for manufacturing industry especially. Eventually the low carbon pathway appears to be the best way forward with the bulk of new found oil being exported. This is also consistent with a global least cost approach of mitigation because Brazil has an important domestic potential of decarbonization at low cost with the penetration of biofuels in the transport sector especially.

Conclusion

The end of this thesis is contemporaneous with the signing of the first universal climate agreement, which sets nothing less than the objective to reach zero net GHG emissions by the end of the century and to peak emissions as soon as possible. To meet these objectives, the new climate architecture is based on the articulation of nationally determined commitments (NDCs) for the medium run in a “development first” perspective. However, everything remains to be done and commitments need to be translated into concrete action plans and will need to be strengthened in a close future to keep a chance to meet the global target in the long run. The Paris agreement may also be a turning point in the research agenda, as the insights provided so far by energy-economy and integrated models might not suffice in this new context to support climate change mitigation policy-making. The major contribution of economic modeling to help designing and assess low carbon strategies may still be ahead. This thesis has sought to clarify some of the methodological challenges behind these turning points on the one hand, and to contribute to the specific policy debate about the low carbon transition in Brazil on the other.

Chronologically, our work has begun with the construction of the first version of the IMACLIM-BR model to study the implications of climate policies in Brazil. These efforts fit into the continuity of the development of innovative modeling tools which has happened at CIRED for the last two decades, sometimes in a significant departure from existing approaches. The further need to put in perspective with existing practices the hybrid approach at the core of IMACLIM models, led us to explore the state-of-the-art modeling toolbox with a focus on models internal visions, implicit assumptions and areas of competence. In this view, we started by performing a methodological assessment of energy-economy hybridization issues in CGE models (chapters 3 and 4). It eventually led us to attempt a broader methodological clarification of state-of-the-art integrated modeling (chapters 1 and 2) which has been conducted in parallel to the empirical studies and which is finally reported at the beginning of the present document.

We retain two conclusions from chapter 1. First of all, there is a gap between the quantitative insights provided by global integrated models and the framing of mitigation issues, with special respect to economics and sustainable development. We have highlighted four issues that are insufficiently addressed: (i) the implications of alternative economic development patterns (economic structure, consumption patterns, location patterns, infrastructures, etc.) on GHG emissions trajectories and the dynamics of final energy demand; (ii) the alignment of climate and other socio-economic objectives in a second-best world; (iii) the short to medium run transition issues (and the barriers that lead to delayed action) and the conditions to bifurcate towards low carbon development pathways; and (iv) the rationale for policy packages at different time horizons and the interplay between carbon prices and other policy levers (fiscal reforms, finance, norms, non-climate policies, etc.). The second conclusion is that existing model diagnostics and taxonomies are not sufficient to characterize the diversity of models conception of energy-economy transformations. So-called model diagnostics only characterize the aggregated behavior of models with a small number of indicators and usual model taxonomies struggle to inform the diversity of recent approaches based on the hybridization of historical modeling paradigms. Therefore the areas of relevance of state-of-the art models remain blurry and it is difficult to clearly identify to what extent some issues remain insufficiently addressed because of remaining gaps in model conception. Understanding these aspects is a prerequisite to improve models and their contribution to the dialog with policy-making.

Chapter 2 aimed to make a step in this direction. Based on a painstaking analysis of the models reported in IPCC AR5, it formalizes and details a *guide* for integrated models based on their internal vision about energy-economy transformations in the context of the low carbon transition. The characteristics of this vision ultimately determine the area of relevance of a model in assessing energy-economy transformation pathways. Our guide characterizes models along three axes: (i) the type of *interdependence* represented as the “snapshot” of the system modeled at each point in time, especially characterized by the type of inter-linkages between the energy system and the broader economy, (ii) the *transformation drivers* of the production frontier embodied by the growth engine and technical change and (iii) the *transition dynamics* which yield the achieved pathways through the interplay between technical constraints, economic behaviors and market forces. Finally, the nature of the computed transformation pathways results from the interaction between these three dimensions. In practice we retain that models mainly differ (i) in the nature of the interdependence between energy sectors and the broader economic structure and (ii) about transition dynamics with the bulk of models representing technical transitions at first best economic equilibrium.

When used in model intercomparison studies, integrated models also tend to be reduced to a common denominator to be able to simulate the same scenarios across the set of models chosen. It finally leads to overlook critical dimensions of policy debates such as about the environment - economic development nexus or transition issues in a second best world.

It is true that development patterns or transition issues are crucial but more regional and national policy concerns, which could justify to treat them in a simplistic manner or even overlook them as second-order issues in assessing global transformation pathways. But then the question would remain about the global - regional articulation and the relevance of down-scaling the information of global assessments at the regional level. In addition, if some issues are of first-order importance in driving regional transformation pathways, they can not reasonably be overlooked in global scenarios. In fact, analyzing low carbon transitions at regional vs global scales is maybe more a question of *detail* than a question of the *nature* of the mechanisms governing transformation pathways. The choice of the level of details and depth of the down-scaling in global assessments is else constrained by computation capacities and the need to control model behavior. Whatever it might be, in practice regional and global energy-economy models are based on the same modeling paradigms and many regional or national studies are carried out with multi-region global models. Finally our model guide applies to both global and regional models.

The second step of the methodological contribution of the thesis narrows the focus on multi-sector CGE models and on the issue of energy-economy hybridization in these models. Multi-sector models provide a more comprehensive treatment of macroeconomic interdependence, non-energy sectors and structural change but have been historically criticized for their lack of technical realism. In the last two decades important efforts have been carried out to embark engineering based representations of technical systems in multi-sector CGE models to improve the dialog between engineers and economists and yield more credible climate policy assessments. Chapter 3 remedies the lack of technical synthesis of these efforts and develops a typology of the existing approaches. We especially highlight the implicit assumptions and consistency issues behind each modeling track, which are not always made clear in published exercises. This is partly due to the priority given by modelers to numerical results and policy insights and less to technical and sometimes cumbersome issues - probably because of time constraints and space limits in publications, which are however crucial for the scientific process of hybrid modeling. We also conclude that the appropriate modeling approach depends on the study objectives and results from a trade-off between consistency and easiness of implementation.

Furthermore, we argue that one key prerequisite to build consistent hybrid CGE models is to work under a hybrid accounting framework based on the dual vision of economic flows both in physical units and money value notably for energy goods - the necessary condition to control the interface between economic and technical systems. Chapter 4 tackles the issue of combining energy and economic statistics to build benchmark hybrid databases for CGE model calibration. It quantifies how the way to combine available information taken from statistical records (energy balances, national accounts, etc.) has a non-marginal impact on the empirical description of the initial state of an economy, and therefore, on the energy policy evaluations drawn from hybrid CGE models of this economy. It concludes that the clarification of the initial empirical description of the energy-economic system is an overlooked aspect of CGE-based energy and climate policy analysis.

In parallel to the methodological exploration of integrated models, we have developed the *IMACLIM-BR* modeling platform to provide the empirical material of the thesis and contribute to the climate policy question in Brazil. Working at the regional level fits into the new climate architecture and the search to align mitigation and socio-economic objectives to define and meet nationally determined climate commitments. In this regard, our empirical contribution aimed at complementing the global scenarios previously examined and provide insights on the specific case of Brazil.

Chapter 5 introduces the Brazilian context and the specific challenges faced in the medium run at the climate - energy - economic development interface. This makes it possible to identify two relevant focuses of research to be developed in the following chapters in the context of the low carbon transition in the medium run: (i) the macroeconomic and distributive implications of carbon tax policies and (ii) the articulation between climate and oil policy. We also sketch the specifications for a relevant modeling tool.

The *IMACLIM-BR* model rationale and detailed features, which are reported in chapter 6, build upon both the *IMACLIM* heritage and our own maturation about methodological issues. It results in a hybrid CGE model grounded on a hybrid accounting system which emphasizes the general equilibrium interdependence between energy and non-energy sectors, economic agents including trade, and key second-best aspects of the Brazilian economy in the medium run including labor market rigidities and imperfect markets of goods. The comparative statics framework makes it possible to generate consistent energy-economy projections while abstracting from controversies on dynamic effects.

Chapter 7 sought to provide new insights about carbon tax policies in Brazil, to

reach up-to-date energy-related mitigation goals until 2030. In a second-best world, the welfare impacts of a carbon tax are not proportional to abatement costs, and the recycling option of carbon revenues is a key determinant of the macroeconomic and distributive implications of the carbon tax policy. Our work maps some possible synergies and trade-offs between mitigation and other socio-economic objectives according to different carbon tax policies. We do so through a variant analysis about both carbon tax policy options and key controversial parameters about technical constraints and the functioning of the economic system to map plausible futures. Our findings can be summarized in three points. First, energy-related mitigation objectives (close to recent INDCs) can be met at reasonable welfare costs with an appropriate carbon tax policy, even if this carbon tax is decided unilaterally. Second, the macroeconomic mechanisms governing trade and labor markets are at least as determinant as technical constraints to the formation of mitigation costs. Third, Brazil has a limited potential for double dividend through decreasing existing tax distortion (like payroll taxes) because it has low labor-energy cost ratios and limited trade openness in addition to being a fossil fuel producer and net exporter. Conversely, recycling carbon revenues with appropriate social transfers enables to limit welfare losses and to reduce income inequality despite implying significant losses of competitiveness. Finally we conclude that an appropriate carbon tax policy in Brazil should emphasize social transfers while protecting sectors exposed to trade competition. This conclusion is also dependent on the hypothesis about the industrial future of Brazil and the degree of future trade openness.

Eventually chapter 8 studied the articulation between energy-related domestic climate objectives and the development of the oil sector in Brazil to solve the “oil-climate paradox”. It highlights two main findings. First, exploring pre-salt oil reserves may provide a significant economic boost until 2030 with higher economic growth, employment and households welfare. However, the economic dividend may be unequally shared, with significant structural changes towards domestic consumption and sizable “Dutch disease” symptoms could happen with competitiveness losses of the manufacturing industry. We especially highlight the crucial role of trade and labor market mechanisms in shaping the results. Second, the official plan to decarbonize further the domestic energy system and export the bulk of additional crude oil, may be by far the best way-out to the oil-climate paradox and makes it possible to align main climate and economic objectives in the medium run. We show that a domestic low carbon pathway based on biofuels expansion and energy efficiency gains (in industry and transport sectors) could yield higher employment and households welfare than an alternative domestic oil intensive trajectory with more limited energy efficiency.

The slightly higher welfare of the low carbon pathway comes at the price of a loss of competitiveness of the manufacturing industry. This effect could be offset if the rest of the world would implement similar carbon constraints which would restore part of Brazilian industrial competitiveness.

At the end of this work, we are conscious that our empirical analysis on Brazil is still far from providing operational guidance to monitor the transition towards a low carbon economy. We only hope to have proved the advantages of working with a hybrid modeling architecture to generate consistent energy-economy projections while taking into account important second-best aspects of the economy in the medium run. Our goal has been to explicit key macroeconomic mechanisms at play with economy-wide climate and energy policy tools to manage the articulation between climate, energy and other economic policy objectives in the specific case of Brazil. This first step opens the way for further research to sharpen the understanding of the transition towards a low carbon economy in Brazil. We identify at least three intertwined research avenues:

- A model relying on comparative statics as the one used in this thesis makes it possible to analyze mechanisms of interdependence at a given time horizon and to compare cross-sections of economic pathways. It is already well suited to articulate in the same framework information from energy, transport or else urban models and to clarify the implications of the set of assumptions in the medium run. Nevertheless it comes to assume that the underlying temporal dynamics are situated on a smooth pathway and no departure from a smooth transition can be taken into account. Understanding the inter-temporal aspects of energy-economy pathways is however crucial to assess low-carbon transitions. This goes beyond the pure intertemporal optimization problem with perfect foresight - which is somehow reduced to a question of discount rate - to include second best aspects such as imperfect foresight coupled with capital inertia. One important question for emerging economies like Brazil is for instance that of the temporal dynamics of infrastructure deployment for power generation, oil exploration or transport services and the macroeconomic implications linked to investment dynamics. A recursive dynamic model like of the IMACLIM-R type is well suited to explore these questions and to understand the pathways effects at different time horizons. One other key question is that of the *triggering* of low carbon transitions by means of appropriate financial mechanisms, which involves specific variables of the short run. A dynamic model articulating short

run and long run mechanisms - beyond current IMACLIM-R framework - is thus required to address these issues.

- Our empirical studies focus on a medium run time horizon (2030) when major technical breakthrough and structural changes are less likely to be of significant importance. A second research avenue thus concerns the analysis of technical change in the longer run and the interplay with broader structural changes. Technical change in the energy supply, conversion and end-use sectors is a fertile topic which still needs to be explored in the specific case of Brazil with the penetration of advanced technologies such as renewable power technologies, third generation biofuels or else electric vehicles. However the literature is more scarce about the co-induction mechanisms between technological change and broader structural changes which are else crucial in the context of emerging economies. The rise of income and decrease of inequalities will frame new consumption patterns which will interact with technical progress. For instance, sustainable urban planning added to the development of efficient transport infrastructure will be key drivers of the demand for mobility. Finally, a more theoretic issue still unresolved in the climate policy literature is that of the feed-back of climate policies on total factor productivity along deep decarbonization pathways. The source of total factor productivity largely remains the "*dark matter of economic growth*" (Grubb, 2013, chapter 11) and there is an issue to understand better the contribution of climate policies in its evolution.
- A third research avenue targets a finer understanding of the articulation between climate change mitigation and other social and economic objectives. A first crucial topic for Brazil are the implications of climate policies in terms of income distribution and possible inequality reduction. We have attempted a step in this direction but the analysis should be refined towards better understanding the sources of income and the patterns of expenses of various households categories including income groups but also other types of distinctions such as urban vs rural population. One important question is also the feed-back on household's saving rates. A second issue are the relationships between climate policies and labor markets at different levels such as: (i) the question of "green" jobs and to what extent climate policies can increase employment and in which sectors, (ii) the question of the skills supply for the low carbon transition and (iii) the implications of climate policies for informal labor markets. Finally, the analysis could be extended to broader Sustainable Development Goals (SDGs) to design sustainable low carbon strategies.

We will conclude this thesis on the need to better articulate the analysis of mitigation issues between regional and global scales. The climate architecture based on national commitments commands country or region specific analyses about the conditions to bifurcate towards low carbon economies. In this view, a new type of studies has recently emerged based on the aggregation of regional projections to provide global scenarios⁶, as opposed to global assessments generated with global models. The low carbon society (LCS) modeling studies ([Kainuma et al., 2012](#)) are other examples of how it is possible to disaggregate a global climate objective into region specific roadmaps to align climate and development objectives. Finally, there is a key issue to articulate the different types of studies and to determine the priorities of issues to be addressed at the different scales, in consistency with the selection of the relevant modeling tools.

⁶See ([SDSN and IDDRI, 2014](#)) for instance.

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Appendices

A Appendix - chapter 2: a guide to integrated models through building blocks

A.1 Towards the integration of a few building blocks

This section specifies the vocabulary used and the building blocks assessed to describe the models in order to build an **updated taxonomy based on technical contents of models**.

Some of the building blocks already appear in traditional taxonomies, and therefore an explanation of why such building blocks as growth base growth engine, model scope or trade modeling is unnecessary. For some others, such as activity levels, economic choice or short term maladaptation, an exposition of the reasoning provides a justification. To understand our choice of building blocks, let us examine fig. A. When assessing climate change mitigation, one central tool is the Kaya decomposition of the drivers of emissions. This decomposition usually takes the form of eq. (A-1), where the studied quantities consist of aggregated values.

$$CO_2 = POP \times \frac{GDP}{POP} \times \frac{FE}{GDP} \times \frac{PE}{FE} \times \frac{CO_2}{PE} \quad (A-1)$$

However, this simplified view, while very useful, hides a more complex dynamics. For instance, the structural change should lead to understand those drivers per sector, and then perform a summation by sector to understand the aggregate value. Another example is that these indicators do not inform on the nature of appliances. In particular, there exist an implicit assumption of appliances between final energy and useful energy, since FE/GDP employs final energy instead of useful energy. That is why we want to provide the detail of the chain of interdependencies and drivers illustrated in fig. A.

In addition, the view of the overall picture in fig. A is often reduced in models. Traditional bottom-up models tend to focus on the boxed part from Activity levels (pkm, $m^2 + mtoe/m^2$) to primary energy, skipping the economic dynamics. Such a view is illustrated by the type of results they aim at: energy balances, that can be illustrated in fig. B. Traditional top-down models focus on GDP formation through the sectoral summation of Activity levels (quantity index), where energy is an input factor. Their reasoning is founded on the Social Accounting Matrix (see table A for a schematic SAM) representing the agents' and sectoral mutual exchanges.

As a consequence, many of the building blocks derive from this expanded Kaya decomposition (fig. A). Table B describes the building blocks we used. Therefore, the

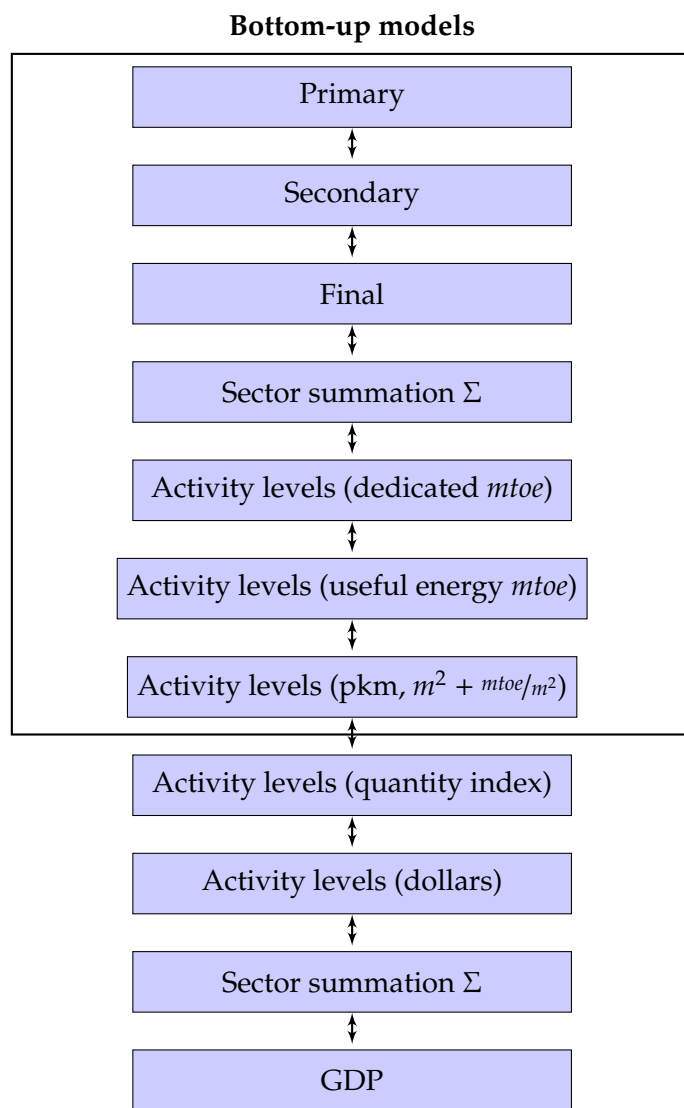


Figure A: Expanded Kaya decomposition

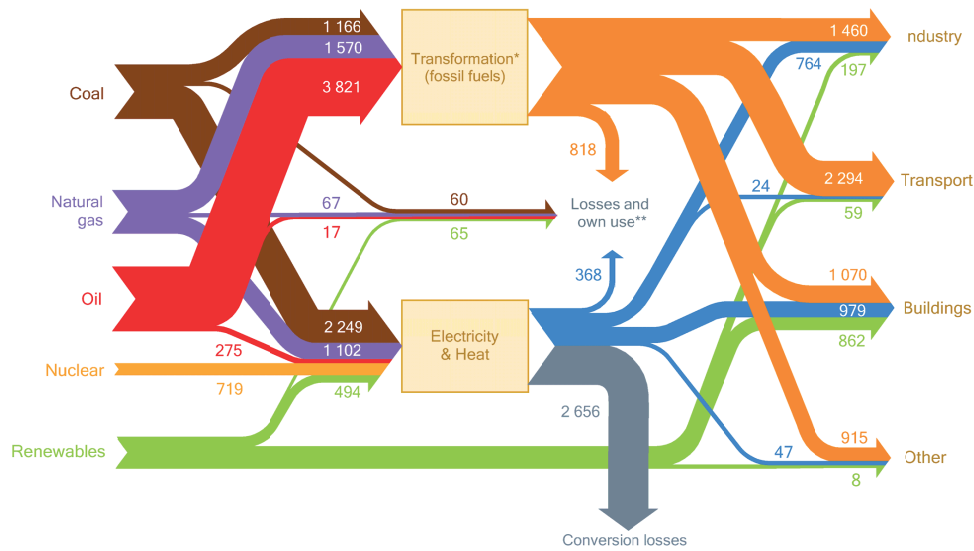


Figure B: Global energy balance (Mtoe) from IEA and OECD (2012)

Receipts	Expenditures						
	Activities	Commodities	Factors	Households	Government	Capital	Rest of world
Activities	Domestic sales						Exports
Commodities	Intermediate inputs	Private consumption			Government consumption	Investment	
Factors	Value added			Allocation matrix		Government transfers	
Households				Income taxes			
Government	Indirect taxes	Import tariffs		Income taxes			
Capital				Private savings	Government savings		Foreign savings
Rest of world	Imports						

Table A: Schematic Social Accounting Matrix

SET OF BUILDING BLOCKS	BUILDING BLOCKS
	Scope
Bottom-up aspects	Primary energy supply Secondary energy supply Final energy demand (from activity levels) Capacities
Top-down aspects	Activity levels (structural change) Corresponding units of energy services Markets of goods Markets of factors (K, L) Trade
Choice representation	Decentralization level Modalities (agents' program) Information level (foresight)
Growth engine	Base engine Technical progress Inertia of capital at the macro level Short-term maladaptation representations
Evolutionary factors	Energy-specific technical change Consumption patterns

Table B: Building blocks

first three sets of building blocks represent the Kaya decomposition blocks: overall scope, bottom-up blocks and top-down blocks. These three sets allows to draw the picture of interdependencies present in the model. The animation of this picture relies on the three other sets of blocks: choice representation, growth engine and evolution factor. These dynamic blocks prove to represent the driving forces behind the evolution of the energy-economy-environment system. Transversally, we see that some blocks will affect the form of the transition dynamics, as the market equilibriums for goods and factors, the modalities and information of the choices.

For some models, building blocks will take the shape of model with theoretical background, while, for others, building blocks will refer to empirical tools. On the one hand, they resort to tools from the economic theory: growth models, Arrow-Debreu general equilibrium theory, Keynesian theory and partial equilibrium. On the other hand, they resort to applied tools from the applied modeling community: the SAM-based model toolbox, the CGE toolbox, the bottom-up model toolbox, the econometric model toolbox and the production function. Next, ?? defines the boundaries of each building blocks and provides a description of the various alternatives for each.

A.1.1 Scope

The scope of E3 models concerns the extent to which they encompass economic activities.

Some models only span **energy sectors**, with more or less extent. The scope for this type of models will be noted as En. The coverage goes from only one sector (such as electricity) to all energy sectors (from oil to electricity including gas, biomass, coal etc). Sometimes, the En models go as far as to represent related markets: for instance the markets including biomass, forestry and agriculture. For our purposes, it is still a partial view of the economy and the extent is still limited to energy-related markets.

Some monosectoral models exhibit an **Economy-Wide coverage with only one Composite good**, noted as EWC. Aggregating all goods into a composite good precludes the representation of the interaction between markets of differentiated goods. Also, the evolution of the basket of goods in the composite good is implicit and in any case not controlled for.

Usually, economy-wide multisectoral models split the composite good into several sectors by means of input-output tables and Social Accounting Matrices (SAM). These models will therefore be deemed **Economy-Wide with Interdependencies** between sectors (EWI). In EWI models, the evolution of the basket of goods as well as the interactions between markets of differentiated goods can be modeled.

However, some models disaggregate the composite good into multiple sectors without the interdependencies being modeled. In this case, the model does not rely on the Input-Output matrix contained within the SAM. We label those types of models **Economy-Wide with Disconnected sectors (EWD)**.

A.1.2 Bottom-up aspects: managing engineering-based information

A.1.2.1 The meaning of bottom-up

In a nutshell, a bottom-up model is aimed at representing explicitly technologies, also called activity analysis. Therefore, the goal is to paint a description with the viewpoint of the engineer: with values, units and mechanisms – whether technological or economical – as well as technological capacities. In this document, we call bottom-up a model that represents all of the four items in the bottom-up manner, which is described below.

The first salient feature of bottom-up representation is the **accounting in physical units**. For the energy models, this means that energy is counted in energy quantities, in a unit that belongs to the world of energy producers. For instance, energy flows are counted as *mtoe* or barrels (*bbl*) for oil, *mBtu* for gas, *tons* for coal or *MWh* for electricity. In contrast, in the economist accounting system everything is counted in monetary values. In particular, in the typical top-down model, energy volumes are derived from monetary flows by means of price indexes but not accounted for directly in physical units. Such volumes derived from monetary values are often referred to as “pseudo-quantities”.⁷ However, some econometric models dedicated to energy do report energy quantities in physical units (for instance [Kaufmann et al. \(2004\)](#) on oil markets, [Considine et al. \(2009\)](#) on shale gas markets), thus this is not a sufficient characterization of bottom-up models.

The second salient feature of bottom-up representation is the explicit description of **engineering costs**, for the modeled processes, whether production or consumption. As a consequence of accounting in physical units, these engineering costs are in physical units (*toe/\$* or *MWh/\$*). On the contrary, economic models often rely on costs shares, meaning the cost of one item over the total cost. This is the main channel for economists who are bottom-up modelers to communicate with engineers. Indeed, the expression of costs in their natural form allows for a ready exchange of information and discussion, when cost shares tend to add an extra layer of complexity to the discussion.

The third feature of bottom-up representation is the description of **mechanisms**

⁷ This issue of the accounting of volumes within models is extensively analyzed in the following chapters.

at the level of technologies. Bottom-up models attempt at describing the mechanisms actually happening at the level of using technology for producers or consumers, consisting of the substitution of energy carriers, the substitution of processes and the efficiency improvements. For producers, these mechanisms involve the production processes with energy inputs, losses and outputs in physical units for the available processes and monitoring their efficiency. This describes the transformation of primary energy into secondary energy, that can be further transformed and will be ultimately transported and distributed to be consumed as final energy. For final energy consumers (including industries, services as well as households), these mechanisms concern the translation of demand for activity levels (i.e., energy service in pkm , tkm , $^{\circ}C/m^2$. . .) into final energy demand through the representation of appliances. For some models, the use of “useful energy” in EJ or $Mtoe$ instead, albeit referring to the energy service, presupposes an interpretation inherent in passing from one to the other. Regarding energy, typical examples of phenomena that modelers try to represent include electricity load curve (both production and demand), the profitability of technologies based on infra-marginal rents, principle-agent problems (e.g., in the residential sector), oligopolistic behaviors. . . The choice of the portfolio of technology is made to abide by technical constraints and energy policies.

The fourth and final feature of bottom-up representation is the **tracking of equipments stocks under the form of machine capital**. This translates into the representation of **capacities** done in their physical units (toe/day or MW). In addition, the construction and depreciation of units is tracked over time: capacities are represented with capital vintages. Furthermore, each of these vintages can be specifically described and result from investment choices as described in the previous paragraph. [Jacobsen \(2000\)](#) makes the case for capacity vintages since they allow the representation of technology diffusion and efficiency improvement. For example, describing such mechanisms as the saturation levels for capacities allows the description of a varying speed the penetration of more efficient technologies. Also, variable efficiencies (with a given park) can be linked to utilization rates: the first units used are the more efficient, and as utilization rate grows, more and more old (and less efficient) capital is used. For electricity, [Jacobsen \(2000\)](#) found that the average fuel efficiency for electricity and heat vary by up to 20 % according to utilization rates. Therefore, tracking capital vintages enables the modeler to describe the inertia of machine capital, and thereby the physical constraints related to capacity limitations. For instance, tracking capital vintages for each technologies allows for the representation of short-term shortage (or on the contrary abundance), as well as the constraint of a maximum production in the instantaneous production (as opposed to the yearly aggregate value) or the hard

constraint of a limited potential (e.g., in hydro or wind power). In a nutshell, the bottom-up representation of machine capital is a discrete conception of capital with distinct vintages characterized schematically by embodied technologies, upper bounds of output and rates of utilization. This is to compare to the continuous, aggregated and monetary-based conception of capital in top-down production functions.

These four features together imply that bottom-up models allow for the description of embodied technology. Indeed, any engineer when presented with vintages capacities, invested in based on a technico-economic rationale, measured in physical units and engineering costs will recognize his own world. That is why bottom-up models are deemed to be able to describe explicitly technology, in an embodied manner since that technology is physically described by machine capital accounted for in physical terms. The main difference between bottom-up models will be the level of description of technologies, from one representative technology to describing every single one production (or consumption) unit.

A.1.2.2 Primary energy supply

Primary energy supply concerns the mining or exploitation of raw forms of energy before transformation to be used by consumers later on. Primary energy can be non-renewable (e.g., fossil fuels, uranium) or renewable (e.g., wind, solar, hydro or biomass energies). Therefore, primary energy supply deals with the activities of coal, oil and gas extraction, as well as biomass energies. Theoretically, wind, solar and hydro energies should be included as well, but are often dealt with power generation technologies since the mining of primary energy and the conversion to secondary electric energy are simultaneous.

The main issues to represent the mining of primary energy supply are the formation of rents and the strategic position of key players. These rents apply to all natural resources whose stock are subject to scarcity: mineral supply (including fossil energies), renewable energies (lands exposed to suitable wind or sun), land, etc. The differential rent (also called Ricardian rent ([Ricardo, 1817](#))) expresses the idea that the first resources to be used are the least expensive. Therefore, when more resources are needed, more expensive resources are mined, therefore giving a rent to the former less expensive resources (the price being equal to the marginal costs). Second, scarcity rents apply when a resource is demanded in greater quantity than can be produced, the excess demand brings about a price higher than marginal costs justify. Thus the difference is a scarcity rent, which can account for a lack of resources or a lack of capacities to exploit those resources. Finally, strategic actors can exact a rent from their consumers

when they have an impact high enough on the market of the commodity they sell. This is typically the case of oil-exporting countries, which form an oligopoly. Also, these rents often depend on the geopolitical context in which the resources are extracted.

In general, integrated models represent supply curves (quantity as a function of prices). Therefore, regional supply curves do not allow the formation of the Ricardian rent inside a region, but only between regions. In addition, most models deal with costs formation (costs in machine capital, resources, and wages). However, they do not assess the price formation (which includes profit, as rents, capital financing costs).

The emblematic topic to be discussed is the dynamics of the oil prices. The representation of oil prices dynamics is controversial and can prove very difficult. Might it be better to leave an exogenous supply curve from a dedicated model rather than modeling incompletely the mechanisms?

In our assessment, most top-down models represent **no bottom-up constraint** on primary energy supply (noted as “-”). That is the case of macroeconomic models as well as aggregated top-down models. Macroeconomic models do not rely on explicit underlying mechanisms but on the observations of the dependences between variables in the past. Some multi-sectoral top-down models however do include part of the mechanisms associated with primary energy supply. Most commonly, they will describe the scarcity rent by means of a fixed factor calibrated on recoverable resources. This fixed factor endowment decreases with cumulated consumption and thus can be seen as proxy to represent the remaining energy supply. This fashion in which top-down models describe rents is labeled as **Resources constraint** in our assessment (e.g., GREEN and WITCH). Some top-down models go further, and not only do they use a fixed factor, but they also calibrate elasticities on supply curves to have an accurate proxy of the cost of supply (e.g., EPPA).

Bottom-up models dedicated to a specific sector (such as oil production or shale gas) often aim at describing production process in a explicit manner, including investment decisions as well as exploitation costs. Examples include (McJeon et al., 2014; Cherp et al., 2013; Mohr and Evans, 2011; Egging et al., 2010; Holz et al., 2008). Bottom-up models that aim at encompassing all the energy sectors tend to use more abstract representations. The default manner is the description of resources recovery with **Extraction cost curves** (ECC). Some models add short-term supply constraints (e.g., MINICAM). Others add explicit capacities for oil, with mechanisms linked to geological constraints such as inertias in the exploration process and depletion effects. For instance, IMACLIM-R models inelastic oil supply with yearly maximal increase of capacities, in line with Rehl and Friedrich (2006).

The modality of primary energy supply representation determines the embodied

vision of energy resources constraints in the model around the availability of the resources, the costs involved, their market price - and the links with rents - and the resulting income distribution.

A.1.2.3 Energy conversion and secondary energy supply

Secondary energy supply covers the energy transformation from primary energy to secondary energy that can then be dispatched to the consumer to be used as final energy. This field mostly concerns electricity generation and petroleum products refineries.

Again, we find an explicit bottom-up approach, as the most extensive family of bottom-up models concern secondary energy supply. Here we will label as bottom-up **explicit** the models that include a representation of secondary energy supply that meets the four bottom-up criteria previously detailed: physical units, engineering costs, technico-economic rationale and accounting for producing capacities. This explicit description can be done at various levels of disaggregation and granularity. Of course, the original bottom-up models fit in that category with an explicit description. This technology explicitness will be extended to hybrid models incorporating a bottom-up submodel, since they will inherit this feature. The explicitness of bottom-up models (whether independent or within a hybrid model) translates into the **explicit description of the thermodynamics properties** of the energy system. The thermodynamic efficiency of energy transformation constitutes a key example of such properties.

One way to emulate bottom-up behaviors in top-down models consist in increasing the sectoral disaggregation so as to represent one type of technology per sector. In doing so, different types of capital stock can be distinguished, in terms of vintages and productive uses. The AMIGA model ([Laitner and Hanson, 2006](#)) thus disaggregate 200 sectors in the United States for a better representation of technology choices.

An alternative to bottom-up explicitness consists in modifying a top-down production function to incorporate data on technology and reach an "intermediate" level of bottom-up explicitness in the sense that not all bottom-up criteria are met. The most common way of doing so will be in expanding the top-down production function to not include directly the primary factors, but rather to build the production function as a nest of Leontief technologies that are substitutable. The usual aggregator of Leontief technologies is of the CES kind. In this case the CES nest will drive the choice between the various technologies, technologies described with Leontief production functions which employ primary factors. We call **CES-Leontief** this modeling technique. Sometimes, the CES is replaced by other production functions, such as logit production

functions in the SGM model. This modeling technique is a convenient way to introduce engineering information within a standard production function. However this representation keeps some key top-down features of the production function including: constant elasticity of substitution between technologies, the monetary metric of energy flows and a "continuous" representation of a monetary capital as opposed to machine capital with identified capacities and utilization rates. The comparison between bottom-up explicitness and the CES-Leontief representation is extensively detailed in chapter 3.

A.1.2.4 Final energy demand

Activity levels (the service provided by transport, heating or lighting, in $pkm, tkm, °C/m^2$) use installed appliances (analogous to production capacities in the case of secondary energy supply).

Another family of bottom-up models aims at depicting the uses of final energy. Modeling the investment, use and competition of these appliances is the core of this type of bottom-up model. Once again, the goal is to represent **explicit** technologies, so that the discussion with engineers be possible.

There is no real alternative to this bottom-up representation so far. That is why most top-down and even top-down-bottom-up hybrid do not account for the consumption side explicitly. In this case, these models will be labeled with "-" to denote that they do not address this issue with explicit bottom-up mechanisms. However, the issue will be dealt with top-down techniques and explained in ?? A.1.3.2.

Some models use a top-down approach linking activity levels to final energy. To do so, they use production functions such as **logit** or **CES** production functions. For instance, GCAM represents the technological choices with logit functions. With the CES paradigm, REMIND links final energy demand to an activity level indicative of the sector's demand evolution. WITCH does the same for non-electric energy.

System dynamics tend to use descriptive relationships, rather than mechanistic, linking the final energy demand to GDP, technology availability and costs.

A.1.3 The blurry articulation between final energy and end-use services: the difficulty to represent energy demand

A.1.3.1 The polysemy of activity levels

As we saw in fig. A, the notion of activity level is very blurry. While in principle, all the models are alluding to the level of activity of one sector that translates into the use

of energy, each model uses his own definition for how to measure it. The easiest way to see this issue is to examine the units in which activity levels are expressed:

- the output of the sector in extensive value in dollars, which can measure either value added or total production value,
- the output of the sector in some sort of quantity index (the number of cars or trains),
- physical units ϕ (such as tons of steel, pkm, or m^2),
- the dedicated energy that goes into one use, measured in *mtoe*, which consists of using final energy as a proxy,
- the useful energy in *mtoe* which measures the amount of energy available for one use.

Therefore, the identify of **multiple metrics for the same object** hints at a polysemous notion, which each model treats differently. The next section aims at clarifying the notion of activity level.

A.1.3.2 Activity levels (structural change)

Activity levels refers to the services provided by energy, either for consumers (such as lighting, heating or transport) or producers (transport, or energy needed in production processes). Aside from primary energy extraction, transformation into secondary energy and final energy usage in appliances, the main driver of energy supply and demand quantities is the activity levels. The change can refer either to substituting the type of uses in the same category (substituting the car to the train for instance) or to the creation of new uses (for instance for the increasing electronics consumption or the development of the service sector within the economy). The description of this driver is therefore essential in E3 models, since it is the main driver of energy demand.

In particular, the interplay between the weight of the different sectors in the economy constitutes is a corollary of the description of the various sectors demands. This interplay is often referred to as “structural change”. Structural change is fundamental in describing the transition of economies from developing to emerging to developed countries since the relative share of agriculture, industry and services will evolve accordingly. In addition, the transition of economies towards greener, more sustainable economies will also rely in part on this mechanism of structural change (replacing unsustainable products with sustainable ones, favoring green activities).

Existing E3 models have adopted several ways to describe the activity levels dynamics.

Some models rely on **econometric description** of the evolution of activity levels (ranging from bottom-up model such as WEM to macroeconometric models). This methodology is very interesting in the sense that it can describe accurately the current mechanisms at play today. The drawback of this strong point is that it can only account for the current mechanisms and may not account for shifts in consumption patterns.

Some bottom-up models aim at representing the use of energy to satisfy activity levels through equipment and appliances. More legibly, they represent the use of final energy according to activity level targets. These activity levels time series can be given as an **exogenous parameter**. These exogenous series can be altered with **own-price elasticities**, as is the case for the MARKAL model. These models will simply represent the changes in demand with an own-price elasticity, with the price formation being described elsewhere in the model (often a bottom-up model, where the cost will be assimilated to the price).

Alternatively, activity levels can result from functional relationships which usually depend on GDP and price. An option is the representation of mechanisms set up through calibration such as **logit sharing**, as for MINICAM. Another option leads to system dynamics models. Here the mechanisms are meant to be represented implicitly through functional relationships. For instance the one system dynamics model we study in depth (T21) represents **projections** depending on population, energy prices and costs, while independent of GDP and consumption patterns.

The picture is more blurry when discussing models with top-down modules. The easiest is in this case the more complex one: models with general equilibrium tend to disaggregate energy goods as far as necessary to grant each energy carrier and energy service a specific sector. In that case, energy services are produced with inputs of energy goods, such as transport or residential demand: we label those models **GE**. Energy inputs may be integrated in one energy good directly consumed to produce a composite good. The aim of the multisectoral models relying on SAM is exactly to represent effectively structural change by accounting for the relative weight of the different sectors in the economy. The models implementing any version of a general equilibrium fall in this category.

When the top-down model is monosectoral, the accounting framework is often in \$ and aggregated and leaves much room for interpretation. Two instances are thus possible. First, when only a composite sector is represented with a constraint on energy consumption through total energy system costs (and optionally investments), the model does not represent explicitly activity levels. Total energy demand is then

directly linked to the composite sector output: that is the case of **monosectoral** models. In this case, energy can be one aggregated good (such as in RICE) or disaggregated further (such as WITCH or MERGE). The second option is a ramification of energy expenses through production function. For instance, energy in the macro output can be further disaggregated through nested CES functions. There an issue arises in the accounting between models trying to explicitly track energy service levels (in *pkm* or other such units) or implicitly through the energy bill. MARKAL-MACRO embodies the former case: energy in the macro output function is further disaggregated with CES functions depending on energy services levels. REMIND exemplifies the latter case: energy in the macro output function is further disaggregated in stationary and transport uses and then further in the different fuels, however the accounting only stands for final energy (i.e., the energy used). There an ambiguity remains whether this useful energy is *mtoe* used for transport or the actual *pkm*. The interpretation as useful energy relies on an implicit assumption on the equipment considered (usually calibrated and whose efficiency evolves through an AEEI), rendering very difficult the control of the actual energy service demands.

A.1.4 Top-down aspects

A.1.4.1 Markets of goods

The markets of goods are represented in various manners which are explained in this section: partial equilibrium, monosectoral and multisectoral SAM-based models, and general equilibrium models.

A.1.4.2 Partial equilibrium

In a partial equilibrium setting, the study focuses on a restricted span of the economy, often a single market, to reach the clearance of the market. The conditions of all other markets are assumed to be constant (under a *ceteris paribus* hypothesis). Therefore, reasoning within a partial equilibrium setting considers as negligible the induced effects on the rest of the economy by the allocation of production factors from the equilibrium on this market. This means that quantities and prices in this market, resulting from the production and consumption patterns, will establish independently from prices and quantities in other markets. In particular, the prices of substitutes, complements, and income levels are kept constant. In addition, there is no limit to the use of any production factor pending their use in other markets, and production factors prices are known and compliant with the production techniques. Usually, the perfect

mobility of production factors between sectors and locations is assumed. The partial equilibrium is then defined as the price vector (generally only one) which equalizes supply and demand on the market (or markets) considered.

Originally, the term of partial equilibrium meant the meeting of supply and demand in theoretical terms to describe microeconomics. (Marshall, 1920, Book V, Chapter V) indeed explained that to understand the workings of the economy, the economist proceeds step by step. Therefore, he breaks up a complex problem into separate simpler problems and combines partial solution into a solution of the total problem. That is where the *ceteris paribus* assumptions plays the key role and where Marshall warns us that the problem is the farthest from real life. "In breaking it up, he segregates those disturbing causes, whose wanderings happen to be inconvenient, for the time in a pound called *Ceteris Paribus*. The study of some group of tendencies is isolated by the assumption other things being equal: the existence of other tendencies is not denied, but their disturbing effect is neglected for a time. The more the issue is thus narrowed, the more exactly can it be handled: but also the less closely does it correspond to real life. Each exact and firm handling of a narrow issue, however, helps towards treating broader issues, in which that narrow issue is contained, more exactly than would otherwise have been possible. With each step more things can be let out of the pound; exact discussions can be made less abstract, realistic discussions can be made less inexact than was possible at an earlier stage."

Bottom-up models may be considered partial equilibrium even when one side of supply and demand is not represented. In that case, the model aims at a quantity to reach or employ a demand or supply function. Technically, this is still an equilibrium between supply and demand, only one in which one side is fixed, thereby allowing to label it partial equilibrium.

This simplification can be questionable. Indeed, for markets for which the interplay between supply and demand influences deeply other markets, this simplification is improper. For instance, the energy markets are often considered small with regards to their economic weight within the whole economy. However, their influence can be very important: all industries using energy intensively will be deeply affected, as well as household consumption. If the impact on these markets is important enough, energy demand will change, leading to a different equilibrium. Hence the introduction of the general equilibrium which takes into account the induced effects on other markets and of other markets on the studied market. This paradigm allows the study of the interrelations between all economic sectors and agents, as described below.

A.1.4.3 SAM-based models

One of the most important applied tools for building models is the Social Accounting Matrix (SAM) (Pyatt and Round, 1985). Indeed, Pyatt (1988) presents a manner in which how SAMs can be useful for the “development and understanding of models and results”. He argues that the SAM framework is useful not only to organize the data, but also to express economic theories. For that, they can be structured in three groups: supply, demand and closure rules. His modeling follows specific guidelines, but in any case most of his conclusions in terms of the usefulness of SAMs is transferable to most macroeconomic models. Notably, he insists on the notion of circular flow of income embedded within the SAM framework, which is at the root of closed macroeconomic models. As put by Robinson et al. (1999), the SAM is a convenient manner in which to represent the variables for discussing the model equations. The SAM is convenient because it is the synthesis of two ideas. The first is the input-output table depicting the interdependencies between productive industries (the purchase of an intermediate input by sector A to sector B is the same sale of sector B to sector A). The SAM generalizes that idea to the whole economy. The second is that income equals expenditures for all agents of the economy.

Indeed, the SAM results from the aggregation of **national accounts** (Lequiller et al., 2014) for all products and branches for one economy. The SAM describes the flows of all economic transactions in an economy. A SAM inherently describes **several agents** since even it represents the flows of wealth from one agent to another, including producers, households, government and rest of the economy (explaining imports and exports) both for the production process and the consumption process. For the production process, the SAM includes an accounting of the goods that are used to produce the goods of a given sector (both imports and nationally produced) within the Input-Output (IO) table. For the consumption process, the SAM includes accounting of all the goods consumed for the production process (intermediary goods), for households and government consumption as well as for investment. The SAM is (usually) a **multisectoral** matrix, disaggregated in various products (which can all be aggregated into one single sector).

In addition, the SAM gives an account of all the monetary flows entering and exiting an economy, therefore the **macroeconomic accounting is closed** at the scale of the country. This closure does not mean that all inward flows are compensated by outwards flows for a given national economy, but rather that all flows are accounted for and the balance is ensured by flows from and to monetary stocks such as debt. The variations of these monetary stocks are then described in the global economic picture

tables (drawn from the SAM).

Therefore, the SAM features **circular flows** within the constraints of a closed macroeconomic accounting. What that means is that all flows between two agents are in closed circuit and correspond in value. The SAM thus constitutes a **double-entry bookkeeping** of all economic flows. Producers use intermediary goods and primary factors they must pay for (usually to households). Households receive the remuneration of capital and labor and buy goods to the producers. The government acts as an intermediary which can make transfers (as well as buy and produce).

In addition, the SAM format usually describes two realities. First, the reality behind the SAM numbers which describes the structural exchanges of values during a given year. Second, the reality behind the rules of these exchanges, in particular the conservation of all flows, basis of all macroeconomic models. "Our approach derives its essential character first from this explicit recognition of two versions of the SAM for a given model and, beyond this, from the possibilities for exploiting the relationships between these two versions." (Drud et al., 1986). That is why they claimed that SAM-based models could be used "with a constructive sense [. . .] in a substantive dialog on policy issues."

A.1.4.4 Single sector models

In monosectoral (top-down) models, the SAM is aggregated to only one composite sector. In doing so, the overall macroeconomic balances are conserved, however the sectoral detailed is lost. In particular, the portion of composite good dedicated to investment is conserved, as well as the share of savings to finance this investment. Furthermore, the trade balances between regions are explicitly kept through the exchange of the regional composite good.

However, the inter-industrial IO matrix is reduced to the auto-consumption of composite good to produce said composite good. In addition, the detail of the structure of the demand is lost (and therefore the possibility of a structural evolution of demand, through the evolution of preferences for instance). A good example of monosectoral models used for E3 issues is given by Nordhaus (1993b).

In this case, the markets of goods are usually implicit, reaching full employment, and the rent on the factors equals their productivity. The split between energy goods and macro composite goods poses consistency issues. Usually, the macro composite good is produced with the factors K and L (as well as energy). Therefore the production of energy which also uses capital and labor creates a conundrum on how to model the factors. Mostly in models, energy supply is modeled with a bottom-up model,

for which the total costs, including labor and capital, are deduced from resources for consumption at the most aggregate level.

A.1.4.5 Multi sector models

Drawing from the features of the SAM accounting, multisectoral models exhibit several useful characteristics. Because of the disaggregation in several sectors, the sectors with the most interest can be finely disaggregated. Once that is done, it is much easier to link sectoral evolution with the technological dynamics and technical progress within a sector. In addition, they allow for the representation of the economic trajectory as a multisectoral dynamic. In particular, the representation of structural change is explicit (by means of the competition between sectors). Therefore, when combining the two, they enable the modeler to represent the co-induction between technical progress and structural change. After separating from monosectoral models, the main schism happened between computable general equilibrium (CGE) models and macroeconometrics. Both models rely on the equilibrium between economic flows. While CGE model rely on a Walrasian equilibrium to do so, macroeconomic models abandon this idea of supply meeting demand through the Walrasian equilibrium to focus on calibrating the model on past data.

A.1.4.6 CGE models and their relation to the Arrow Debreu framework

It is difficult to find an indisputable definition of CGE models because it is in practice applied in many different forms to address very different issues. In addition since the first CGE model from Johansen ([Johansen, 1960](#)), many streams of CGE modeling have developed carrying a debate about what is a CGE model after all.

Today after 60 years of development, we can venture a large encompassing definition inspired from [Thissen \(1998\)](#): *“A CGE model may be defined as the fundamental macroeconomic general equilibrium links among incomes of various groups, the pattern of demand, the balance of payments and a multi-sector production structure”*.

So first of all, a CGE model is fundamentally multi-sector with a core input-output structure. Consequently, aggregated growth models with single output, although economy-wide, should not be qualified as CGE models. In addition, a CGE model is basically a model of *interdependence* between demand patterns, production structure and income flows from decentralized representative economic agents. In the meantime the mechanisms of interdependence are fundamentally constrained by supply-use equilibria and accounting balance of the SAM which is the base of the equilibrium concept. Equilibrium refers to market, income and budget balance. Moreover CGE

models are based on a price-quantity formulation of flows and stocks of goods and production factors. Eventually, a CGE model is based on walrasian markets - in the larger sense - at least for goods, with prices as key endogenous variables.

It is to be noted that such a large definition of CGE models does not prescribe *a priori* any specific type of behavior of economic agents, quality of markets or else technical constraints of production and consumption. Within the large landscape of CGE models, one specific type of CGE model has concentrated attention of modelers since the beginning and continues representing a canonical benchmark: the first best CGE model.

The first best CGE model is an attempt to translate the microeconomic theory of the competitive general equilibrium of Walras and Arrow Debreu into an empirical macro formulation of general equilibrium. [Walras \(1896\)](#) simply attempts at modeling the economy to explain the formation of prices. This problem is formalized into an equations systems. For n goods and therefore n markets, he puts forward that there are $2 \cdot n$ equations given by supply and demand and thus as many unknowns and concludes that there should be a solution. However, a system of linear equations can have one solution, none or an infinity. The existence of a solution to the general equilibrium (GE) remained without solution for a long time. [Arrow and Debreu \(1954\)](#) describe a formalized framework in which they demonstrate the existence of the general equilibrium given an additional set of constraints. They include assumptions of perfectly competitive markets and decentralized optimizing behaviors with perfect information.

Therefore, neo-classical applied CGE models reuse such assumptions to provide microfoundations to macroeconomic behaviors and markets. In practice such models add at least two key assumptions to the general CGE framework beyond income and accounting balance: market clearing for all goods and production factors and zero profit condition ([Sue Wing, 2004](#)). This reflects the idea that every agents are surplus maximizing on perfect markets (perfect competition) so that all markets clear with no marginal rent and provide a first best state of the whole economy. In addition, this formulation requires sufficient regularity of technical systems to reach market clearing. This conditions is often insured by using CES production and demand functions. The assumption of optimality makes it possible to calibrate such production functions on a given year SAM - taking exogenous elasticity of substitution - through Shepard lemma. Finally, the canonical model gained success owing to the ease of implementation and the possibility to expand analysis in a lot of regional contexts with standardized software.

Today most CGE models departs somehow from the canonical model to adapt to

specific situation and improve realism of analysis. For instance, what [Thissen \(1998\)](#) calls “*macro CGE models*” were developed in the sake of Johansen to provide policy analysis in developing countries ([Robinson, 1989](#); [Taylor, 1990](#)). These models are extensions of Leontief’s input-output analysis and linear programming models. They usually depart from the pure neoclassical first-best model with specific structural assumptions and the implementation of non-optimizing behaviors.

A.1.4.7 Markets of factors (K, L)

The capital and labor factors are one of the most studied in economics since they embody two ubiquitous factors in any production. In addition, most of the study of growth has been embodied by the link between output growth and the evolution of the endowment of these two factors. In E3 models, the treatment of the markets for K and L factors are very diverse.

Bottom-up models use capital and labor to produce energy (or any other material) but tend to omit the markets for capital and labor and usually assume that the impact of energy on these markets is negligible (thereby justify their constancy). In these models, the markets of K and L factors are omitted, thus we label them with “-”.

Monosectoral economy-wide models do represent the use of capital and labor within a compact production function, similar to the Cobb-Douglas function in the Solow growth model. Within this framework, therefore the use of these two factors is explicit, but the material content of these markets (the hours and the machines) are not visible. In particular, the evolution in the content of each factor in the production cannot be related to the evolution of the content of production. Furthermore, the remuneration of the owners of these factors is not explicit and thus cannot be considered as represented (the assumption is that all factors are owned by the whole population). That is why we label them as **implicit**. Another word might be implicit: K and L are used and pertain to economic growth, however, no information is given on the link with material production.

Then in multisectoral economy-wide models, the SAM allows for the representation of the use of capital and labor in the production process as well as their remuneration for it. This explicit representation can fall within two categories. These markets can be represented as **perfect markets**, with the assumption of full employment and no friction, that is the case of most CGE models. Alternatively, the markets represented (or one of them) can be represented with imperfections and frictions: that is **imperfect markets**. An example of introduction of imperfection in the labor markets is the introduction of a wage curve, leading to a share of unemployment of the labor force.

The capital market can be imperfect as well: for instance the introduction of imperfect expectations coupled with an imperfect allocation of capital can lead to partial employment of install capacities. This is one key point of the departure from first best settings towards the incorporation of second-best features so as to model empirical mechanisms.

A.1.4.8 From closed to open economies: the issue of trade

The most common approach to addressing this issue, the [Armington \(1969\)](#) specification, assumes that the domestic and imported varieties of the same good aggregate in a common quantity index, although in an imperfectly substitutable way which is typically derived from assuming that the two varieties combine through a constant elasticity of substitution (CES) function. This allows representing markets in which both domestic production and imports have a share, despite the fact that they are priced differently. An alternative is the use of the Heckscher-Ohlin specification ([Heckscher et al., 1991](#)), in which goods are perfect substitutes.

A.1.5 Growth engine

A.1.5.1 Base growth engine

In our review, some models will not integrate a growth model. In this case, they rely on a fully exogenous assumption. Then, most models will express growth in a Solow framework, either in a recursive-dynamic way or in a Ramsey model with intertemporal decision-making. Some models will exhibit derived forms for those frameworks. One instance will be the expression of GDP as a direct function of L and energy prices. In doing so, the growth engine is in line with the Solow framework, however energy prices are surrogates for using K and E factors. Another example will be the use of TFP, which is Hicks-neutral technical progress, instead of labor productivity increase.

The classical Solow-Swan engine and its derivatives The long-term growth engine basically relies on one phenomenon: capital accumulation. The Harrod-Domar model constitutes the first attempt at a formalized theory to express long-run economic growth ([Harrod, 1939](#); [Domar, 1946](#)). Their theoretical breakthrough consisted in formally describing the dynamics of **capital accumulation**. Thus, capital accumulation resulted from investment, once deduced the depreciation of obsolete capital. The real issue

emphasized by Harrod and Domar was that of the **intertemporal trade-off between consumption** in the present and saving for future consumption.

The Solow-Swan model (Solow, 1956; Swan, 1956) extended the Harrod-Domar model by adding labor as a factor of production (which adds the arbitrage between capital and labor). The Solow-Swan model constitutes the neoclassical exogenous growth model. Since the proportion of capital and labor in production are not fixed anymore, the variation of capital intensity can be distinguished from technological progress. The explanation of the long-run economic growth in this setting originates from capital accumulation, population growth and productivity increases.

The Solow-Swan model describes an economy with a single good, produced with two factors of production, labor (L) and capital (K) in an aggregate production function such as a Cobb-Douglas (equation A-2).

$$Y(t) = K(t)^\alpha (A(t)L(t))^{1-\alpha} \quad (\text{A-2})$$

α ($0 < \alpha < 1$) represents the elasticity of output with respect to capital, and $Y(t)$ total output. A stands for a stock of knowledge improving the efficiency of labor, "associated" with a technology, with $A \cdot L$ the effective labor. All factors of production are fully employed, and initial values $A(0)$, $K(0)$, and $L(0)$ are given. The labor force and the level of technology grow exogenously at rates n and g , respectively: $L(t) = L(0)e^{nt}$ and $A(t) = A(0)e^{gt}$, allowing effective labor to grow at rate $n + g$.

The capital undergoes an investment-depreciation dynamics described in equation A-3. Capital depreciates at a constant rate δ . A fraction of the output $s = 1 - c$ is saved for investment. The output results in $c \cdot Y(t)$ for consumption (with $0 < c < 1$) and $s \cdot Y(t)$ saved for investment.

$$\dot{K}(t) = s \cdot Y(t) - \delta \cdot K(t) \quad (\text{A-3})$$

The production function $Y(K, AL)$ displays constant returns to scale and thus can be written as output per unit of effective labor, as shown in equation A-4.

$$y(t) = \frac{Y(t)}{A(t)L(t)} = \frac{K(t)^\alpha (A(t)L(t))^{1-\alpha}}{A(t)L(t)} = \frac{K(t)^\alpha}{(A(t)L(t))^\alpha} = k(t)^\alpha \quad (\text{A-4})$$

Rewriting equation A-3 in the same fashions exhibits the dynamics of capital intensity $k = \frac{K}{AL}$ in equation A-5. The term $s \cdot k(t)^\alpha = s \cdot y(k(t))$ is the fraction of output per unit of effective labor dedicated to investment, that is to say the investment per unit of effective labor. The term $(n + g + \delta) \cdot k(t)$ is the break-even investment, that is to say the amount of investment needed to prevent k from decreasing.

$$\dot{k}(t) = s \cdot k(t)^\alpha - (n + g + \delta) \cdot k(t) \quad (\text{A-5})$$

With additional assumptions on optimality (in particular for the capital-labor arbitrage), eq. (A-5) implies that $k(t)$ converges to a steady-state value of k^* (see eq. (A-6)), defined by $sk(t)^\alpha = (n + g + \delta)k(t)$. This steady-state shows neither an increase nor a decrease of capital intensity.

$$k^* = \left(\frac{s}{n + g + \delta} \right)^{\frac{1}{1-\alpha}} \quad (\text{A-6})$$

Regardless of its starting point, the Solow-Swan model may converge to a balanced growth equilibrium. Output growth is then fully determined by the rate of technological progress. In this balanced growth, capital and effective labor are growing at $n + g$, and so is output because of the constant returns.

$$MPK = \frac{\partial Y}{\partial K} = \alpha A^{1-\alpha} / (K/L)^{1-\alpha} \quad (\text{A-7})$$

The marginal productivity of capital in eq. (A-7) is inversely related to the capital to labor ratio (since $\alpha < 1$). Therefore, if productivity A is equal across countries, countries with a lower capital to labor ratio (less capital per worker) exhibit a higher return on capital investment. Thus, investment should flow from developed countries to less industrialized countries, until the capital to labor ratio (K/L) and the income per worker (Y/L) become equal across countries.

This basic model as been extended in two ways: - ramsey, contrairement à solow, on est dans le normatif: perfect expectations, long lived agent, peut etre tout à fait débattu: hahn "ramseification of solow was its proper consumption"

The Ramsey-Cass-Koopmans model The Solow-Swan model was extended in the way it is used as well. Indeed, [Cass \(1965\)](#) and [Koopmans \(1965\)](#) transformed what is fundamentally a Solow-Swan growth model. They integrated the analysis of consumer optimization developed by [Ramsey \(1928\)](#). This extension basically constitutes an attempt at the resolution of the intertemporal arbitrage between saving and consumption. Instead of resorting to an exogenous trend for the saving propensity, the Ramsey-Cass-Koopmans endogenized this coefficient making this arbitrage an integral part of the growth path choice. The result is that the optimal growth path allocates capital optimally in the yearly equilibrium as well as intertemporally. The assumptions made are that of a given discount rate to weigh the future against present day decisions and that the consumer (and ultimately producer) is infinitely lived, with a

propensity to save that can vary across time because he will reap the benefits (or at least his descendants will).

The addition of human capital: the Mankiw-Romer-Weil model According to the Solow-Swan model, international investment should flow to poor countries to make up for the lack of productive capacity (manifested in a greater marginal productivity, i.e., profitability, of capital). The incapacity of the Solow model to account for why productivity is lower in poor countries made Lucas suggest that lower levels of human capital might account for the lower productivity (Lucas, 1988). However, Mankiw, Romer and David Weil posited the existence of human capital consisting in education, training. . . to account for the failure of international investment to flow to poor countries (Mankiw et al., 1992). The production function here (equation A-8) respects the same assumptions as in the Solow-Swan model, making it similar to a Cobb-Douglas.

$$Y(t) = K(t)^\alpha H(t)^\beta (A(t)L(t))^{1-\alpha-\beta} \quad (\text{A-8})$$

This model therefore explains the low output and marginal product of machine capital (K) in developing countries by the lower accumulation of human capital. As we will see when we examine closely the current integrated models, this type of endogenous growth engine is currently not widespread.

A.1.5.2 Macro technical change

Here we refer to the classical specification for the growth engine technical change. The Harrod specification (or Solow) prescribe an evolution of the endowment of the labor factor through through the joint evolutions of population and labor production. The Hicks-neutral specification, relying on Total Factor Productivity, in contrast, considers an evolution of all the factor in the production without a specific direction. We use the labels in the same manner regardless of the functional form that is used (the idea is similar, even the formal specification is different). There is some effort to endogenize this evolution, inspired by theoretical work. However, only compact model use it at the moment and most IAMs keep with exogenous trends. Sometimes, the energy factor gets an additional specific treatment, cf. ?? A.1.7.1.

A.1.5.3 Inertia of capital at the macro level

As seen in ?? A.1.2.1, capital inertia is an essential component to describe adequately the capital dynamics at the sectoral level, in particular for long-lived capital in the

energy sector. Does this requirement at the macroeconomic level for E3 models?

The main channel for macroeconomic models (i.e., top-down models) to represent the evolution of the technology is through the technical change coefficient. This coefficient can either be fully exogenous (as in the Solow model) or endogenized (as in the Mankiw-Romer-Weil model). For E3 models, this coefficient translates into an energy efficiency improvement coefficient (either autonomous or endogenous). The capital is for the most part an intangible production factor, fully flexible. That is why it is called malleable capital. The question is here whether the assumption of the capital being malleable still holds. This issue alludes to the discussion between putty-putty models (fully flexible) and putty-clay models (fully flexible a priori, unflexible a posteriori), and the intermediate solution: putty-semi putty.

In this section, only models with a top-down component are concerned. Most models do not feature inertia as a characteristic of macro-economic capital. That is true for most monosectoral models: the scale of the composite sector, in addition to the fact that a long-term perspective is taken, leads to foregoing the short to medium term inertia effect to examine long-term issues (for which inertia is deemed to have no effect).

Multisectoral models inherited this features, however some models started to include inertia. In particular, they added a putty-clay assumption: before investment, capital is fully flexible (it is only money), while after investment capital is much less flexible (it is under the form of factories and machines already built). If the capital is not malleable at all, the capital is labeled as putty-clay. If the capital is somewhat malleable (a share of the capital can be “disinvested” in to be invested in another sector of the economy), the capital is referred to as putty-semi putty.

Econometric models may be considered to include inertia as well, albeit implicitly. The calibration of the econometric equations indeed include short-term as well as long-term effects and therefore the response may be different for the two horizons.

A.1.5.4 Short-term “maladaptation” representations

Thus, short-term maladaptations alludes to the possibility of having short-term disequilibria occurring. The key point is the importance of these representations of inertia are very different according to the nature of expectations. With perfect expectations, the impact of inertia is almost non-existent (past an adjustment period from the initial setting). Without inertia, imperfect expectations do not matter since the adjustment is immediate. The combination of imperfect expectations with inertia create the possibility of disequilibrium within the modeled trajectory.

Many models rely on perfect markets, often perfect expectations, therefore these disequilibria cannot occur. However, some models introduce imperfections to account for such possible disequilibria: imperfect expectations with inertia, partial employment of factors, stocks, non competitive behaviors. Many of these imperfections will refer to Keynesian theory. The representation of financial markets and money constraints would also lead to such disequilibria, but are absent from most of the studied models.

A.1.6 Choice representation

The choice representation, particularly the investment decision, is the cornerstone of the model specifications. We surmise that to inform adequately how the choice is represented, we need to understand three aspects: the decentralization level (i.e., who are the agents), the modalities of the choice (the agents' program) as well as the information level available (referring to the foresight).

A.1.6.1 Decentralization level

The decentralization level of the decision making alludes to who is making the decision. We encountered various way of representing the decision makers.

The first type is naturally **explicit producers and consumers** of goods. In this setting, the agents are represented and the decision making relate to that of the real world. This will typically be the case for bottom-up models where the aim is to describe very few sectors in a realistic manner. Sometimes, a few agents can be symbolically aggregated together (for instance all the producers of a same energy carrier).

On the other end of the spectrum, some models decide of an objective function for the whole system (i.e., whole energy system or whole economy). This objective function is then maximized by a **centralized agent** encompassing the objective of all the actors through this objective function. This centralized agent stands for a social planner, making the decisions for all the actors, with a way to weigh the consequences of the choices of the agents against one another.

Somewhere in the middle, the models relying on a SAM express the choices of the agents that are depicted in the SAM. **SAM agents** are more simplified than explicit producers and consumers, however each sector does have one representative agent. In the SAM, producers are explicitly represented for all productive sectors, as well as consumers, either a representative household or disaggregated into further household classes (e.g., categories defined by ranges of revenues). For these actors, the choices are made explicitly. Other actors are usually implicitly represented: the government, the

primary factor – other than labor – owners. In a CGE context, households are assumed to maximize their welfare, while producers are assumed to maximize their profit. The second welfare theorem then leads to a Pareto general equilibrium.

Within a macroeconometric or system dynamics context, no specific assumption is made for agents. Indeed, their choice behavior is **implicit** and results from functional relationship embodying their past decisions (for econometry) or an assumed evolution (for system dynamics).

Finally, in the models we labeled as IO/SAM/GE (as opposed to IO/SAM/CGE, which are described in the previous paragraph), the choices households and productive sectors are explicitly represented. In fact, instead of automatically being in maximizing paradigm, the **SAM agents can have *ad hoc* behaviors**, especially as described by bottom-up models. This main difference will be essential in the top-down-bottom-up hybridization and will be discussed further in chapter 3.

A.1.6.2 Modalities (agents' program)

The representations of the modalities of choices, i.e., the agents' program, fall in two categories: either the maximization of an objective function or the explicit description of an *ad hoc* behavior.

Since one of the objective of the economic science is the optimal allocation of resources, it is only natural that the maximization of an objective function be one of the main option to describe behaviors. In this context, depending on the scope and disaggregation of the model, many options exists. Partial equilibrium models will aim at **cost minimization** (which corresponds to the profit maximization for the agent in the scope of the model). Then models whose scope is economy-wide will maximize an objective function, either intertemporally in a model with an optimal trajectory, or at each time step for dynamic-recursive models. Intertemporal models usually aggregate temporal utility within a welfare function through discounting and perform a **welfare maximization**. Ramsey models carry out this optimization through the temporal arbitrage between consumption and savings. So-called dynamic-recursive models usually perform short-term **surplus maximization** for each period. The succession of optimal welfare points of course does not guarantee that the trajectory is optimal.

The other category is based on the acknowledgment that the agents might not be completely rational, at least that the conditions of the *homo oeconomicus* with perfect knowledge might not represent adequately the real world. That is why the models in this category developed behavioral representations. The first in this category are **implicit with econometric** models, which aim at elucidating past behaviors through

econometric relations and extend these behaviors in the future. Of course, that precludes any fundamental change in the mode in which the decision is made, but relates more accurately to past trends. To solve this issues, some models incorporate behaviors that are **implicit with system dynamics** to allow for the modification of past trends. Other models integrate **behavioral descriptions** (that might also emerge from econometric studies) of the relationships between the various context parameters and the variable choices. These models target the description of the mechanisms at play. One example of this is the logit sharing function to decide on which technology to use. Contrary to cost minimization, the logit sharing function will not allocate all the production to the sole technology with the lowest costs, but will distribute production across all technologies, with a preference for lower cost technologies, but leaving room for all. There is an extensive list of models using this to represent technology choices, especially in conjunction with intangible costs.

Finally, extending the previous type, some models describe the behavior in two phases. *Ex ante* behavior is represented for instance with behavioral relations (e.g., a bottom-up model). Then, when capital is installed, *ex post* behavior for the confrontation of supply and demand relies on utility maximization and supply functions.

A.1.6.3 Information level (foresight)

The two main formulations of expectations in E3 models are myopic and perfect. Usually, each formulations goes with one type of model solution. **Perfect** expectations describes a world in which perfect information is given to the agents described in the model. Therefore this type of expectations formulation suits quite natural the optimal trajectory models (either optimal energy systems or optimal growth models). **Myopic** expectation refers to a formulation in which the agents only know what has happened up to the point of the decision. The myopia of these expectations refers to the fact that they integrate the values of today as estimates for the values in the future. In particular, it means that agents can form expectation a priori that will turn out to be wrong a posteriori. Myopic expectations are a form of imperfect expectations.

In our review of the models, we encountered other types of expectations. The first type of expectations we want to shed light on is the expectations that will be characteristic of CGE models. We label their expectations as short-term perfect expectations. Short-term perfect expectations seem to echo the mode of resolution of the model which was short-term welfare maximization. Indeed, the two are coupled in CGE and related. The nature of the expectations in recursive-dynamic CGE is that for each period of the study, agents find a Pareto equilibrium resulting from the confrontation

of supply and demand on all markets. In the formation of costs and demands agents use the prices and quantities of the current equilibrium to be found. The simultaneity of this equilibrium with the investment dynamics and the equilibrium on the capital markets leads to an equilibrium where the choices are made with the values for the current period which are an output of the equilibrium found. That is why we deem the expectations perfect for the current period, hence the label **short-term perfect expectations**.

We labeled as **limited expectations** the second type of expectations we encountered. This type of expectations extends the framework of myopic expectations to a formulation where the agents do not know more than the past facts, but do formulate a better guess than current values. For instance, if demand grows by 10% every year for the past 20 years, a guess of a growth of 10% for this year too seems more likely than the current demand. In this type of expectations, then agents inform their expectations with *ad hoc* previsions. Limited expectations are thus another type of imperfect expectations or foresight. In this context, econometric and system dynamics models natively incorporate **implicit limited** expectations within their reaction function to the context. In econometry models, the agents use past data to inform an estimate for the evolution of value that is not restricted the values of the past year (as in the real world). In system dynamics models, the agents implicitly have the expectations that would lead to the prescribed dynamics evolution. The other case of models using limited expectations are dynamic-recursive simulation models that attempt are integrated past data and deduce the possible evolution of values further than the order zero of the guess (the present values).

One type of expectations that is absent from our review is the rational expectations (form of stochastic perfect expectations) where the estimate is perfect for the average expected value. However random noise around the expected value makes the estimate imperfect. The models we are reviewing tend to be deterministic and therefore without a stochastic component.

A.1.7 Evolutionary factors

In our classification, the long-term growth engine results from capital accumulation and labor force growth. In the classical growth framework, another term is not accounted for by these two factors: the evolution of Solow's residual. This residual originally labeled as technical change recover various realities. In this document, we will distinguish two aspects: technical change and the evolution of consumption patterns.

A.1.7.1 Energy-specific technical change

Most models incorporate a component of global energy efficiency evolving with time. This energy efficiency seems to correspond to the same logic as Solow's residual explained as technical progress. Energy efficiency may be either completely prescribed exogenously. In this case, the progress will be labeled as autonomous energy efficiency improvement (AEEI). Energy efficiency may also be endogenous within the model framework and therefore will be labeled as endogenous energy efficiency improvement. This part of the evolution of activity levels is present in all E3 models, whether En, EWC or EWI – which explains why it is not repeated for all models in the table. This part of the evolution of activity levels may represent both the substitution effect and the change in uses, therefore encapsulating structural change ([Dowlatabadi and Oravetz, 2006](#)).

This section address the technical change specific to energy when other than Hicks-neutral technical change. In fact, when the only technical change affecting energy is Total Factor Productivity (TFP) increase, it will only be mentioned in the corresponding column in the growth engine.

Following the debate spanning the last decades on technical change, models strove to move from exogenous to endogenous technical change. Therefore, the first discriminating factor between two models is whether technical change affecting energy is either **eXogenous – X** or **enDogenous – D**. In addition to AEEI or EEI, the main routes of energy-specific technical change will be learning-by-doing for specific technologies, usually endogenous with installed capacities, and R&D.

A.1.7.2 Consumption patterns

The evolution of households consumption patterns can assume distinct forms depending on the model examined.

In some bottom-up models, the representation of the variation of consumption patterns are represented is either exogenous or sometimes mechanistic. For instance, the models of residential energy consumption consider the rebound effect ([Giraudet et al., 2012](#)) and effects that may alter the behavior of consumers in the future. Another example is MINI-CAM which exhibits elasticities that evolve in time.

The monosectoral models seem inherently unable to represent this phenomenon due to the absence of multiple goods to choose from.

In mechanistic EWI models (i.e., models with a top-down multisectoral component), the expression of the choice between the disaggregated goods is modeled through a utility function. This utility function is usually a Constant Elasticity of

Substitution function. Sometimes, the CES function is a Cobb-Douglas function where the substitution elasticity equals 1. With this representation, the most natural form of the evolution of consumption patterns relies on the evolution of preferences. More concretely, the **elasticity of substitution between goods evolves** across time, either exogenously or endogenously. With the CGE framework (relying on the optimization behaviors in a first-best setting without any additional constraint), this is equivalent to **altering the expense shares** of the goods in the income of households. Furthermore, some models use LES functions as utility function, which can be described as Cobb-Douglas with floor for goods, representing basic needs that do not provide utility. The endogenous evolution of preferences can also stem from the **temporal evolution of such floors on consumption levels**. Finally, recognizing that the consumption of some goods reaches satiety (full satisfaction), they reach some level of consumption asymptote in quantity. The modification of the **ceiling on consumption quantities** constitutes yet another lever for representing the evolution of consumption patterns. Just the presence of ceiling renders the elasticity of substitution mechanistically endogenous, and depending on the evolution of the variables in each scenario.

In heuristic EWI models (whether system dynamics or econometric models), the evolution of the variables described for mechanistic models is implicit. Furthermore, their future evolution is conditional to their past evolution contained in the data used for the calibration. Therefore, it can be said that these models contain the evolution of consumption patterns, however three drawbacks plague this representation: (i) they cannot be made explicit or related to specific mechanisms, (ii) they cannot be controlled since they must abide by the relations contained within past data, and as a corollary, (iii) they cannot become a scenario variable even though they may be crucial in envisioning low carbon path as well as sustainable development paths.

A.2 Assembling the building blocks to understand the integrated models structure

A.2.1 Models and blocks

Historic families usually comprise bottom-up, top-down, sometimes combined into hybrid models, as well as IAM. Building from the modeling toolbox presented in section ??, both theoretical and applied tools are today combined into integrated models. Each model rests on theory, tools and data. In our taxonomy, model families are defined by their building blocks. For instance, the typical CGE uses the Arrow-Debreu axiomatic, combined with a Solow growth engine from theoretical foundations toolbox, the production function and the SAM-based modeling from the applied toolbox.

The typical CGE in addition resorts to elasticities estimation and SAMs for data.

Therefore we plead for abandoning the historical taxonomy in favor of a technical taxonomy. A historical taxonomy is very instructive and allows for understanding the evolution of models: for instance how MIND evolved into REMIND which is today closer to MARKAL-MACRO and MERGE than to compact models such as RICE and RESPONSE. Our point here is that the evolutionary trends have blurred the distinction by historical families and today a more relevant form of taxonomy is through the building blocks that are included in the models and their links.

Table C. Models to blocks

	Scope	BU				TD					Economic choice			Growth				Evolutionary factors	
		Primary energy supply	Secondary energy supply	FE demand from activity levels	Cap	Activity units, and struc.	levels: abs. change	Good markets/Macro balance	Factors markets (K,L)	Trade	Decentralized level	Modalities (program)	Information level (fore-sight)	Base engine	Macro technical change	K_{mac} in-ertia	ST Maladaptation	Energy-specific technical change	Consumption patterns
MINICA	En	$ECC_t + ST$	expl	logit	\emptyset	EJ_{usef_1} f(GDP,P)		PE-energy	-	HO En	expl agts	Behavior (logit)	M	-	-	-	-	X techno. EI on demand & primary	actLev σ_p evolution
Markal RICE	En EWC	ECC	expl	expl	y n	ϕ/EJ_{us} σ_p \$ -		PE-energy impl F(K,L) SAM_m	- P impl P	HO En -	Centralized Centralized	ECmin EWmax	P P	- R	- X/D Hicks	- n n	Technos X/lbd	-	
Gould GREEN	EWI EWI	- FF	-	-	n n	\$ GE GE		SAM/neoCGE SAM/neoCGE	P P	- HO oil A goods	SAM agts SAM agts	EWmax ASmax	P ST P	R S	D X Hicks KLF	n n	- Specific AEEI	-	
CMDM	EWI	-	-	-	n	\$ econom		SAM	I	econom	SAM agts	econom	impl	econom	imp	y	econom		
CIMS	En	ECC	expl	expl	y	ϕ Exogenous forecast		PE-energy	-	A En	expl agts	Behavior (em-pirical logit)	L	-	-	-	-	AEEI	-
GCAM	EWC	ECC + ST	expl	logit	y	EJ_{usef_1} f(GDP,P)		PE-energy	-	HO En	expl agts	Behavior (logit)	M	GDP= $f(L, P_{ener}^\alpha)$			n n	X techno costs	actLev σ_p evolution
REMIN	EWC	ECC	expl	$E_i = \text{nestCES}(FE_k)$	y	Proxy Y = nestCES (K,L,E1,E2)		impl nonEn expl En SAM_m	P impl P	HO En+Cp	Centralized	EWmax	P	R	X Hicks KLE	n n	Supply techno. learning	-	
Markal Macro	EWC	ECC	expl	expl	y	ϕ/EJ_{us} Y = CES (K,L,Energy services)		impl nonEn expl En SAM_m	P impl P	HO En	Centralized	EWmax	P	R	X Har-rod	n n	technos lbd AEEI on actLev	AEEI D depend on time	
MERGE	EWC	ECC	expl	-	y	Proxy FE Y = CES (K,L,Elec, Nonelec)		impl nonEn expl En SAM_m	P impl P	HO goods	Centralized	EWmax	P	R	X Har-rod	putt clay	n	lbd+aei	-
WITCH	EWC	FF	CES-Ltf	Nonelec= nestCES(FE_k)	n	Proxy FE Y=CES(K,L, Elec, Nonelec, EE)		impl nonEn & En SAM_m	P En P	HO En	Centralized	EWmax	P	R	X Hicks KLE	n n	Technos lbd & R&D + EE R&D	-	
EPPA	EWI	FF	CES-Ltf	-	n	\$ GE		SAM/neoCGE	P	A goods HO Oil	SAM agts	ASmax	ST P	S	X Har-rod	putt sem putt	n	AEEI + techno. FF endowment increase with production	Adjustment to consumption shares & σ
IMACLIN R	EWI	ECC_t ST Oil hubbert	expl	expl	y	ϕ GE		SAM/non neoCGE	I	HO En A goods	Households Productive sectors	Ex ante: BU Ex post: ST utility max Ex post supply f(prod/cap)	L	S	X Har-rod	putt clay	y	D energy productivity (EE R&D) + technos lbd	Prefs = f(revenue) + variable consumption floor/ceiling
E3MG	EWI	-	expl	-	y	\$Prox FE for elec		econom SAM	I	econom bilateral	SAM agts	econom	impl	econom	imp	y	X AEEI (paid for by investment)	econom	
T21	EWD	xxx (SD)	σ_{SD}	E = f(GDP _{tot} , technos, inertia)	n	ϕ σ_{SD} disconnected from TD		3 goods = f(A,K,L)	I	En SD	Economic & other agents	impl with SD	impl with SD	S-based SD	D with SD	n SD expl	BU: X progress	X Engle curves	

Legend: ECC Extraction Cost Curve, CES-Ltf CES-Leontief, TD, E-A intErtemporal-intrAtemporal, W-C-S welfare-cost-surplus, P-M-L perfect-myopic-limited, R-S Ramsey Solow, actLev activity levels, exogenous-enDogenous, P-I Perfect-Imperfect, expl-impl explicit-Implicit, ST Short-term constraint, FF fix factor, σ elasticity, econom econometry, SD System dynamics

X-D

A.2.2 The building blocks of historical models

Let us start with the bottom-up and top-down historical paradigms. Most of the models in these categories are not used as such anymore, but often in hybrid paradigm where the level of integration grows with time. However, they are very useful in that they allow to explain our analysis grid on explicit example and fix the vocabulary that will be used for the rest of the models.

In the **bottom-up** paradigms (the first two lines: *MINICAM* and *MARKAL*), the most distinctive feature is the explicit description of technologies. This explicit description occurs for secondary energy supply, that is the transformation of primary energy into an energy carrier for transport and distribution in *MWh* or *toe*. The original bottom-up energy model was often designed for just this side of the energy system. However, later improvements included the description of useful energy demand following an activity variable dynamics exogenously prescribed. This dynamics translates a demand for useful energy, in the units of the sector: *pkm* or *tkm* for the transport sector, *tons* of steel or cement, into a demand for final energy in *toe* or *MWh*. The particularity of the bottom-up models is a description of the capital in physical terms (*MW*, $\$/toe$. . .) corresponding to production plants and consumption appliances. The dynamics of the activity levels is left to a simple function which usually only dispatches an exogenous aggregate demand into several types of demand via elasticities or logit sharing functions. The bottom-up models only cover the energy sectors (possibly auxiliary goods such as biomass for bioenergy) but do not cover the whole economy and thus do not represent non-energy goods, or factors. In addition, they do not incorporate a growth engine (which is implicit in the exogenous demands). Two types of choice representations are implemented and create two subfamilies. On the one hand, *MARKAL*-type models represent an infinitely-lived agent, omniscient even in the future (i.e., with perfect expectations) and solely responsible for the choice to minimize actualized energy system costs through an intertemporal optimization. On the other hand, *MINICAM*-type models aim at implementing the description of agents' behaviors. The agents represented are explicit producers or consumer of goods, whose expectations of the future are myopic. This dichotomy will persist throughout the models description.

The next four lines (i.e., *RICE*, *GOULDER*, *GREEN* and *CMDM*) represent the typical instances of the **top-down** paradigm. These four types of models have been created for various purposes. The compact models such as *RICE* aim at finding the optimal path, with the cost-benefit arbitrage between mitigation and avoided damages. The CGE models such as *GREEN* have their original purposes in fiscal and trade policies (and the representation of structural change). The intertemporally optimizing CGE

models (e.g., GOULDER) have not become a standard climate policy assessing tool but are rather used for scientific experiments on R&D and endogenous technical change issues. Finally, the macroeconometric models aim at integrating the historical SAM evolutions within an econometric framework to study the future evolution that would stem from reproducing the mechanisms and behaviors observed in past data.

The first type of **top-down monosectoral compact optimal growth models** can be distinguished in that they are monosectoral (Economy-Wide with only one Composite good, i.e., EWC), which precludes the representation of markets and trade interactions, in particular structural change. The markets for primary factors are implicit in the sense that there is an explicit representation of an endowment of capital and labor, however, these markets are (usually) not relying on an explicit description but rather represent the full employment of factors, with their price (or rather their cost) being the shadow value of the constraint on that specific good. Their growth engine consists of a Solow model inserted in a Ramsey framework of intertemporal choice (which we conveniently call Ramsey growth engine), without any short-term effects such as capital inertia or maladaptation. Monosectoral optimal growth models are very similar to intertemporally optimizing bottom-up models regarding the fashion in which the choices are represented. An infinitely-lived omniscient-in-time agent realizes all choices at once. The only difference lies in the scope of this choice: while for intertemporally optimizing bottom-up models the choice is made for the intertemporal aggregated energy system costs, for the monosectoral optimal growth models, the choice is made to maximize welfare.

The transition towards **optimal CGE growth models** thus is natural: the sole composite good is split into several sectors by means of Social Accounting Matrices (SAM). These models (as well as the following ones) will therefore be deemed Economy-Wide with Interdependencies between sectors (EWI). These models rely on the Walrasian theory of the general equilibrium, formalized by Arrow and Debreu. In addition, they add the assumption of the existence proof in the particular case demonstrated by Arrow and Debreu. These restrictive assumptions significantly impact the results, in particular, they rest on perfect markets, profit-optimizing producers and utility-maximizing consumers. In this setting, all the agents being maximizing, a social optimum (of Pareto) will be deduced from the maximization of welfare and will be concomitant with one infinitely-lived omniscient-in-time agent who would realize all choices at once.

The classical **dynamic recursive CGE models** (such as GREEN) forego the intertemporal optimization to rely on the exogenous labor dynamics coupled with the endogenous capital accumulation, as expressed by the Solow growth engine. The exogenous

nature of the saving rate breaks the time dimension of the choice, relying on the recursive dynamics evolution in which each choice is independent of the future choices to be made. In one time-step, all agents maximize their objective (profits for producers and surplus for consumers) leading to a welfare maximization in the short-term. The use of classical production function where technical choices are concomitant with economic choice prescribes that within this time step foresight is perfect. However, this is not true in the long term, as the optimization in the short term can lead to a suboptimal intertemporal trajectory. This is often confused with myopic expectations (where agents only know up to the present), therefore we will designate this type of expectations short-term perfect expectations. More and more CGE models incorporate capital inertia to account for the lifetime of installed capital. In doing so, the capital resulting from past years decisions is fixed (Leontief inputs) while new capital is flexible (often with a CES production function). This is one step in the direction of describing transitional phenomena with short term effects.

Finally, the **macroeconomic models**, such as CDM, do not rely on an explicit representation of the mechanisms at play. Rather, these models aim at finding and reproducing mechanisms observed in past data, within a macroeconomically complete (closed) setting. Thus make use of econometric relationship to express activity levels, supply and demand. The specificity of macroeconomic models in the line of Jorgenson is to deduce the econometric relationships within a setting compatible with the past evolution of SAM, therefore respecting the sectoral interdependencies contained within the SAM. However, for most of the models in this category, the current models seem to use sectoral econometric estimations, grouped together and subject to accounting constraints within the SAM. In addition, the use of econometric relationship allows the implicit representation of imperfect markets, short-term maladaptation and capital inertia contained within the calibration dataset. The implicit representations of behaviors also affects the choice representation: SAM agents decisions are made according to the estimated behavior with expectations matching the past data (and thus necessarily limited, even though they cannot be explicitly understood).

A.2.3 The building blocks of integrated models

We can now comment how the classification in table D relates to the building blocks previously presented. Seven kinds of integrated model families have been identified. The first type of integrated models consist in models whose coverage is carried out through a monosectoral composite good. Such models are the convergent evolution of bottom-up models (for instance from MINICAM to GCAM or from MARKAL

Typical Model of the family	Examples
GCAM	WEM, CIMS
MARKAL-MACRO	Message-Macro, Remind, BET, MARIA, GRAPE
MERGE	Eta-Macro (aka Global 2100), EC-IAM
WITCH	
Hybrid CGE	EPPA, FARM, GTEM, Phoenix, SGM, AIM/CGE
IMACLIM-R	
E3MG	
T21	

Table D: Classification of integrated models according to their building blocks

to MARKAL-MACRO) as well as compact monosectoral top-down models (from MIND to REMIND for example). The second type of integrated models consist in models whose economy-wide coverage is carried out through the evolution of a SAM. Such models are the natural evolution of CGE models (for instance EPPA from GREEN) or of macroeconometric models (from CMDM to E3MG).

Among the monosectoral integrated models, the dynamic-recursive bottom-up paradigm evolved into a **recursive-dynamic bottom-up model coupled to a macro-economic feedback loop** (e.g., GCAM) still in a partial equilibrium paradigm, but integrated in a model where growth depends both on an exogenous labor dynamics and on energy costs. It is a weak form of the Solow model, where the long-term capital evolution is not limiting in growth (only labor is), except in the energy sector in transition. It retains all the formulation of the original bottom-up model in representing bottom-up physical capacities and choices.

The equivalent paradigm in an intertemporal optimization framework is often the base of the IAM models, with in addition a climate module, a damage module, and depending on the model, an adaptation module and land-use module. The **optimal bottom-up model coupled to a macro-economic feedback loop within a intertemporal optimization framework** (e.g., REMIND, MARKAL-MACRO and MERGE) naturally integrate the compact optimal growth historical model with the historical energy system optimization model. Since both model are intertemporally optimizing, there is not conflict of paradigms. However, the two optimization programs must be combined, which happens through the discard of the energy system objective, which becomes a constraint to the larger economy-wide optimization program following a Ramsey paradigm. The various instances of this modeling framework are thus very similar in their operation. A main difference will be in the scope of the bottom-up model (for instance MARKAL-MACRO includes demand-side technologies where MERGE

and REMIND do not). Nonetheless, the difference that will impact the results most is the manner of the linkage between the top-down and bottom-up models.

Going to multisectoral models, the main paradigm in use and development for E3 forward-looking analysis is the CGE. The main innovation of the integrated model is the incorporation of bottom-up information to create **recursive-dynamic CGE models with bottom-up Leontief technologies**. This was done through the transformation of the description of the production of energy goods from a KLE CES function, to a CES function of Leontief technologies for energy supply. The incorporation of backstop technologies, which are non-existent at the base year is often realized through the endowment fixed factors, which grows over time. The most documented example of the genre is the EPPA model.

The exact same evolution, but this time applied to a monosectoral optimal growth model, gave rise to the WITCH model. This model is alone in its own family, as far as we know, because of the uniqueness of coupling a **monosectoral optimal growth model with bottom-up Leontief technologies within a CES setting**. The WITCH model kept the monosectoral production function for a unique composite good, however this good is produced with intermediate good that are described by a mix of CES and Leontief production functions, especially detailing the energy inputs. The intermediate goods production is nonetheless not described through an input-output matrix (IOM) and the agents only consume the composite good, thus without the use of a SAM (which would also include the IOM).

The IMACLIM-R model constitutes an attempt to overcome the limitations of classical production functions, such as their inability to represent non-smooth trajectories. In addition, foregoing classical production functions allows to avoid the assumptions of Shephard's lemma on the optimization behaviors and the optimal status in the long run of the initial SAM to inform the short term production functions. The IMACLIM-R model aims at replacing the classical production functions altogether by bottom-up modules which are summarized in every static equilibrium through a Leontief technology. This model constitutes an attempt of a **general equilibrium model with bottom-up models incorporating short-term disequilibria**. Lifting the assumptions of Shephard's lemma enables us to represent imperfect markets, oligopolistic behaviors and short-term maladaptations. In particular, the production functions are not prescribed *ex ante* (before the simulation), but rather result from bottom-up modules and can thus be entitled *ex post*. The households decide on bottom-up behaviors before the general equilibrium (*ex ante* formulation) and maximize their utility given the results of their behavior (*ex post* function), under limited foresight. In the same fashion, the producers decide on technological choices in bottom-up modules before the general equilibrium (*ex ante*

formulation), and within the equilibrium present an *ex post* short-term supply function depending on capacity utilization rate.

The study of E3 issues, in particular climate policies, leads to the assessment of unprecedented economic situations. The evolution of the energy sector especially cannot follow the observed past relations. This observation motivated the incorporation of bottom-up modules to simulate the evolution of the energy sectors, thus building **macroeconomic models coupled with bottom-up module for energy**. For instance, E3MG incorporates a bottom-up module to represent the electricity sector evolution.

Finally, a bit out of the picture usually, but interesting as well are the system dynamics model, for which the representant is T21 (used for instance by UNEP for their national assessments). Also, it was the type of model used in the Limits to growth report (Meadows et al., 1972). This type of model is similar to macroeconomic models in that they describe relationship between variables without having to resort to mechanistic explanation between those variables. Most of the building blocks therefore report “System Dynamics” relationship, meaning that they neither pertain to traditional economic or engineering types of models to describe the mechanisms.

A.2.4 The importance of the link between building blocks: the comparison of REMIND, MERGE and MARKAL-MACRO

MARKAL-MACRO, MERGE and REMIND are built on the same central building blocks: the same growth model (an intertemporal welfare optimization following *à la* Ramsey) coupled with a bottom-up energy supply model. A gross assessment would lead to assimilate them to the same model.

However, in Edenhofer et al. (2010), MERGE and REMIND are described differently as if they were very different models, with different wordings. “Both are optimal growth models where a social planner maximizes global welfare over a given period.” “MERGE [. . .]. Key features include [. . .] a combined ‘top-down’ Ramsey- type economic and ‘bottom-up’ engineering modeling approach, a simple climate model, and international trade. Regional technological learning with global spillovers and costly climate-change impacts enhance the regional links and interactions (Magné et al., 2010, this Issue). Technologies for electricity generation (including options for CCS), and secondary fuel production (synthetic fuels from coal and biomass, H2 from a range of sources, including options for CCS) are explicitly included in MERGE. Technological learning is represented by two- factor learning curves for technology investment costs. A limitation in MERGE is that the model relies on perfect competition and information, production/utility function continuity, representative agents, etc. The low level of tech-

nology detail also permits only a generic representation of end-use energy efficiency as explicit end-use technologies are not represented.

The global multi-region model REMIND represents an intertemporal optimizing energy-economy-environment model which maximizes global welfare subject to equilibrium conditions on different markets. REMIND is a hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model via a hard-link. The main advantage of REMIND is a high technological resolution of the energy system with more than 50 conversion technologies and intertemporal trade relations between the 11 world regions. Trade is modeled for coal, gas, oil, uranium, and the residual composite good as well as for emission permits. Macroeconomic output is determined by a nested CES production function of labor, capital and several end-use types of energy. The switch between energy technologies is a crucial element of endogenous technological change in REMIND. This is supplemented by learning-curve effects that impact the investment costs of wind and solar technologies. While providing a first-best solution based on the perfect foresight assumption, a drawback in REMIND is that it ignores market imperfections and treats technological change as exogenous in the macroeconomic sector.” What makes those two models different lie within the links between the ramsey growth model and the bottom-up energy supply model.

The REMIND model chose a hard-link methodology (which will be discussed in chapter 4) while it seems MERGE opted for a softer methodology. To understand this, Bauer et al. (2008) demonstrates that an intended soft-link does not deliver as well on a simplified case. MARKAL-MACRO is similar to REMIND, however the detail on end-use sectors are more detailed, allowing for a description of specific energy services.

The critical point here will be the linkage of energy supply (in all three case represented by a bottom-up intertemporally optimizing model) to final energy demand. MARKAL-MACRO represents energy services in physical units or useful energy, allowing for an explicit expression of that link. REMIND uses energy as a factor in the aggregate production function, measured in energy (EJ). The demands for final energy then result of the various energies, counted in EJ , being aggregated in a CES production function. MERGE displays a much cruder link, where the production function chooses between Electric and Nonelectric and the bottom-up model supplies it at the lowest cost. This crucial difference will impact the results since the forward-looking vision in each model will be conditional to this link.

In addition, several other points of linkage change to increase the difference. The issue of the capital being both at the aggregate level and in the energy supply calls for understanding whether the rental prices are the same. It seems that the coupling of

both markets is effective in REMIND while ineffective in the other two.

Furthermore, the trade availability linking the markets in different regions alters the energy-economy-environment system evolution pathways. REMIND considers trade for both composite and energy goods, while MERGE only consider trade for the composite good and MARKAL-MACRO only for energy goods. For all models, the substitutability is either perfect or no trade takes place. The issue of trade has a potentially important impact on the costs of mitigation.

In conclusion, while the three models exhibit the same constitutive building blocks, the manner in which they are linked differentiates the models. Consequently, the forward-looking vision will exhibit different properties. The conclusion of this study is that while the building blocks already give a lot of information, the study of the coupling is a crucial issue.

B Appendix - chapter 4

B.1 Technical details of the IMACLIM hybridization procedure illustrated on the example of France for 2010

B.1.1 Step 1: Elaborating supply-use tables in physical units

Because tables of resources and uses of physical flows and prices are not available from statistical institutes in a standardized manner, they must be built through the collection of different data sources.

2010 - Million ton oil-equivalent, Mtoe		Primary energy	Final energy	Non-valuable energies	Total
R1	Production	1	121	13	135
R2	Imports	68	94	0	162
R3	Exports	-0	-33	0	-33
R4	Marine & Aviation bunkers	0	0	0	0
R5	Total Primary Energy Supply	69	182	13	265
R6	Transformations	-69	-17	-0	-86
R7	Energy industry own use	0	-10	0	-10
R8	Losses	0	-4	0	-4
R9	Total Final Consumption	0	151	13	164
R10	Iron and steel	0	4	0	4
R11	Non ferrous metals	0	1	0	1
R12	Non metallic minerals	0	4	0	4
R13	Construction	0	1	0	1
R14	Chemical and petrochemical	0	6	0	6
R15	Paper, pulp and print	0	2	1	2
R16	Mining and quarrying	0	0	0	0
R17	Transport equipment	0	1	0	1
R18	Other industries	0	9	1	11
R19	Transport	0	48	0	48
R20	Residential	0	36	8	45
R21	Agriculture and forestry	0	4	0	4
R22	Fishing	0	0	0	0
R23	Other sectors	0	27	3	30
R24	Non-energy uses	0	8	0	8

Source : IEA, 2010

Table E: Simplified structure of the IEA energy balance

The methodology, explained as follows, has been carried out for those energy sectors : Crude oil/ LNG/feedstocks, Natural gas, Coking coal, Bituminous coal, Coke oven coke, Other coal products, Gasoline, LPG, Jet Fuel, Diesel and heating oil, Heavy fuel oil, Other petroleum products, Biomass and Waste, Biofuels, Electricity, Nuclear, Hydro, Wind/Solar PV/Tide, Heat/Geothermal/Solar Th. For the sake of simplicity we illustrate the method with only two aggregated energy types: primary energy and

final energy.

Starting from IEA energy balance, statistical gaps and stock changes are first distributed between primary supply and consumptions (transformations or final consumption). Then, we isolate in marine and aviation bunkers, the consumption corresponding to national company to return those volume of energy in the sector of transport. The amounts of remaining energy are returned to exportation. After those pre-treatments, we can identify (Table E) domestic production (R1), international trade (R3-4), transformation processes and the distribution of final consumption across activities (R10-24).

Difficulties of the transformation from the energy balance to a supply-use format are twofold. On the one hand, the energy balance does not distinguish between intermediate consumption of productive sectors and households' final demand because it does not include information whether energy consumption serves to produce goods or directly the final consumer's needs (for mobility, heating, etc.). This question arises essentially for transport (R19) and residential (which mixes residential and tertiary-R20), and the decomposition for these two activities is dependent upon the availability of complementary datasets (e.g., transport and households' surveys). On the other hand, energy flows must be explicitly reconstituted to exclude the elements of the balance that do not correspond to commercial energy uses (e.g., non-energy uses, renewable energies, transformation by autoproduction of secondary heat or electricity).

In practice, the elaboration of physical accounting systems can be divided in three sub-steps:

Sub-step 1.1 : disaggregating the description of certain products or uses. This step requires additional information from external statistical sources to define the split of quantities reported in an aggregate manner in the balance (in the absence of information, ad-hoc assumptions must be made). In the case of France, an important feature is, for example, to distinguish fuels used for households' mobility of those used for transport sectors. To this aim, the description of refined products in the energy balance must be complemented by more precise information on the details of uses. Table Fillustrates the disaggregation of the transport sector (R19-20) using external sources of information.

Sub-step 1.2 : delineating the domain of analysis. In practice, this comes down to isolating the crucial components of the balance for the question under consideration. This means suppressing the rows and columns that correspond to activities outside the core analysis without introducing disequilibria in the balance. For example, the

2010 - Million ton oil-equivalent, Mtoe		Primary energy	Final energy	Non-valuable energies	Total
R1	Production	1	121	13	135
R2	Imports	68	94	0	162
R3	Exports	-0	-33	0	-33
R4	Marine & Aviation bunkers	0	0	0	0
R5	Total Primary Energy Supply	69	182	13	265
R6	Transformations	-69	-17	-0	-86
R7	Energy industry own use	0	-10	0	-10
R8	Losses	0	-4	0	-4
R9	Total Final Consumption	0	151	13	164
R10	Iron and steel	0	4	0	4
R11	Non ferrous metals	0	1	0	1
R12	Non metallic minerals	0	4	0	4
R13	Construction	0	1	0	1
R14	Chemical and petrochemical	0	6	0	6
R15	Paper, pulp and print	0	2	1	2
R16	Mining and quarrying	0	0	0	0
R17	Transport equipment	0	1	0	1
R18	Other industries	0	9	1	11
R19	Transport - Households	0	24	0	24
R20	Transport - Sectors	0	24	0	24
R21	Residential	0	36	8	45
R22	Agriculture and forestry	0	4	0	4
R23	Fishing	0	0	0	0
R24	Other sectors	0	27	3	30
R25	Non-energy uses	1	12	0	13

Source : IEA; Odyssee Enerdata - 2010

Table F: Energy balance after sub-step 1.1

withdrawal of renewables and wastes is not problematic because it is a rather independent production process and it is then sufficient to add the volume of electricity produced from these sources . On the contrary, suppressing non-energy uses requires an equivalent decrease of resources.

Sub-step 1.3 : aggregating and allocating quantities of the energy balance in Table F according to the nomenclature of the final input-output matrix. This imposes to adopt a level of aggregation compatible with the nomenclature of national accounts, which comes down to aggregating columns and rows consistently with the level of description adopted in the input-output matrix. In our illustrative example, the columns have not to be modified because they directly correspond to the level of disaggregation of energy in national accounts; but, concerning rows, the study being focused on households, intermediate consumption by tertiary activities must not be isolated and can then be aggregated with the consumption by other sectors.

Sub-steps 1.2 and 1.3 cannot be completely automated because they involve a number of tradeoffs depending on available datasets, the context and the question under consideration. The most important choices concern:

1. **How to assign final energy use.** When surveys on consumption per use are missing, it becomes necessary to use information from similar economies where these data exist (e.g. Odyssee Enerdata database for transport sector) or to deduct the diffracting coefficients from national accounts by adapting the Leontief technique (Moll et al., 2007).
2. **How to establish input-output description consistent with the level of aggregation.** Volumes of energy must be allocated in accordance with the concepts of supply and use tables (Resources, Uses and Intermediate Consumption). The way to do this assignment depends on the level of aggregation used. In the example of France, only cross-sectoral exchanges associated with refining are described (disaggregated industry), other processing methods are not detailed (aggregated sector).
3. **How to assign own uses.** Most of the time, the amount of own used energy is not linked to any economic transaction, but must be recognized because it account for the estimation of technical coefficients, CO₂ emissions, and the opportunity cost they represent during the introduction of the carbon price (because losses and own uses reduce the net efficiency of the transformation). In particular, it seems consistent to identify own uses with distribution losses for coal, gas and electricity, and to transformation processes for refineries.
4. **How to describe the processes of co-productions.** The relationship between coproductions is not described in the symmetrical input-output tables, which conventionally postulates a separation of the conditions of goods' production. This assumption is not acceptable for some sectors (for example, in studies of agricultural production systems) and flows of co-production must then be described as well as the technical fundamentals which link the productions. In the example of France, this question remains of second order: in the circuit of commercial energies, only a small amount of refined products and industrial gases are by-products of other production processes (petrochemicals and inorganic chemistry) and we treat them as domestic resources into refined products and gas.

From sub-steps 1.1 to 1.3, we are finally able to get the input-output table in physical

unit, represented in Table G. For the sake of simplicity towards next steps explanation, non-energy sectors have been aggregated into one composite sector.

2010 - Million ton oil-equivalent, Mtoe	Intermediate consumption			Final consumption			Total uses	Production	Import
	Composite	Primary energy	Final energy	Final demand	GFCF*	Export			
Primary energy	-	-	70.2	-	-	0.1	70.3	2.4	67.9
Final energy	86.6	0.04	18.9	60.0	-	32.8	198.5	109.1	89.4

* Gross fixed capital formation

Table G: Energy Input-output table

Sub-step 1.4 : computing the energy expenses and resources of the economy in monetary values. It simply consists in multiplying on a one-to-one basis the input-output tables in quantities and prices to obtain a table in monetary units which corresponds to energy bills at the desired level of aggregation (Table H). This table is fully consistent with the energy statistics on the diversity of prices, energy consumption, carbon content, etc.

2010 - Million of euros	Intermediate consumption			Final consumption			Total uses
	Composite	Primary energy	Final energy	Final demand	GFCF*	Export	
Primary energy	-	-	29 986.0	-	-	43.8	30 029.8
Final energy	59 386.9	18.9	4 224.3	72 288.6	-	16 612.1	152 530.7

Imports	29 535.0	28 305.8
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* Gross fixed capital formation

Table H: Balance of energy bills

B.1.2 Step 2: Aligning monetary and physical matrices

Once the input-output table that describes the economic circuit of energy flows in quantity, value and price have been built, it remains to integrate it into the national accounts input-output table without changing the important variables for empirical analysis. This is the hybridization step *per se* (Figure C) that can be analyzed in two stages: a set of actions on the rows of the table (1 - adjustment of uses) to insert the monetary sub-table resulting from step 1 and inform the energy expenses of the economy; and a set of actions on the columns (2 - adjustment of resources) to provide the description of the content of energy expenses: the cost structure of one litre of

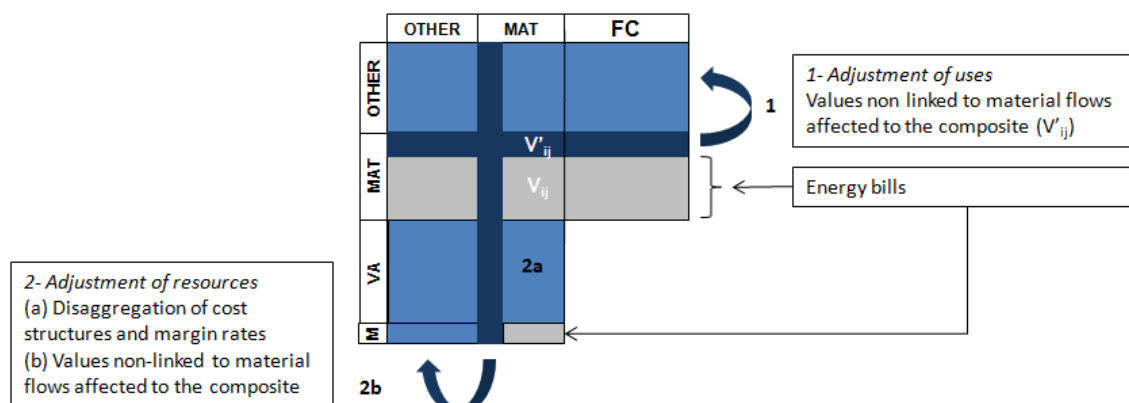


Figure C: Principles of alignment of material balances and monetary flows

fuel purchased, one kWh, etc.. These columns describe the fixed and variable costs of industries that supply, process and distribute energy to consumers.

The result is a modified input-output table in which the value added of energy flows is isolated from those corresponding to non-energy products from “energy branches” aggregated in the composite sector. This rearrangement in the nomenclature maintains the total value added of the economy as well as its sub-totals (wage bill, gross operating surplus, etc.), total imports and totals of final uses (Households’ consumption, exports) while specifying the description of energy circulation.

To carry out this step 2 in the case of France, we start from the input-output table obtained from National Accounts (Table I).

Millions of euros	Intermediate consumption			Final consumption			Total uses
	Composite	Primary energy	Final energy	Final demand	GFCF	Exports	
Composite	1 576 798	263	27 077	1 532 623	376 721	444 564	3 958 046
Primary energy	1 698	0	39 270	-	-	1 255	42 224
Final energy	78 302	11	49 340	80 350	-	14 334	222 338
Value added	1 710 991	264	30 160				4 222 607
Total production	3 367 789	538	145 847				
Imports	448 519	41 539	22 606				
Taxes	141 738	147	53 885				
Total resources	3 958 046	42 224	222 338	4 222 607			

Table I: Input-Output tables in National Accounts

Sub-step 2.1 : adjustments of uses. Starting from the IOT (Table I), we replace the values of energy branches (R2, R3 in orange) by the values of reconstructed energy

bills from Table H. Differences are added to uses and imports of composite (all R1 and R6-C1, in dark blue). These operations do not affect the total value of uses, but change those of different products. Therefore, the supply-use balances are broken for individual sectors.

Millions of euros	Intermediate consumption			Final consumption			Total uses
	Composite	Primary energy	Final energy	Final demand	GFCF	Exports	
R1 Composite	1 667 967	727	10 450	1 540 684	376 721	443 497	4 040 047
R2 Primary energy	-	-	29 986	-	-	44	30 030
R3 Final energy	59 387	32	4 212	72 289	-	16 612	152 531
R4 Value added	1 710 991	264	30 160				4 222 607
R5 Total production	3 438 345	1 022	74 807				
R6 Imports	454 823	29 535	28 306				
R7 Taxes	141 738	147	53 885				
R8 Total resources	4 034 906	30 704	156 998	4 222 607			
Resources - Uses	-5 141	674	4 467				
	C1	C2	C3	C4	C5	C6	

In this example, the intermediate consumption of the composite good for the production of energy (first row, second or third column: L1-C3(2)) is estimated in order to keep the input ratio Composite/Energy for energy products given by the IOTnational accounts (R1-C3(2) / [R2-C3(2) + R3-C3(2)]). The balance of inputs is assigned to the composite consumption good for the production of composite (R1-C1).

Table J: Input-Output table after adjustments of uses

Sub-step 2.2 : adjustment of resources. Balances between uses and resources are restored by manipulating the cost structure of industries (columns of the IOT). Values of imports and intermediate consumption are given by the energy statistics and other cost components - value added, margins, taxes on products - are adjusted to restore equality of resources with uses (Table K). Since, in our example, energy taxation is known (R7-C1/C2), the adjustment is made by value added (R4). Finally, in the case of France, the margin rate is modulated according to buyers, which helps to distinguish the purchaser prices of energy products. After this last step, all accounting identities of the hybrid description are satisfied.

It is useful to keep in mind some principles to guide the choice of adjusting resources. We can offer a procedure to select the set of assumptions to be used to isolate the cost structures of two products (Figure D) with the objective of mobilizing the maximum statistical information available on intermediate consumption and unit costs of each input, labor, consumption of fixed capital and operating margin.

We can then guide the search for information by discussing the conditions of

	<i>Millions of euros</i>	Intermediate consumption			Final consumption			Total uses
		Composite	Primary energy	Final energy	Final demand	GFCF	Exports	
R1	Composite	1 667 967	727	10 450	1 540 684	376 721	443 497	4 040 047
R2	Primary energy	-	-	29 986	-	-	44	30 030
R3	Final energy	59 387	32	4 212	72 289	-	16 612	152 531
R4	Value added	1 716 132	-410	25 693				4 222 607
R5	Total production	3 443 486	348	70 340				
R6	Imports	454 823	29 535	28 306				
R7	Taxes	141 738	147	53 885				
R8	Total resources	4 040 047	30 030	152 531	4 222 607			
	Resources - Uses	0	0	0				
		C1	C2	C3	C4	C5	C6	

Table K: Input-Output table after adjustments of resources

production:

- **First case:** productions P1 and P2 are the result of separate units, the level of dependence is low. It is then likely that the information on one or the other of the structures of this cost is available. This is the case of industries specialized and concentrated, like the nuclear industry that can be isolated from other energy industries.
- **Second case:** P1 and P2 are products within the same units but with different processes. Information on technical coefficients (the unit quantities of inputs, capital, and labor) can be used to distinguish costs. This is the case, for example, for refined petroleum products which are derived from a combination of different methods of physico-chemical separation implemented in refineries.
- **Third case:** the production unit and the processes are similar. Therefore, it is justified to retain the assumption of the same cost structure. Information is used either on unit costs or on the technical coefficients, but for both productions. Associated with the assumption of returns to scale and / or factor prices, this information can help reconstructing a structure of unitary costs for aggregates (since the total quantities produced are known). This case corresponds, for example, to the distinction between diesel and heating oil, used for transportation or heating (but these products are actually physically identical).

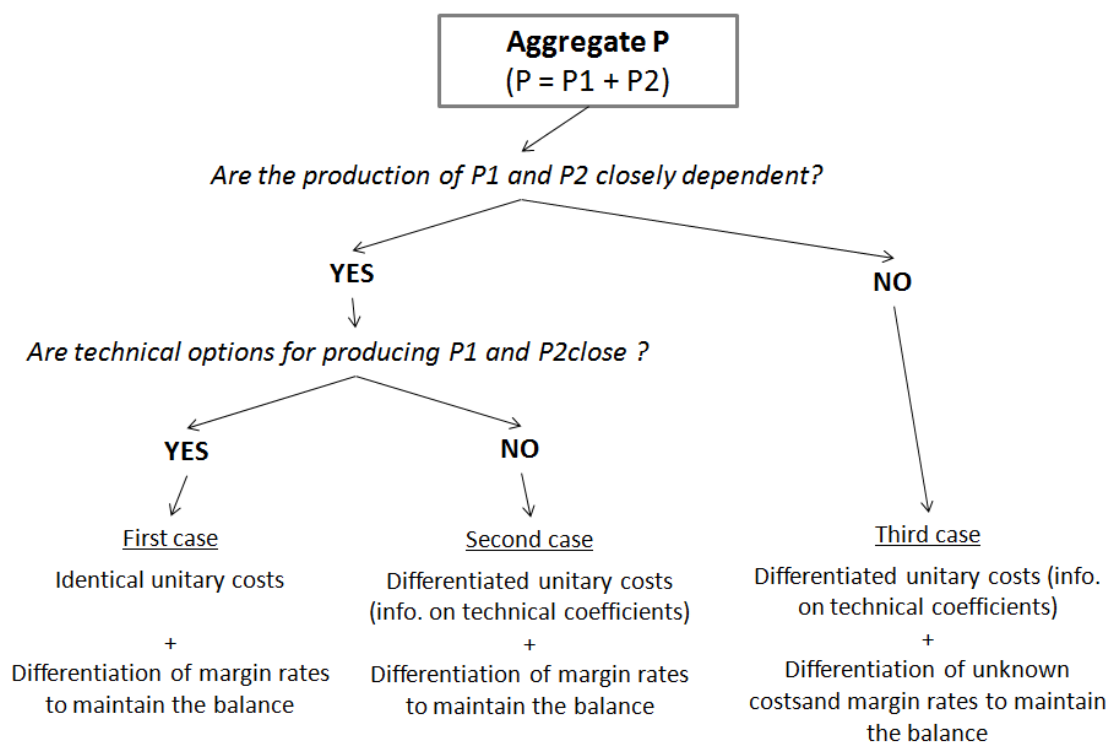


Figure D: Methodology for disaggregating cost structures and margin rates

B.2 Hybrid input-output table for France 2010

France 2016	Millions of euros	Crude oil	Natural gas	Coking coal	Bituminous coal	Coke oven coke	Other coal products	Gasoline + biogasoline	LPG	Jet fuel	Diesel and biodiesel	Heating oil	Heavy fuel oil	Other petroleum products	Electricity	Heat, Geothermal, Solar Th	Iron and steel	Non ferrous metals	Non metallic minerals	Construction	Chemical and petrochemical	Paper, pulp and print	Mining and quarrying	Transport equipment	Transport - Sectors	Agriculture and forestry	Fishing	Agriculture industry	Composite	Public consumption	Household consumption	Investment	Export	TOTAL USES		
Energy sector		Crude oil	-	-	-	-	1 408	773	2 360	10 897	4 149	2 025	1 699	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	24	29 246		
		Natural gas	3	-	-	0	0	70	7	22	103	39	19	15	1 379	826	262	71	504	19	264	287	24	188	36	100	0	967	4 313	10 436	-	-	513	20 470		
		Coking coal	-	-	-	602	163	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20	784		
		Bituminous coal	-	-	-	-	-	-	-	-	-	-	-	-	642	2	273	0	70	-	54	5	-	-	-	-	-	45	24	70	-	-	2	1 187		
		Coke oven coke	-	-	-	-	-	-	-	-	-	-	-	-	1 042	-	27	-	-	6	-	-	-	2	-	-	-	8	12	-	-	32	1 129			
		Other coal products	-	-	-	81	22	-	-	-	-	-	-	-	148	-	113	-	-	-	-	-	-	-	-	-	-	2	58	-	-	1	426			
		Gasoline + biogasoline	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	10	6	3	73	2	2	5	337	33	2	12	364	13 380	-	-	4 419	18 642		
		LPG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	10	28	-	873	16	15	17	7	308	-	98	712	1 945	-	-	513	4 551		
		Jet fuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2 704	4 421		
		Diesel and biodiesel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	28	28	139	62	1 581	46	50	104	8 445	1 644	161	260	7 961	21 211	-	-	1 408	43 026		
		Heating oil	-	-	-	-	-	-	-	-	-	-	-	-	77	1	8	8	38	17	434	4	51	2	947	197	25	22	2 156	5 141	-	-	9 126			
		Heavy fuel oil	-	-	-	-	-	-	-	-	-	-	-	-	350	0	6	145	-	127	20	5	0	308	19	-	104	48	84	-	-	3 456	4 674			
		Other petroleum products	-	-	-	-	-	-	-	-	-	-	-	-	54	90	6	85	329	-	1 211	-	-	-	-	-	-	2	131	151	-	-	1 327	3 385		
		Electricity	16	10	-	3	0	0	40	4	13	59	22	11	9	-	105	431	315	387	17	1 166	388	35	367	609	246	9	839	12 762	19 737	-	-	2 237	39 836	
		Heat, Geothermal, Solar Th	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	-	181	1 400	74	-	1 659		
		Iron and steel	-	-	-	-	1	35	5	8	0	37	8	4	6	29	1	5 330	1 287	444	296	418	28	17	4 012	24	22	-	19	22 740	336	-	121	16 346	51 981	
		Non ferrous metals	-	-	-	0	8	9	2	0	69	2	1	1	1	7	0	1 287	311	107	72	101	7	4	969	6	5	4	5 693	81	-	29	3 949	12 460		
		Non metallic minerals	-	-	-	0	2	1	2	0	9	2	1	1	185	4	300	72	4 429	2 016	759	142	321	1 119	147	301	26	305	22 521	3 987	-	-	4 761	41 457		
		Construction	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1 482	-	-	-	-	-	-	-	-	3	-	-	3	-	45 699		
		Chemical and petrochemical	-	-	-	5	4	32	57	3	256	55	27	40	2 459	52	596	144	497	227	24 204	1 052	132	1 703	130	6 690	371	1 424	30 404	33 990	25 869	-	-	74 547	205 653	
		Paper, pulp and print	-	-	-	0	0	1	2	0	10	2	1	2	22	0	18	4	265	61	1 363	3 404	27	191	75	158	6	1 708	14 569	4 959	-	-	6 413	33 229		
		Mining and quarrying	-	-	-	14	9	1	0	2	0	0	0	2	0	2 185	530	1 263	180	1 113	121	138	73	8	117	43	705	2 513	76	-	-	627	9 790			
		Transport equipment	-	-	-	0	0	1	2	0	7	1	1	1	16	0	32	8	41	7	49	13	8	33 749	1 853	172	2	64	17 328	64 747	142	26 006	81 526	225 752		
		Transport - Sectors	-	-	-	0	0	3	6	0	25	5	3	4	33	1	29	7	67	33	199	28	13	80	10 974	48	4	167	20 939	25 161	2 836	-	-	16 453	77 128	
		Agriculture and forestry	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13 757	-	-	32 874	5 199	28 793	-	1 348	12 967
		Fishing	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	42	1 903	362	-	-	519	6 430	
		Agriculture industry	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	27 956	36 229	120 103	210	-	24 876	218 917		
		Composite	206	2 363	-	4	41	82	274	486	29	2 174	462	225	336	8 377	178	12 274	2 965	7 515	23 652	26 656	7 200	1 890	60 751	35 031	9 842	565	28 611	1 053 198	733 310	492 996	305 003	200 613	3 016 897	
Value-added		Labour net	21	1 287	-	1	3	14	20	35	2	156	33	16	24	4 485	94	2 129	514	3 161	5 182	7 616	2 021	570	9 349	24 533	11 018	330	13 249	854 675	-	-	4 222 897	-		
		Labour taxes	9	357	-	1	1	6	9	15	69	15	7	11	11	1 948	41	935	226	1 389	2 217	3 346	898	259	4 187	10 718	4 840	145	5 826	287 605	-	-	627	9 790		
		DB Labour taxes	2	137	-	0	0	1	2	4	0	17	4	2	3	480	10	230	56	342	561	824	219	62	1 012	2 656	1 193	36	1 434	70 868	-	-	-	-		
		FCF	116	1 343	-	2	2	7	16	28	2	124	26	13	19	4 700	100	1 104	267	849	1 154	2 968	939	1 303	5 069	11 563	10 743	343	4 190	222 606	-	-	-	-		
		Output taxes	-6	287	-	2	2	11	19	1	87	18	9	13	1 006	21	272	66	409	435	1 102	278	99	1 063	1 351	-6 418	-1	1 488	55 693	-	-	-	-			
		Netoperating surplus	66	1 099	-	-2	6	3	40	70	4	315	67	33	49	3 848	82	442	107	639	2 698	4 145	1 07	-332	-2 547	-3 210	4 738	-90	-982	287 215	-	-	-	-		
		BT	28 751	9 799	784	1 039	311	35	627	1 163	1 932	8 117	1 912	1 729	619	1 025	-	18 826	4 547	6 683	-	62 069	9 223	2 871	66 458	2 965	8 183	1 368	26 736	245 164	-	-	-	-		
Specific margins		Crude oil	25	-	-	107	96	16	368	654	39	2 927	623	303	452	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Natural gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Coking coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Bituminous coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Coke oven coke	-	-	0	-	-5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Other coal products	-	-	0	-	-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Gasoline + biogasoline	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		LPG	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Jet fuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Diesel and biodiesel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Heating oil	-	-																																

B.3 Formulary of the “KLEM” model of section 4.3.1

We successively detail the production of the aggregate energy and composite resources, final consumption and investment, international trade, price formations and market clearings. Variable names indexed with a “0” designate the specific values calibrated on 2010 benchmark data; they thus indicate parameters of the equation system. Whenever required, good-specific variables are indexed by E for the energy good, by C for the composite good.

B.3.1 Production of the aggregate resource

The input trade-offs of each production (energy and the composite good) are represented as nested structures of Constant Elasticity of Substitution functions (cf. Figure 4.3). At each tier of these structures, standard cost minimisation defines the consumption of any input A traded off with another input B (capital K and labour L , value-added KL and energy E , KLE aggregate and composite input αY or domestic output Y and imported variety M) to produce some aggregate AB (value-added KL , KLE aggregate, domestic output Y or total resource Q) as:

$$A = \left(\frac{\alpha_{AB}}{p_A} \right)^{\sigma_{AB}} \cdot \left(\alpha_{AB}^{\sigma_{AB}} p_A^{1-\sigma_{AB}} + \beta_{AB}^{\sigma_{AB}} p_B^{1-\sigma_{AB}} \right)^{\frac{\sigma_{AB}}{1-\sigma_{AB}}} \cdot AB \quad (\text{B-1})$$

with σ_{AB} the central elasticity parameter (cf. values reported Table 4.4); α_{AB} and β_{AB} coefficients calibrated on benchmark 2010 data; p_A and p_B the purchaser prices of good A and B .

B.3.2 Final consumption and investment

The consumed income of households R is the sum of primary factor payments and taxes, i.e. Gross Domestic Product (GDP), net of public expenses $p_G G$, investment $p_I I$ and the trade balance $p_X X - p_M M$:

$$R = GDP - \left(\sum_i p_{G_i} G_i + \sum_i p_{I_i} I_i + \sum_i p_{X_i} X_i - \sum_i p_{M_i} M_i \right) \quad (\text{B-2})$$

Households' utility is a constant elasticity of substitution function of their consumptions of the energy and composite goods, H_E and H_C . Facing prices p_{H_i} and elasticity σ_u , utility maximisation induces:

$$H_i = \left(\frac{\alpha_U}{p_{H_i}} \right)^{\sigma_U} \cdot \left(\alpha_U^{\sigma_U} p_{H_E}^{1-\sigma_U} + \beta_U^{\sigma_U} p_{H_C}^{1-\sigma_U} \right)^{\frac{\sigma_U}{1-\sigma_U}} \cdot R \quad (\text{B-3})$$

Public spending G_i is a constant share s_{G_i} of GDP (traditionally nil for energy goods i.e. $s_{G_E} = 0$)

$$p_{G_i}G_i = s_{G_i}GDP \quad (\text{B-4})$$

Investment has a constant ratio s_{I_i} to consumed income, amounting to a constant savings rate (of course $s_{I_E} = 0$):

$$p_{I_i}I_i = s_{I_i}R \quad (\text{B-5})$$

B.3.3 International trade

Following the Armington specification of international trade ([Armington, 1969](#)), the trade-off between domestic production Y and imports M is settled by a CES function—the upper tier of the production function of aggregate resource introduced above. Y and M thus follow the general form of (1). Exports X_i are defined as elastic to terms-of-trade:

$$X_i = X_{i_0} \left(\frac{p_{X_i} p_{M_{i_0}}}{p_{M_i} p_{X_{i_0}}} \right)^{\sigma_{X_i}} \quad (\text{B-6})$$

For lack of a better assumption both σ_{X_i} are set to 1.

B.3.4 Market clearings and accounting identities

Market balance for each good i equates total resource Q_i to the sum of intermediate consumptions $\alpha_{ij}Y_j$, household consumption H_i , the consumption of public administration G_i , the consumption for investment I_i and the exports X_i :

$$Q_i = \sum_j \alpha_{ij}Y_j + H_i + G_i + I_i + X_i \quad (\text{B-7})$$

Labour and capital demand by the two productions i sum up to total exogenous labour supply L and capital endowment K (through the adjustment of wage w and rent p_K):

$$\sum_i L_i = L \quad (\text{B-8})$$

$$\sum_i K_i = K \quad (\text{B-9})$$

B.3.5 Producer and Purchaser Prices

The cost of labour p_L is equal to the net wage w plus payroll taxes levied at a constant rate τ_{CS} :

$$p_L = (1 + \tau_{CS})w \quad (\text{B-10})$$

The price p_{AB} of any CES aggregate AB (value-added KL , KLE aggregate, domestic output Y , total resource Q) is the standard function of prices p_A and p_B :

$$p_A = \left(\alpha_{AB}^{\sigma_{AB}} p_A^{1-\sigma_{AB}} + \beta_{AB}^{\sigma_{AB}} p_B^{1-\sigma_{AB}} \right)^{\frac{1}{1-\sigma_{AB}}} \quad (\text{B-11})$$

An exception, p_Y adds to this generic form a constant ad valorem output tax $\tau_Y p_Y$.

International prices p_{M_i} are fixed (the international composite good is the numéraire of the model; the price of imported energy relative to that of the international composite good is constant). The purchaser's price of good i consumed in the production of good j (p_{ij}), by households (p_{H_i}), by public administrations (p_{G_i}), in investment (p_{I_i}) or by exports (p_{X_i}) is the sum of: its resource price p_{Q_i} ; a constant, agent-specific, ad valorem margin τ_{SM} ; an exogenous, agent-specific excise tax t ; an exogenous, agent-specific ad valorem sales tax τ :

$$p_{ij} = \left(p_{Q_i} (1 + \tau_{SM_{ij}}) + t_{ij} \right) (1 + \tau_{ij}) \quad (\text{B-12})$$

$$\forall A \in [H, G, I, X] p_{Ai} = \left(p_{Q_i} (1 + \tau_{SM_{Ai}}) + t_{Ai} \right) (1 + \tau_{Ai}) \quad (\text{B-13})$$

All tax and excise rates are calibrated on benchmark data. Calibrating on non-hybridized matrices mechanically induces nil values for all τ_{SM} , i.e. prices are only differentiated by explicit tax differences across agents. The energy quotas simulated in section 0 use the t excises (on firms or household consumptions only, or on both agents simultaneously) as variables to comply with consumption cuts targets.

B.3.6 Accounting aggregates

GDP is the sum of factor payments and taxes T :

$$GDP = \sum_i wL_i + \sum_i p_K K_i + T \quad (\text{B-14})$$

while T is the sum of taxes levied of labour, productions and consumptions:

$$T = \sum_i \tau_{CS} \omega L_i + \sum_i \tau_{Y_i} p_{Y_i} Y_i + \sum_i \sum_j \frac{\tau_{ij}}{1 + \tau_{ij}} p_{ij} \alpha_{ij} Y_j + \sum_i \sum_j t_{ij} \alpha_{ij} Y_j + \sum_{A=H,G,I,X} \sum_i \frac{\tau_{A_i}}{1 + \tau_{A_i}} p_{A_i} A_i$$

(B-15)

C Appendix - chapter 6: Data, variables, parameters and calibration choices for IMACLIM-BR reference settings

C.1 Data: construction of the benchmark hybrid Social Accounting Matrix 2005

The benchmark SAM 2005 is used to calibrate all IMACLIM-BR versions.

C.1.1 Construction of the SAM

National accounting statistics provide a comprehensive numerical framework for macroeconomic simulation exercises. In its current version, IMACLIM BRAZIL is calibrated at base year 2005 on a SAM built on data from two synthesis tables produced by the *Instituto Brasileiro de Geografia e Estatística* (IBGE):

- The MIP (*Matriz Insumo Produto*, input-output table) balances the uses and resources of products—up to 110 of them in its most disaggregated version.
- The CEI (*Contas Econômicas Integradas*) details the primary and secondary distribution of income between 6 “institutional sectors”, i.e. aggregate economic agents: financial firms, non-financial firms, households, non-profit organisations, public administrations, “rest of the world”.

Raw MIP data are processed to obtain a description of production and consumption in a square “product - product” system, with no accumulation of stocks. The CEI is aggregated into 4 institutional sectors (households, firms, public administrations and “rest of the world”), and its many entries are simplified into a set of transfers at a level of aggregation comparable to that of the MIP. Basically the primary distribution of income is composed of productive factor remuneration (labor, productive capital and land) and income from property (financial income). The secondary distribution of income is made of indirect taxes and social transfers. Its use ultimately allows extending the traditional framework of general equilibrium modelling to the distribution of national income between economic agents, the resulting changes in the financial positions of those agents, and the corresponding debt payments. MIP and CEI data are finally combined in a unique SAM framework.

C.1.2 Data Hybridization

Considering its focus on climate policy assessment, IMACLIM BRAZIL requires a high degree of realism in the description of the energy inputs to production, and the energy

consumptions of households. Indeed, the greenhouse gas emissions targeted by climate policies arise from the consumption of explicit physical quantities that are poorly represented by the quasi-quantities commonly obtained from the MIP through the normalization of output prices. Therefore, a rigorous calibration of the model requires some accurate accounting of the physical quantities of energy consumed, expressed in a relevant unit (e.g. million-tons-of-oil-equivalent, Mtoe).

Such an accounting is found in the national energy balance (*Balanço Energético Nacional*, BEN) compiled by EPE (*Empresa de Pesquisa Energética*). It is also possible to gather from various sources (BEN, ANE – *Agência Nacional do Petróleo*, etc.) observed final prices for each type of energy, or aggregate thereof, which are indeed end-use specific. The term-by-term product of energy balances and agent-specific prices (the single-price assumption is abandoned) defines a matrix of energy consumptions in monetary terms, which does not match that embedded in the MIP for energy products, for a variety of reasons (the inclusion of services beyond the sheer energy consumptions, the heterogeneity of products, biases from the statistical balancing methods, etc.). Hybridization of the MIP then consists in imputing the differences between the values found in the MIP, and those computed from energy statistics, to some non-energy goods and sectors. For lack of a better hypothesis the value-added of the energy products are corrected pro-rata this imputation. In this way, the product disaggregation is amended, while the cross-sectoral totals are kept consistent with the original statistics. The calibration of the model on this hybrid MIP (which is included in the final benchmark SAM) eventually leads it to depict (i) volumes of the non-energy goods that are traditionally derived from the single-(normalized)-price assumption, and (ii) volumes and prices of the energy goods that are strictly aligned on the available statistics. The differences in price of the same energy good from one agent to the other (e.g. the variable average prices of 1 kWh of electricity) are accounted for by calibrating “specific margins” to the different uses.

The technical details of the hybridization procedure are reported in section B.1 on the case of France 2010. We follow the same procedure to build the hybrid I-O table for Brazil 2005.

C.1.3 Disaggregation of households in 6 income groups

The disaggregation of the “representative household” in 6 income classes is based on an extrapolation of the Household Budget Survey 2002-2003 (IBGE, 2004), which extensively covers the resources and uses of Brazilian households. The method of disaggregation in 6 income brackets carried-out, is similar to that of [Grottera et al.](#)

(2015).

C.2 Variables, parameters and choice of parameters values

The quantitative model implementation distinguishes between model variables, calibrated parameters and non-calibrated parameters. The set of variables characterizes the state of the energy-economic system at the time horizon studied. Calibrated parameters are characteristic of the system and are estimated so that the model reproduces base year SAM. Exogenous non-calibrated parameters are of two types: (i) structural parameters: parameters controlling the functioning of the economic system - elasticity of substitution for instance - and (ii) scenarios parameters - including policy parameters like the carbon tax - used to generate contrasted scenarios.

C.2.1 Variables and parameters in IMACLIM-BR 6 reference setting

Table L, table M and table N provide the complete list of variables, calibrated and non-calibrated parameters.

Variable	Description
α_{ij}	Technical coefficient, quantity of input i per unit of output j
a	Endogenous multiplier for net wages evolution
C_i	Level of HH final consumption of good or service i , real terms - physical unit for energy (ktoe)
$C_{i_{min}}$	Level of HH basic need for good or service i in the LES utility function
CPI	Consumer Price Index (Fisher)
δ_{Lg}	Rate of decrease of payroll tax rate in case of related carbon tax recycling scheme
$FCAP_h$	Self-financing capacity of HH
$FCAP_f$	Self-financing capacity of $FIRMS$
$FCAP_g$	Self-financing capacity of GOV
$FCAP_m$	Self-financing capacity of ROW
GDP	Gross Domestic Product
$GFCF_h$	Gross fixed capital formation of HH
$GFCF_f$	Gross fixed capital formation of $FIRMS$

$GFCF_g$	Gross fixed capital formation of GOV
G_i	Level of GOV final consumption of good i , real terms
GOS	Gross operating surplus (land rent excluded)
I_i	Level of final consumption for investment in good i , real terms
k_j	Capital intensity of sector j
l_j	Labor intensity of sector j
LAND	Total land rent across sectors
ld_j	Land intensity of sector j
M_i	Level of imports of good i , real term
M_S	Total specific margin - Nil at base year
N	Total population
NS	Total active population
OT	Others transfers
OT_h	Others transfers to HH
OT_f	Others transfers to FIRMS
OT_g	Others transfers to GOV
p_i	Average price of i
p_{BTICij}	Before tax purchaser's price of good i for sector j
p_{BTZi}	Before tax purchaser's price of good i for final demand sectors
p_{Ci}	Purchaser's price of good or service i for HH final consumption
p_{Gi}	Purchaser's price of good i for GOV final consumption
p_{Ii}	Purchaser's price of good i for investment (Gross capital formation)
p_{ICij}	Purchaser's price of good i for sector j
p_K	Cost of capital input (weighted sum of investment prices)
p_{Lj}	Cost of labor for sector j
p_{LDj}	Cost of land for sector j (BIO, CATT and AGRI sectors)
p_{Mi}	Import / world price of good j

p_{xi}	Purchaser's price of good i for exports
p_{Yj}	Producer's price of good j
ρ_f	Rate of private transfers per capita
ρ_g	Rate of social transfers per capita
R_h	Gross disposable income of HH
R_f	Gross disposable income of $FIRMS$
R_g	Gross disposable income of GOV
RBT_h	Revenue before tax / Gross primary income of HH
RBT_f	Revenue before tax / Gross primary income of $FIRMS$
R_{CONS}	Consumed income of HH
$\tau_{BM_{COMP}}$	Rate of business margin (negative) for $COMP$ sector
$\tau_{TM_{COMP}}$	Rate of transport margin (negative) for $COMP$ sector
T	Total tax revenues
T_{hf}	Indirect transfers from HH to $FIRMS$
T_{hg}	Indirect transfers / tax from HH to GOV
T_{Carb}	Total carbon taxes
T_{CONS}	Total sales taxes
TI_h	Income tax payments from HH
TI_f	Corporate tax revenues
TL_f	Payroll taxes paid to $FIRMS$
TL_g	Payroll taxes paid to GOV
TY	Tax on production
u	Rate of unemployment
w_j	Average net wage in the production of sector j
w	Average net wage across sectors
X_i	Level of exports of good i , real term
Y_i	Level of production of good / sector i , real term

Table L: List of variables

Calibrated parameters	Description
$\overline{\pi}_i$	Mark-up rate (rate of net operating surplus) in the production of good i
$\overline{\tau}_{Yj}$	Rate of tax on production
$\overline{\tau}_{Bmi}$	Rate of business margin on purchase of good i
$\overline{\tau}_{Tmi}$	Rate of transport margin on purchase of good i
$\overline{\tau}_{MSiCi}$	Specific mark-up rate on intermediate consumption of energy good i . Defined during the hybridization process
$\overline{\tau}_{MSzi}$	Specific mark-up rate on final consumption of energy good i . Defined during the hybridization process
$\overline{\tau}_{CONSi}$	Rate of aggregate sales tax on purchase of good i
$\overline{\tau}_{Lfi}$	Rate of payroll taxes paid to private companies by sector i
$\overline{\tau}_{Lgi}$	Rate of payroll taxes paid to public administration by sector i
$\overline{\omega}_{Kh}$	Share of capital income accruing to HH
$\overline{\omega}_{Kf}$	Share of capital income accruing to $FIRMS$
$\overline{\omega}_{Kg}$	Share of capital income accruing to GOV
$\overline{\omega}_{LDh}$	Share of land rent accruing to HH
$\overline{\omega}_{LDf}$	Share of land rent accruing to $FIRMS$
$\overline{\omega}_{LDg}$	Share of land rent accruing to GOV
$\overline{\omega}_{OTh}$	Share of others transfers accruing to HH
$\overline{\omega}_{OTf}$	Share of others transfers accruing to $FIRMS$
$\overline{\omega}_{OTg}$	Share of others transfers accruing to GOV
$\overline{\tau}_{hf}$	Rate of indirect tax levied on HH and accruing to $FIRMS$
$\overline{\tau}_{hg}$	Rate of indirect tax levied on HH and accruing to GOV
$\overline{\tau}_{ih}$	Rate of tax on income of HH
$\overline{\tau}_{If}$	Rate of corporation tax (on $FIRMS$)
$\overline{\alpha}_i$	Share coefficient for good i in LES utility function
$\overline{\lambda}_{ij}, \overline{\lambda}_{Lj}, \overline{\lambda}_{Kj}, \overline{\lambda}_{LDj}$	Share coefficients of CES production function for intermediate input i , labor, capital and land for production of sector j
$\overline{\beta}_i$	coefficient linking total fixed capital consumption and fixed capital formation of good i
$\overline{\gamma}_{ij}$	CO2 emission factor linked to consumption of good i in production of good j
$\overline{\gamma}_{ih}$	CO2 emission factor linked to consumption of good i in final consumption by HH

Table M: List of calibrated parameters

Table O shows the values of a first set of structural parameters in the reference setting of IMACLIM-BR 6.

Basic needs and sh shares parameters are estimated to reflect slightly contrasted income elasticities of consumed goods and services. Subsequently, energy goods, food

and manufactured goods and services show respective 1.1, 0.9 and 1 income elasticities.

In production trade-offs the elasticities of substitution between the varying part of technical coefficients are set to $\sigma = 1.2$ for all sectors. Similarly as the LES demand system, technical asymptotes makes it possible to adjust output and furthermore substitution elasticities of the different inputs and factors. For some sectors like the power sector, the choice of technical asymptotes is made to mimic bottom-up scenarios about the abatement potential of the power sector until 2030. In practice, following the national energy plan, the power generation system would not change significantly with a carbon price of 100\$US: around 5-10 Mt of emissions abatement would result from additional hydro power and wind power capacities. Table P shows the values of technical asymptotes for all production factors and sectors.

As shown in table Q, the elasticity of the wage curve of -0.3 is taken from [Estevão and Carvalho Filho \(2012\)](#) and reflects rather flexible wages. Finally, with $sh_r = 0.5$, the wage curve is half indexed on nominal and half indexed on real wage in the reference setting.

C.2.2 Specific non-calibrated parameters in IMACLIM-BR 12-ext reference setting

Table R shows the set of specific non-calibrated parameters of IMACLIM-BR 12-ext version.

Table S shows the values of the specific structural parameters.

Non-calibrated parameters	Description
Structural parameters	
sh_i	Share of base year consumption per capita needed to compute basic needs of good i
σ_j	Elasticity of substitution between production factors of sector j
$\beta_{ij}, \beta_{Lj}, \beta_{Kj}, \beta_{LDj}$	Shares of base year technical coefficients corresponding to floor values for intensity of input i , labor, capital and land for production of sector j
σ_{Mi}	Elasticity of the ratio of imports to domestic production of energy good i , to the corresponding terms of trade
σ_{MYi}	Elasticity of imports of non-energy good i to GDP - "income" elasticity of imports
σ_{Xi}	Elasticity of exports of good i to the corresponding terms of trade
σ_u	Elasticity of efficient wage to unemployment rate
sh_r	level of indexation of the wage curve on real wages
Scenarios parameters	
δ_N	Rate of total population growth
δ_{NS}	Rate of active population growth
ϕ_{Lj}	Rate of labor productivity gain of sector j implementing as factor augmenting
u_{ref}	Reference rate of unemployment
ψ_{ij}	Rate of decrease of production intensity of input i for production of good j - structural driver
ψ_{Kj}	Rate of decrease of capital intensity of production of good j - structural driver
ψ_{LDj}	Rate of decrease of land intensity of production of good j - structural driver
δ_{PMi}	Rate of variation of world price of good i compared to composite
τ_S	Saving rate of HH
sh_{Mi}	exogenous variation of M/Y ratio compared to base year outside terms of trade for energy sector i - non-price structural change of energy imports
δ_{Xi}	Rate of growth of exports outside terms of trade - structural change for energy sectors and proxy of rest of the world growth for non-energy sectors
t_{Carb}	Carbon tax
t	time horizon

Table N: List of non-calibrated parameters

Parameters	Values					
	BIO	FF	ELEC	AGRI	INDUS	COMP
sh	0	0	0	0.2	0.1	0.1
σ	1.2	1.2	1.2	1.2	1.2	1.2
σ_M	1.2	1.2	1.2	1.2	1.2	1.2
σ_{MYi}	-	-	-	1.1	1.1	1.1
σ_X	1	1	1	1	1	1

Table O: values of structural parameters

Parameters	Values					
	BIO	FF	ELEC	AGRI	INDUS	COMP
	0.8	0	0.9	0	0	0
	0	0.8	0.9	0	0	0
	0.5	0.5	0.9	0	0	0
	0.95	0.95	0.95	0.95	0.95	0.75
	0.95	0.95	0.95	0.95	0.95	0.75
	0.95	0.95	0.95	0.95	0.95	0.75
β_L	0.8	0.8	0.8	0.8	0.8	0.75
β_K	0.8	0.8	0.8	0.8	0.8	0.75
β_{LD}	0.8	0.8	0.8	0.8	0.8	0.75

Table P: values of structural parameters

Parameters	Values
σ_u	-0.3
sh_r	0.5

Table Q: values of structural parameters

Parameter	Description
Structural parameters	
sh_i	Share of base year consumption per capita needed to compute basic needs of good or service i
σ_{MR}	Elasticity of substitution between food goods
σ_{RES}	Elasticity of substitution between housing energy sources in final demand
σ_{VF}	Elasticity of substitution between <i>INDVHC</i> and <i>FTRA</i> in final demand
σ_F	Elasticity of substitution between <i>BIOTRA</i> and <i>ROILTRA</i>
Scenarios parameters	
δ_{RESi}	Rate of non-price based change of intensity of energy source i in residential energy demand
$\delta_{EffFuel}$	Rate of fuel efficiency gain of private transportation - AEEI
δ_{YOIL}	Rate of increase of total domestic oil production

Table R: Specific non-calibrated parameters

Parameters	Values			
	FD	TRA	RES	OTH
sh_i	0.15	0	0.1	0.1
σ_{MR}	0.1			
σ_{RES}	0.4 (Gurgel and Paltsev, 2014)			
σ_{VF}	0.3 (Gurgel and Paltsev, 2014)			
σ_F	5			

Table S: values of specific structural parameters

Résumé long

Cette thèse s'ouvre sur le constat d'un changement de paradigme dans la lutte contre le changement climatique avec l'accord universel de Paris ([FCCC-UN, 2015a](#)) qui entérine l'objectif d'annuler les émissions nettes de GES avant la fin du siècle et d'inverser la courbe des émissions dès que possible. Cet objectif global est assorti d'engagements nationaux de moyen terme, certes encore insuffisants au regard de la cible globale, mais qui instaurent une nouvelle façon de concevoir les politiques climatiques: celle qui vise à aligner objectifs d'émissions et objectifs plus généraux de développement dans une stratégie transversale.

Historiquement, la discussion scientifique sur l'atténuation des changements climatiques a été centrée sur le climat et les enjeux technico-économiques d'abattement des émissions à long terme. La question de la transition bas-carbone est aujourd'hui plus vaste et inclut celles de l'articulation d'objectifs divers (dont objectifs d'émissions et de développement économique) et la question des moyens opérationnels d'enclencher et de piloter la transition à court - moyen terme pour respecter les cibles de long terme.

Pourtant, au regard des derniers rapports du GIEC qui rassemblent l'état de l'art de la connaissance des enjeux d'atténuation notamment, il semble que l'on ne soit pas encore en mesure d'apporter des réponses satisfaisantes à ces questions. En regardant plus en détail, on constate même par exemple, un recul de l'information quantitative consacrée aux questions économiques de compétitivité, de réforme fiscale, de finance ou encore concernant les modes de développement. Finalement se pose la question du contenu quantitatif des scénarios générés et celle des modèles de prospective énergie-économie qui les alimentent.

Dans les quinze dernières années, le besoin urgent de diagnostics pour les décideurs a provoqué l'explosion du nombre de scénarios produits, de modèles et d'équipes de modélisation avec un résultat en demi-teinte. Malgré une progression indéniable des connaissances, on constate un obscurcissement du paysage des modèles avec l'incorporation de mécanismes de plus en plus complexes et une hybridation des approches au delà des paradigmes historiques de modélisation.

Cette thèse a un double objectif: (i) contribuer à l'analyse méthodologique de la boîte à outil de modélisation des transformations énergie-émissions-économie et (ii) contribuer au débat sur la transition bas-carbone au Brésil via la construction d'un outil de modélisation dédié. La première partie de la thèse est donc consacrée aux aspects méthodologiques déclinés en 4 chapitres et la seconde à la transition bas-carbone au Brésil en 4 chapitres.

Le chapitre 1 propose une synthèse critique de l'état de l'art de la modélisation intégrée à l'interface énergie-économie-atténuation du changement climatique. Pour cela il s'appuie sur les scénarios globaux de transformation de long terme du Cinquième rapport d'évaluation du GIEC (AR5 - [Edenhofer et al. \(2014\)](#)) qui mobilisent des outils représentatifs du paysage des modèles disponibles. L'analyse montre tout d'abord que la production de scénarios a explosé depuis l'AR4 ([Metz et al., 2007](#)) en même temps que les équipes de recherche et les modèles disponibles. L'examen approfondi des scénarios produits permet d'abord de mettre en évidence les progrès qu'ils ont permis dans la compréhension des enjeux d'atténuation du changement climatique à l'échelle mondiale. Ces nouvelles clés de compréhension s'articulent autour de deux éléments: (i) le rôle des technologies bas-carbone décisives comme la capture et stockage du carbone, les technologies renouvelables ou les bioénergies pour atteindre les objectifs climatiques; (ii) l'analyse des conséquences d'une action climatique retardée et de régimes d'accession à l'effort climatique des différentes régions sous-optimaux. Ces travaux mettent l'accent sur les implications sur le coût global de l'action et la ventilation du coût pour les différentes régions du monde, d'hypothèses alternatives sur ces éléments. Par ailleurs, dans la perspective d'inclure les politiques climatiques dans des stratégies plus larges de développement durable, l'AR5 fournit une analyse des "co-bénéfices" de l'action climatique en terme d'objectifs de développement (sécurité énergétique, biodiversité, qualité de l'air, emploi, etc.). Enfin, d'un point de vue méthodologique la plupart des scénarios produits sont le fruit de travaux qui mobilisent un jeu de plusieurs modèles et les scénarios produits sont cohérents sur les jeux de modèles. Cette méthode multi-modèle permet une meilleure robustesse des résultats et une meilleure gestion de l'incertitude liée à la conception alternative des modèles.

Pourtant, il semble que de tels efforts nous laissent encore au "milieu du gué" si l'objectif est de fournir des préconisations opérationnelles et des leviers d'action pour "piloter" la transition vers des économies bas-carbone. En effet, ces scénarios sont dans l'ensemble des scénarios de long terme qui mettent l'accent sur des transformations technologiques dans un environnement économique optimal sans friction.

Nous identifions plus précisément quatre directions d'analyse qui devraient compléter les travaux existants. Premièrement, les scénarios incluent généralement des hypothèses très agrégées sur les trajectoires de développement et n'explorent pas les conséquences de trajectoires de développement alternatives sur la demande d'énergie finale et les émissions de GES. Pourtant, les modes de consommation, le type de planification urbaine, la dématérialisation de l'économie, sont des déterminants fondamentaux des émissions et sont la marque de contenu "matière" alternatifs de la croissance économique. En somme, la plupart des travaux reflètent des trajectoires d'abattement à la marge de trajectoires de développement données. Deuxièmement, au delà de trajectoires économiques optimales, se pose la question de l'articulation entre objectifs climatiques et objectifs socio-économiques dans un monde "second-best" marqué par d'importantes distorsions par rapport au paradigme d'optimalité. Dans cette optique, intégrer les barrières et sous-optimalités institutionnelles, comportementales, de marché, principales dans l'analyse, permettrait d'identifier les éventuels co-bénéfices économiques de l'action climatique. Troisièmement, ces scénarios reflètent des trajectoires de *transformation* de long terme et négligent les enjeux de *transition* de court-moyen terme qui se posent et les conditions de déclenchement de ces transitions. Enfin, dans la plupart des cas, les trajectoires bas-carbone reposent sur la seule implémentation d'un prix du carbone. Pourtant, il existe en pratique tout une palette d'instruments disponibles et complémentaires pour organiser la transition bas-carbone dans une perspective multi-objectifs, depuis les réformes fiscales carbone plus larges jusqu'à la planification urbaine et les politiques d'infrastructures, en passant par des mécanismes financiers pour déclencher la transition à court terme.

D'un point de vue méthodologique, il semble que l'approche multi-modèle n'exploite encore que partiellement le potentiel d'analyse d'incertitude liée à la conception alternative de ces modèles. Ainsi la plupart des travaux se focalisent sur les résultats qui sont robustes sur le panel de modèles utilisés mais étudient peu la question de pourquoi les résultats diffèrent entre les modèles. Un effort récent a consisté à produire des diagnostics des modèles basés sur une caractérisation de leur réponse agrégée à des chocs de politiques climatiques standardisés selon des indicateurs globaux comme l'identité de Kaya ou le coût macroéconomique actualisé (Kriegler et al., 2015a). De tels efforts permettent une meilleure connaissance de la "boîte à outils" mais n'aident pas réellement à clarifier les liens entre les résultats obtenus et les choix alternatifs de structure interne des modèles, pré-requis nécessaire pour une analyse d'incertitude réelle.

Ce diagnostic critique de l'état de l'art des scénarios intégrés pose finalement la question du statut des modèles eux-même vis à vis de leur conception et leur struc-

ture interne qui conditionnent leur domaine de compétence. Un enjeu clé est ainsi de comprendre dans quelle mesure les écarts sur l'analyse produite s'expliquent par des variables et mécanismes manquants. A ce titre, les typologies usuelles peinent à caractériser la diversité de conception des outils et de leur représentation des transformations énergie-économie. Les paradigmes historiques de modélisation *bottom-up* et *top-down* ont fait place à une "jungle" de modèles intégrés faiblement caractérisés par leur périmètre d'analyse, niveau de détail ou flexibilité au-delà d'éléments historiques comme le changement technique. Le concept de modèle *hybride* fournit une "carte mentale" intéressante mais nécessite d'être développé. Nous concluons ce chapitre sur le besoin de nouveaux "guides" des modèles pour progresser dans la compréhension de la boîte à outils existante et construire des outils innovants.

Le chapitre 2 s'attache à développer un guide transverse des modèles intégrés pour décortiquer puis synthétiser leur vision interne des transformations énergie-économie dans le contexte de transition bas-carbone, au delà des typologies historiques et en se basant sur leur contenu technique. Les caractéristiques de cette conception interne déterminent les domaines de compétence des modèles. Notre guide peut ainsi servir de "guide utilisateur" des modèles existants et d'outil de dialogue entre modélisateurs, mais aussi de "carte mentale" pour améliorer ces outils. Il caractérise en pratique la vision des transformations énergie-économie selon trois dimensions complémentaires: (i) le schéma d'*interdépendances*, (ii) les *moteurs de transformation* et (iii) la *dynamique de transition*. Le schéma d'*interdépendances* correspond à la vision "statique" du système représenté à un instant donné à travers les relations d'*interdépendances* entre les éléments constitutifs du système (secteur économiques et énergétiques, technologies, agents économiques, etc.). Il peut être synthétisé par le système comptable du modèle. Les moteurs de transformation déterminent l'évolution tendancielle du système comme moteurs d'évolution, en amplitude et direction, de la frontière de production au cours du temps qui, dans le plan production-émissions, correspond à la courbe instantanée de production potentielle selon le niveau d'émissions. Enfin, la dynamique de transition dessine la trajectoire énergie-émissions-économie effective à travers la détermination inter-temporelle de la frontière de production et l'écart dynamique entre l'état effectif de l'économie et sa frontière de production instantanée, qui est la marque d'un monde de second-rang.

L'application de ce guide aux modèles existants fournit des éléments de diagnostic selon les trois dimensions d'analyse.

Tout d'abord, les modèles intégrés diffèrent significativement selon le schéma d'*interdépendance* représenté. Lorsque le système énergétique contribue directe-

ment à la formation du PIB (rétroaction absente des modèles en équilibre partiel), une dichotomie existe entre les modèles basés sur une conception mono-sectorielle de l'économie et les modèles fondés sur l'interdépendance de secteurs et agents économiques multiples. Les premiers reflètent une vision agrégée de la valeur ajoutée et du PIB et ignorent les relations inter-sectorielles, alors que les seconds ventilent la valeur ajoutée dans des secteurs identifiés et représentent les structures de consommations intermédiaires et finales. Une conséquence importante pour les modèles mono-sectoriels est la difficulté de représenter des secteurs de consommation d'énergie finale explicites (transport, industrie, bâtiments) à travers des variables d'activité, des équipements et infrastructures explicites et leur contribution au PIB. En revanche la structure macroéconomique simplifiée permet d'inclure des technologies explicites par analyse d'activité pour les secteurs d'offre et de conversion énergétique, alors que les fonctions de production des modèles multi-sectoriels peinent à représenter les détails technologiques.

En ce qui concerne les moteurs de transformation, les modèles se rejoignent sur un point: il laisse la source de changement technique général inexplicite pour se focaliser sur le changement technique spécifique qui a lieu dans les secteurs énergétiques et les processus de consommation d'énergie finale. En outre, les degrés d'incarnation technologique et d'induction du changement technique varient largement entre les modèles. Les modèles mono-secteur macroéconomique incluent en général des mécanismes d'induction à l'échelle technologique dans les secteurs de conversion énergétique (courbes d'apprentissage, dépense R&D, etc.) mais une vision simpliste du découplage entre énergie finale et PIB. A l'inverse, les modèles multi-sectoriels peinent à représenter l'induction du changement technique au niveau technologique mais capturent la ventilation sectorielle des changements d'intensité énergétique du PIB. Finalement, la question des *drivers* et de l'induction des changements structurels plus larges au delà du pur changement technique reste peu abordée.

Enfin, la plupart des modèles énergie-économie incarne une vision simpliste de la dynamique de transition et représentent des transitions techniques et technologiques à l'équilibre économique proche du premier rang. Les modèles mono-secteur basés sur un modèle de croissance à la Ramsey ajoute à l'optimum économique instantané, l'optimalité inter-temporelle avec anticipations parfaites. Les modèles dynamique-récurif autorisent la sous-optimalité inter-temporelle par des comportements myopes. Néanmoins, l'inertie limitée du capital et la flexibilité des ajustements intra-périodes empêchent de représenter des effets importants de dépendance au sentier et des effets de "lock-in" significatifs. Par ailleurs des mécanismes de second-rang et des imperfections de marché sont parfois inclus dans ces modèles mais restent marginaux dans

une approche néo-classique basée sur un formalisme micro-économique rigoureux. Certains modèles intégrés ont toutefois généralisé les mécanismes de second-rang en renonçant à la fonction de production standard et ses micro-fondations ou en incluant des aspects des théories post-keynésiennes (frictions dans l'ajustement du système de prix, du marché du travail, etc.). Les modèles qui s'aventurent dans cette direction fournissent des évaluations renouvelées des trajectoires de transformation et des coûts des politiques climatiques.

Dans le chapitre 3, nous réduisons le périmètre d'analyse aux modèles d'équilibre général calculables (MEGC) multi-sectoriels et à la question de la représentation des systèmes techniques à l'échelle des secteurs économiques. Ces modèles fournissent une vision plus complète des interdépendances macroéconomiques, des secteurs non-énergétiques et du changement structurel mais ont été critiqués historiquement pour leur manque de réalisme technique. Dans les deux dernières décennies d'importants efforts ont été déployés pour incorporer des informations techniques assises sur des modèles bottom-up d'ingénieurs, autrement qualifié d'effort d'*hybridation* des représentations bottom-up et top-down . Les efforts d'hybridation sont clés pour au moins deux raisons: (i) les hypothèses sur le fonctionnement des systèmes techniques dans les MEGC ont un impact crucial sur les résultats d'évaluation des politiques climatiques et énergétique (Böhringer, 1998; Ghersi and Hourcade, 2006) et (ii) ils permettent d'instaurer un dialogue entre ingénieurs et économistes et améliore le contrôle qualité et la crédibilité des exercices de modélisation. Pourtant, très peu de travaux fournissent une analyse comparée des tentatives existantes d'incorporer des représentations d'ingénieur dans les MEGC. Ceci nous amène à construire une typologie de ces tentatives basée sur la *nature* et la *cohérence* de l'intégration des représentation bottom-up dans les MEGC au delà des questions algorithmiques de couplage entre modèles. Pour cela nous considérons que la représentation bottom-up des systèmes techniques est basée sur l'analyse d'activité (Koopmans, 1951) et la distinction de technologies discrètes contenues dans des capacités de production identifiées. Les tentatives d'hybridation sont ainsi examinées à l'aune de l'écart avec une telle représentation en partant de l'outil standard des MEGC qu'est la fonction de production agrégée. Notre typologie distingue trois types d'approches:

- *Les représentations top-down étendues*, basées sur l'inclusion de coûts technologiques dans des fonctions de production usuelles (comme les CES), fournissent un schéma intéressant de capture de dynamiques technologiques explicites sans remettre en question le paradigme de la fonction de production. Néanmoins

l'analyse d'activité reste "subrogée" dans la fonction de production, ce qui maintient une différence de *nature* par rapport à l'analyse d'activité à deux niveaux: (i) une vision agrégée de la substitution technologique basée sur la comparaison de coûts actualisés et (ii) une vision top-down du capital différent en nature des capacités de production discrètes opérant à des taux d'utilisation variables.

- *Les intégrations bottom-up partiellement cohérentes* regroupent toutes les approches qui mobilisent un formalisme bottom-up - basé sur l'analyse d'activité - mais au prix d'une mise en *cohérence* que partielle avec le formalisme top-down de l'équilibre général. On peut ensuite distinguer deux sous-catégories: (i) les couplages partiels (*soft-link*) entre un modèle bottom-up et un MEGC par simulation itérative et (ii) l'intégration d'une *forme réduite* d'un modèle bottom-up dans un MEGC. Dans les deux cas, des questions de cohérence se posent autour: (i) du type de comportements microéconomiques entre les deux modèles (myopie vs anticipations parfaites), (ii) de la correspondance et convergence imparfaites entre les variables de liaison parfois exprimées dans des unités différentes, et des liens manquants entre les deux modèles qui induisent un chevauchement des représentations (persistance de deux représentations concurrentes et non-convergentes du capital installé par exemple). Les formes réduites bien construites offrent les meilleures conditions de contrôle et de mise en cohérence.
- Les représentations complètement intégrées accommodent l'analyse d'activité dans les systèmes techniques (technologies de génération électrique par exemple) avec les caractéristiques de l'équilibre général selon deux approches: (i) l'incorporation directe de contraintes bottom-up dans le programme d'optimisation du MEGC par la formulation d'un *Mixed Complementarity Problem* (MCP), (ii) la séparation entre des choix techniques et d'investissement *ex ante* informés par des modèles bottom-up, et le calcul de l'équilibre général basé sur des fonctions de production *ex post* (au sens de Johansen) avec taux d'utilisation variable du capital installé. Malgré la plus haute cohérence entre représentation bottom-up et top-down, la plus grande complexité de mise en œuvre de ces approches est une contrainte pratique à leur développement.

Finalement, le choix de mise en œuvre d'une approche ou d'une autre doit dépendre des objectifs d'étude. Dans certains cas une intégration partielle sera suffisante pour apporter un premier niveau de dialogue entre les différentes dimensions du problème étudié et pourra tirer parti de modèles de grande échelle déjà existants. Dans d'autres cas, la mise en cohérence fine sera un objectif pour l'analyse précise d'un secteur

économique particulier dans un contexte d'équilibre général (secteur électrique, transport, etc.). Le choix d'approche est aussi souvent un arbitrage entre degré de cohérence et niveau de complexité de mise en œuvre. Dans tous les cas il est important de préciser les enjeux de cohérence inhérents à l'approche choisie pour la pertinence scientifique de la démarche de modélisation et des résultats produits.

Un pré-requis à l'amélioration des conditions de couplage et à la construction de MEGC hybrides et de progresser dans la gestion et la qualité des données de calibrage à l'interface énergie-économie. Disposer de base de données énergie-économie cohérentes permet d'assurer une meilleure correspondance entre variables de dialogue et est un pré-requis pour construire des architectures de modélisation hybrides avec représentation intégrée complète. Dans ce dernier cas, les systèmes de données comptables doivent articuler données économiques, technologiques et énergétiques. Plus fondamentalement il apparaît nécessaire de travailler avec un schéma comptable dit *hybride*, basé sur une vision duale des flux économiques à la fois en unité "physique" et en valeur monétaire, pour les biens énergétiques en particulier.

Le chapitre 4 explore la problématique de la combinaison de statistiques énergétiques et économiques pour construire des bases de données hybrides pour la calibration de MEGC. Un premier objectif est de montrer que la façon de combiner les données pour construire une matrice de comptabilité sociale (*Social Accounting Matrix - SAM*) hybride a un impact non-marginal sur la description empirique de l'état initial d'une économie. Nous montrons que les différentes méthodes d'hybridation des données, c'est à dire les procédures de mise en cohérence des données de volumes énergétiques des bilans énergétiques, de prix des énergies et de flux économiques des tableaux entrées-sorties de la comptabilité nationale, ont un impact significatif sur la description initiale de grandeurs qui sont cruciales pour l'évaluation des politiques énergétiques et climatiques: la part des secteurs énergétiques dans le PIB, le partage de la facture énergétique nationale entre consommation intermédiaire et consommation finale des ménages, les prix relatifs au consommateur entre les différents agents économiques (ménages vs secteurs productifs) et finalement la ventilation des volumes d'énergie consommés par ces agents.

Ce problème méthodologique est général car les écarts statistiques entre sources de données ne sont pas simplement dus à des biais liés à la collecte des données mais à des différences de nomenclature concernant les opérations économiques ou énergétiques et les contenus des agrégats énergétiques. Nous proposons dans ce chapitre une méthode d'hybridation des données qui, en comparaison des autres approches, remplace la nomenclature des flux matériels des tableaux entrées-sorties par

la nomenclature utilisée dans les statistiques énergétiques. Cela permet de conserver la taille totale de l'économie (PIB) telle qu'elle apparaît dans la comptabilité nationale tout en incluant sans altération l'information quantitative sur les flux énergétiques en volume et prix telle qu'elle apparaît dans les statistiques énergétiques spécialisées. La qualité de la description repose dans ce cas sur la pertinence de ces statistiques et de leur agrégation. En pratique, l'hybridation des données peut être étendue à la description de flux matériels au delà de l'énergie - comme les surfaces de terre ou de logement (m²), les indicateurs de mobilité (p.km ou t.km), etc. - dans la perspective de développer de nouvelles générations de modèles hybrides pour l'analyse des trajectoires de développement durable. L'intérêt du travail sur l'hybridation des données, outre qu'il offre une base au dialogue entre analyses technico-économiques et macroéconomiques, est qu'il permet de fournir une mesure des incertitudes empiriques liées aux données disponibles. Il est ensuite possible d'utiliser un MEGC pour analyser l'incertitude sur les résultats de modèle liée à l'incertitude sur les données de base. Même avec un MEGC compact (deux secteurs économiques) et standard de premier rang, nous montrons que les incertitudes sur les données initiales et les agrégats énergie-économie engendrent des incertitudes au moins aussi grandes sur les résultats d'analyse de politiques énergétiques globales. Nous concluons que l'analyse des incertitudes sur les données initiales reste un point peu abordé de la modélisation énergie-économie.

La première partie de cette thèse appelle à une réflexion sur l'articulation entre scénarios globaux et nationaux. Nous avons mis en évidence le besoin de faire évoluer une partie des modèles pour améliorer l'étude des enjeux de trajectoire de développement, de co-bénéfices économiques de l'action climatique dans un monde "second-best", de transition, de paquets de politiques, etc. Ces questions sont certainement encore plus cruciales pour l'analyse des trajectoires bas-carbones à l'échelle nationale mais ne peuvent être ignorées dans les scénarios globaux. Finalement il y a un enjeu autour du choix des outils de modélisation aux différentes échelles et en pratique les outils sont basés sur les mêmes paradigmes de modélisation entre échelles globales et régionales. On mentionnera néanmoins un effort plus important d'analyse des effets macro-économiques de court terme et de transition "second-best" dans les approches nationales. Finalement, le guide que nous avons proposé au chapitre 2 fournit un cadre pour organiser les objectifs de modélisation et le dialogue entre modélisateurs aux différentes échelles. Les principes de modélisation hybrides développés aux chapitres 3 et 4 sont également valables pour les contextes nationaux et globaux.

La deuxième partie de la thèse applique les enseignements méthodologiques tirés de la première à l'analyse de la transition bas-carbone de moyen terme dans le contexte national brésilien. Ce choix d'un focus national s'inscrit dans le nouveau paradigme d'action climatique de coordination d'engagements nationaux et la volonté d'illustrer la complémentarité d'approches nationales avec les scénarios globaux. C'est l'occasion de traiter de sujets insuffisamment abordés dans les scénarios globaux. En pratique nous étudions l'articulation entre objectifs climatiques, de développement énergétique et économique et les outils de politique publique associés (fiscalité carbone, etc.) en mettant l'accent sur des mécanismes d'interdépendance macroéconomique de moyen terme dans un cadre "second-best".

Le chapitre 5 introduit le contexte brésilien et les challenges spécifiques qui se présentent à moyen terme à l'interface climat - énergie - développement économique. Premièrement, le Brésil présente des profils énergétiques et d'émissions de GES singuliers parmi les économies émergentes. Il possède historiquement un système énergétique bas-carbone basé sur l'hydroélectricité (80%) et l'usage de la bioénergie - via la filière éthanol au delà de la biomasse traditionnelle. En même temps, jusqu'à 2010 la majorité des émissions de GES provenait de l'usage des terres *via* la déforestation et les élevages bovins. Une action volontariste de frein à la déforestation pendant les années 2000 et l'adoption du plan national sur le changement climatique (PNMC) en 2009 a permis de construire un statut d'économie bas-carbone. Suite à cette période réformiste, deux éléments ont imposé de nouveaux défis de moyen terme. Tout d'abord, la découverte de larges gisements de pétrole en eaux ultra-profondes dits "pré-salt" a introduit un changement de paradigme de développement économique avec des investissements massifs dans l'exploration pétrolière et la perspective de garantir l'indépendance énergétique du pays et au-delà de devenir un exportateur de pétrole de premier plan. En même temps, le défi climatique était en train de passer du challenge de la déforestation à celui du contrôle des émissions énergétiques car les émissions sont amenées à augmenter à nouveau après 2020 en raison de l'augmentation de la demande énergétique de l'industrie et des transports tirée par la croissance économique. D'un point de vue du développement économique, malgré une croissance forte dans les années 2000 et une réduction importante des inégalités et de la pauvreté, la période récente montre que l'économie brésilienne reste fragile. En particulier la voie d'une croissance fondée sur l'expansion des marchés de commodités et des ressources fossiles ne semble plus être un chemin facile. Le Brésil doit en particulier construire un système économique plus robuste, soutenu par des gains de productivité, une diversification des activités tout en continuant de réduire les inégalités. Les

défis à l'interface climat-énergie-développement économique sont donc significatifs pour le Brésil. D'un côté le pays s'est engagé en 2015 à poursuivre la diminution de ses émissions via des NDCs ambitieux, ce qui passe par une maîtrise de la demande énergétique dans les transports et l'industrie essentiellement (dont efficacité énergétique) et la pénétration de sources énergétiques bas carbone (expansion des agro-carburants, des renouvelables, etc.). D'un autre côté, le Brésil doit retrouver le chemin de la croissance économique en comptant en partie sur la manne des hydrocarbures, et continuer la réduction de la pauvreté et des inégalités.

L'exploration des travaux existants sur le Brésil montre un déficit d'analyses en équilibre général dans le nouveau contexte énergétique et concernant les engagements climatiques post-COP21 dans une perspective multi-objectifs. Ce travail préalable nous permet d'identifier deux axes de recherche pertinents:

- Les effets d'une fiscalité carbone pour articuler à moyen terme objectifs climatiques et socio-économiques (émissions, PIB, pouvoir d'achat, compétitivité, emploi, etc.)
- L'articulation entre contrainte climatique et exploration du pétrole 'pré-salt'

Pour étudier ces questions, nous avons développé un nouveau modèle de l'économie brésilienne de la famille IMACLIM.

IMACLIM-BR est une plateforme de modélisation en équilibre général (MEGC) hybride de l'économie brésilienne spécifiquement conçue pour générer des projections cohérentes du système énergie-émissions-économie brésilien à moyen ou long terme. Elle permet en particulier d'évaluer les conséquences macroéconomiques de politiques prix ou quantité de politiques énergétiques et climatiques. L'approche adoptée met l'accent sur les mécanismes d'interdépendance macro-économique entre les secteurs énergétiques et non-énergétiques, les agents économiques (y compris le commerce international) et des éléments structurels de second-rang de moyen terme de l'économie.

Plus précisément, IMACLIM-BR se distingue d'un MEGC standard par plusieurs aspects. Tout d'abord, comme un MEGC standard, IMACLIM-BR repose sur la représentation de marchés "walrasiens" de biens et services et des équilibres emploi-ressources. Par ailleurs, comme la plupart des MEGC appliqués aux politiques climatiques et énergétiques, IMACLIM-BR repose sur un cadre comptable énergie-économie hybride et garantit en plus l'équilibre des flux en unités physiques et monétaires (avec un focus sur les balances énergétiques).

En revanche, il se distingue premièrement d'une approche plus standard par le fait que la description des arbitrages des consommateurs et producteurs et les systèmes

techniques sous-jacents sont spécialement conçus pour faciliter la calibration sur des expertises d'ingénieurs avec l'objectif d'assurer un réalisme technique des simulations y compris dans le cas de bifurcations éloignées de la trajectoire de référence. Deuxièmement, IMACLIM-BR représente un système économique de "second-rang" - qui s'écarte du modèle canonique d'économie compétitive - et simule des équilibres de marché de biens futurs caractérisés par le possible sous-emploi de facteurs de production (travail) et des marchés imparfaits (biens et facteurs de production). Pour cela le modèle repose sur une représentation spécifique du capital et sur d'autres hypothèses de mécanismes structurels. En cela IMACLIM-BR peut s'inscrire dans la tradition des MEGC dit "structuralistes" (Taylor, 1990). Troisièmement, les simulations d'IMACLIM-BR fonctionnent en statique comparative: le modèle génère des projections énergie-économie de moyen terme en un pas de temps unique et compare à l'horizon temporel étudié ces différentes projections comme différents "contrefactuels" déterminés par des jeux de paramètres de politique publique alternatifs. Les résultats que l'on en tire sont valides sous l'hypothèse que les transitions simulées entre l'année de base et un future donné se produisent après une série d'ajustements techniques et économiques dont la durée et l'ampleur sont embarquées dans les fonctions comportementales retenues à l'horizon de temps d'étude. Le processus de transition lui-même n'est en revanche pas décrit mais est supposé suffisamment régulier pour éviter les équilibres multiples, les effets d'hystérèses, etc. La statique comparative permet de se focaliser sur les mécanismes d'interdépendance en équilibre général tout en s'affranchissant des controverses sur les effets dynamiques.

Le chapitre 7 contribue au débat sur les enjeux d'une fiscalité carbone au Brésil à l'horizon 2030. Les politiques climatiques sont généralement analysées sous un angle technologique et sectoriel basé sur des considérations de coût d'abattement ou l'articulation entre contributions sectorielles dans un cadre d'équilibre général multi-sectoriel. Dans ces cas là les coûts des politiques climatiques sont des coûts d'abattement, des coûts sectoriels ou des pertes de PIB. L'analyse d'incertitude vise souvent la disponibilité des technologies et le progrès technique. Enfin, les politiques climatiques prennent la forme d'un prix du carbone qui reflète un coût marginal d'abattement. De telles analyses sont importantes pour comprendre le challenge de la contrainte climatique mais ne sont aujourd'hui qu'une partie du problème. Dans un contexte nouveau de stratégies bas-carbone nationales, ce type d'analyse n'est plus suffisant pour construire des stratégies transversales qui visent l'articulation d'objectifs au delà de la décarbonation. Par exemple, l'introduction d'un prix du carbone n'est pas seulement une question de coûts marginaux mais également une question de transferts

de revenus entre agents économiques, car une taxe carbone génère des revenus qui peuvent être redistribués. De tels transferts ont en pratique des impacts importants sur les coûts de mitigation agrégés mais aussi sur le partage des coûts et des dividendes parmi les secteurs et agents économiques. De ce dernier point surgit la question de l'articulation des objectifs car la fiscalité carbone peut avoir des impacts très contrastés sur des indicateurs socio-économiques clés comme l'emploi, la compétitivité, le budget public, les inégalités de revenu, etc. Enfin, les spécificités structurelles de l'économie considérée, relativement au marché du travail ou au commerce, sont de facteurs clés de l'effet ultime d'une fiscalité carbone.

Nos résultats dans le cas du Brésil illustrent ces considérations générales. Nous montrons tout d'abord que le recyclage des revenus d'une taxe carbone permet de réduire les pertes de PIB d'une réduction des émissions énergétiques de 25% en 2030 d'un facteur deux - par rapport au cas où les revenus de la taxe alimentent le budget public. Ce résultat est conforme à l'hypothèse d'un double dividende faible. En outre, selon le mode de recyclage considéré, des arbitrages apparaissent entre différents objectifs macroéconomiques pour des pertes de PIB similaires. Par exemple, la redistribution des revenus carbonés aux ménages par chèque universel conduit à un pouvoir d'achat des ménages supérieur de 2% comparé au cas de redistribution par baisse des taxes à la consommation mais induit une baisse de 5% des exportations par perte de compétitivité. De manière intéressante, réduire les charges sur le travail est certainement l'option la plus favorable à l'emploi mais n'apparaît pas comme la meilleure solution pour compenser les pertes de compétitivité à moyen terme. Ce résultat provient de la structure spécifique de l'économie brésilienne qui présente un faible ratio travail-énergie et un faible taux de chômage tendanciel, ce qui se traduit par une récupération du recyclage de la taxe en hausse des salaires nominaux et donc des prix domestiques. Dans l'ensemble, du fait de son statut de producteur et d'exportateur de pétrole, le Brésil a un potentiel de double dividende plus faible que celui de la France par réduction des charges sur le travail, avec un niveau plus faible de distorsion initiale des charges sur le travail. Par ailleurs le faible transfert de charge fiscale vers les ménages empêche le même cercle vertueux qui pourrait être observé dans le cas de la France, de se produire. Les allègements de charges qui pèsent sur le travail se traduisent simplement par une hausse du contenu en travail de la production et une hausse des prix domestiques par hausse du salaire nominal. Dans l'ensemble il apparaît intéressant pour le Brésil de viser les classes les plus pauvres pour le recyclage d'une taxe carbone car cela permet en même temps de diminuer la pauvreté et de réduire les inégalités. En même temps, favoriser la consommation des ménages semble une option macroéconomique intéressante dans un pays doté d'un important marché

domestique. Dans ce cas là, des politiques complémentaires devraient être mises en place pour limiter les pertes de compétitivité des secteurs économiques exposés à la concurrence internationale.

Le chapitre 8 étudie les compromis et synergies de moyen terme existants entre objectifs énergétiques, climatiques et macroéconomiques au Brésil pour construire une stratégie de développement bas-carbone. L'analyse se focalise sur l'articulation entre le développement du secteur pétrolier *via* l'exploration du pétrole "pre-salt" et la décarbonation des secteurs de consommation d'énergie finale (transports et industrie). Pour cela, nous simulons des paquets de politiques alternatives portant sur le niveau de production pétrolière, l'instauration de politiques fiscales sur les carburants pétroliers ou de taxe carbone plus générale et de mesures d'efficacité énergétique.

Un premier résultat de nos simulations montre que le développement de la production pétrolière en accord avec les plans actuels pourrait être une source de croissance significative comparé au cas où la production pétrolière se maintient à son niveau de 2015 jusqu'en 2030. En pratique, nous observons que l'allocation de plus de ressources à un secteur économique à forte productivité du travail, et qui génère par ailleurs d'importants revenus d'exportation, induit une hausse substantielle des salaires réels et du PIB. Il en résulte un effet de croissance par hausse de la consommation domestique au profit des secteurs de services. L'amplitude de l'effet "output" net reste en pratique très incertain et dépend de paramètres clés liés à la flexibilité de la structure de production, au commerce international et à la flexibilité des marchés du travail. Les bénéfices économiques pourraient être supérieurs en pratique si le recyclage des revenus pétroliers vers l'éducation et la santé permettait des gains d'efficacité supplémentaires. En revanche l'effet macroéconomique positif se paie de changements structurels significatifs et d'un affaiblissement de la compétitivité qui impacte l'industrie manufacturière qui reste exposée à la concurrence internationale. C'est pourquoi des mesures complémentaires pourraient être nécessaires pour soutenir les industries les plus exposées.

Dans un second temps, si le Brésil n'entend pas ignorer la manne économique potentielle du "pre-salt", une question clé est de comprendre quelles seraient les conséquences macroéconomiques et environnementales de politiques domestiques alternatives sur les carburants ou les émissions de carbone fossile, par ailleurs associées à des allocations alternatives de la ressource de pétrole brut entre marchés externes et domestiques. Nos résultats soutiennent la conclusion qu'une stratégie bas carbone basée sur la décarbonation du système énergétique domestique - dont une plus forte pénétration des agrocarburants, des mesures d'efficacité énergétique - dans les trans-

ports spécifiquement - et l'exportation des nouvelles ressources pétrolières comme pétrole brut serait de loin la meilleure voie de sortie du paradoxe pétrole-climat et permettrait d'aligner objectifs climatiques - proches des NDCs - et macroéconomiques à moyen terme. Les résultats invalident également l'hypothèse d'une tension entre diminution des émissions et croissance économique et remettent en cause la pertinence à moyen terme de la tentation de court terme de subventionner les carburants pétroliers pour soutenir le pouvoir d'achat. Pour aboutir à ces conclusions, nous mettons en évidence l'existence d'"équilibres multiples" comme des trajectoires alternatives avec des PIB similaires mais des structures énergétiques et des niveaux d'émission très contrastés. La stratégie consistant à imposer des prix des carburants pétroliers bas pour favoriser le pouvoir d'achat se révèle peu payante d'un point de vue macroéconomique avec un gain en PIB faible. En fait, l'effet positif des prix faibles des carburants est atténué à moyen terme par l'effet d'une baisse de l'efficacité énergétique dans les transports d'une part et par les limites à l'ajustement à la hausse des salaires réels par réduction des revenus pétroliers externes d'autre part, en plus d'une aggravation du déficit public. En même temps, favoriser la consommation de carburants fossiles affaiblit significativement les industries d'agrocarburants et induit une hausse significative des émissions. A l'inverse, la stratégie bas-carbone permet d'atteindre des objectifs climatiques ambitieux sans perte de PIB et augmentation du pouvoir d'achat tout en contrôlant le déficit public, grâce à une fiscalité carbone à budget constant, la forte substituabilité entre carburants pétroliers et agrocarburants, les effets productifs d'une plus grande efficacité énergétique et la maximisation des revenus d'exportation pétrolière. Néanmoins, ces résultats positifs se paient par un affaiblissement de la compétitivité de l'industrie manufacturière lié aux excédents pétroliers plus importants.

A la fin de ce travail nous sommes conscients que notre analyse empirique sur le Brésil est encore loin de fournir un guide opérationnel pour implémenter une transition bas-carbone. Nous espérons seulement avoir démontré les avantages de travailler avec une architecture de modélisation hybride pour générer des futurs énergie-économie cohérents en tenant compte de mécanismes structurels de second rang à moyen terme. Notre but était de mettre en évidence des mécanismes macroéconomiques clés liés à l'implémentation de politiques climatiques et énergétiques qui visent à articuler objectifs climatiques et énergétiques avec d'autres objectifs socio-économiques dans le cas spécifique du Brésil. Cette première étape ouvre la voie à des travaux futurs pour affiner la compréhension des enjeux de transition vers une économie bas-carbone au Brésil. Nous identifions trois directions de recherche. Tout d'abord le raison-

nement en statique comparative, même s'il permet déjà un degré élevé d'intégration d'informations et d'analyse d'interdépendances, reste muet sur les conditions dynamiques de transition. Ce problème de transition est bien plus large que celui de dynamique en anticipation parfaite et vise par exemple la compréhension des enjeux macroéconomiques du déploiement d'infrastructures énergétiques ou de transport en anticipation imparfaite et les instruments de court terme - comme les mécanismes financiers - pour déclencher la transition. Ensuite, nos travaux se focalisent sur un moyen terme où les ruptures technologiques et changements structurels restent limités. Une autre voie de recherche concerne donc l'analyse du changement technique de long terme et le lien avec des changements structurels plus larges. Enfin, un troisième axe concerne la recherche plus large d'une articulation d'objectifs au delà de l'objectif climatique et une extension aux objectifs de développement durable par exemple.

Au delà du cas brésilien, cette thèse a finalement dessiné un besoin de mieux articuler l'analyse des transitions bas-carbone entre niveaux globaux et nationaux. L'architecture climatique basée sur des engagements nationaux commande des analyses nationales des conditions de ces transitions. En même temps il est nécessaire de contrôler la résultante des efforts nationaux en terme de trajectoire globale et de conséquence pour les objectifs de long terme. Dans cette perspective coexistent aujourd'hui deux types de travaux. Les exercices globaux d'analyse des trajectoires de transformation à long terme d'une part. Des initiatives plus récentes basées sur la désagrégation de l'objectif global en feuilles de route nationales qui visent à aligner objectifs climatiques avec objectifs de développement d'autre part. Finalement la nécessaire articulation entre ces deux types de travaux doit permettre de sélectionner les questions prioritaires à aborder aux différentes échelles, en cohérence avec la sélection des outils de modélisation pertinents.

Titre: Enjeux d'hybridation dans les modèles intégrés énergie-économie et représentation de la transition bas-carbone: une application au cas brésilien

Mots clés: modélisation énergie-économie, politiques climatiques, Brésil

Résumé: Cette thèse apporte des éclairages sur les enjeux d'hybridation dans les modèles intégrés énergie-économie et sur la représentation intégrée de la transition bas carbone, et propose une application au cas brésilien. Constatant l'écart existant entre la formalisation du problème de la transition vers des économies décarbonées et les résultats de la modélisation intégrée, elle fournit un guide de la boîte à outils disponible qui apporte un regard nouveau sur la vision interne aux modèles des trajectoires de transformation énergie-carbone-économie. Cela fournit des éléments de cadrage des domaines de compétence des outils existants et permet d'en saisir certaines limites. La thèse souligne en particulier la pertinence de travailler dans un cadre de modélisation hybride qui articule formalisme macroéconomique et représentation technico-économique pour améliorer la crédibilité des diag-

ostics produits et détaille les enjeux méthodologiques de la construction de modèles multi-sectoriels hybrides énergie-économie. Une partie de ces principes méthodologiques sont appliqués à la construction d'un outil d'analyse de la transition bas carbone de moyen terme au Brésil. Nous montrons comment une réforme fiscale carbone permet d'articuler plusieurs objectifs de politique publique à l'horizon 2030 visant pouvoir d'achat, compétitivité, emploi et distribution du revenu, au-delà de l'objectif climatique. Notre diagnostic souligne l'importance des spécificités structurelles du contexte énergie économie brésilien et de mécanismes macroéconomiques liés au commerce extérieur ou aux rigidités du marché du travail qui sont souvent négligés dans les exercices existants. Nous apportons enfin un éclairage particulier sur l'articulation entre politique climatique et développement du secteur pétrolier au Brésil.

Title: Hybridization challenges in energy-economy integrated models and representation of the low carbon transition: an application to the Brazilian case

Keywords: energy-economy modeling, climate policy, Brazil

Abstract: This thesis provides insights about the hybridization challenges in energy-economy integrated models and about the integrated representation of the low carbon transition, and proposes an application to the Brazilian case. Noting the existing gap between the framing of transition issues towards low carbon economies and the results brought by global integrated models, it provides a guide of the available model toolbox which brings a new view on the internal vision of models about energy-carbon-economy transformation pathways. This makes it possible to better delimit the areas of competence of existing tools and to understand some of their limitations. Our work especially underlies the relevance to work under a hybrid approach which articulates a macroeconomic framework with engineering based representations

in order to improve the credibility of the assessments produced and we detail the methodological issues to build multi-sector energy-economy hybrid models. Part of the methodological principles are applied to build a tool to analyze the low carbon transition of the medium run in Brazil. We show how a carbon tax policy makes it possible to articulate several policy objectives until 2030 targeting purchasing power, competitiveness, employment and income distribution, beyond climate goals. Our diagnostic underlies the importance of the structural specifics of the energy-economy context in Brazil and of macroeconomic mechanisms linked to trade and labor market rigidities, which are often overlooked in existing studies. We eventually provide specific insights about the articulation between climate and oil policy in Brazil.