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Producing economy-wide outlooks of energy transitions: hybrid modelling open to second best constraints

Frédéric Gherzi

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CNRS

Centre International de Recherche sur l'Environnement et le Développement
UMR 8568



**Producing economy-wide outlooks
of energy transitions: hybrid
modelling open to second best
constraints**

*Prospective économique des
transitions énergétiques : une
modélisation hybride ouverte aux
contraintes de second rang*

Accreditation to Supervise PhD Research
Habilitation à Diriger des Recherches

Defended on September 19th, 2019 at Université Paris-Nanterre before
Soutenue le 19 septembre 2019 à l'Université Paris-Nanterre devant

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Table of contents

Table of contents.....	3
<i>Curriculum Vitae</i>	7
Formation.....	9
Parcours professionnel	9
Publications et travaux.....	10
Participation à des programmes de recherche	15
Activités d’enseignement.....	16
Activités de valorisation	16
Organisation de colloques et séminaires	17
Completed Research	19
Introduction	21
1. The IMACLIM approach to hybrid energy-economy modelling.....	22
1.1. Two coupling avenues.....	22
1.1.1. Calibration of reduced forms of bottom-up, technology-rich models.....	24
1.1.2. Coupling through iterative exchange of trajectories of linking variables	26
1.2. Data harmonization requirements Building hybrid energy/economy accounting tables.....	30
1.2.1. Building from IEA energy balances and energy price data.....	31
1.2.2. Building from BU model variables at base year	33
1.2.3. Calibration of agent-specific prices through specific margins	34
1.2.4. Impact on policy modelling	34
2. Applied analyses.....	35
2.1. Climate policies in the French context.....	36
2.1.1. Earlier exploration of the double dividend hypothesis	36
2.1.2. Later analyses extended to distributive impacts.....	38
2.2. International climate negotiations.....	41
2.2.1. Meta-modelling of the Kyoto Protocol consequences.....	41
2.2.2. An IMACLIM-POLES assessment of post-Kyoto burden sharing.....	44
2.3. Sectoral analyses.....	45
2.3.1. The transportation sector	45
2.3.2. The residential sector	47
2.4. <i>Varia</i>	48
2.4.1. Free-time preference and its global carbon emission impacts	48

2.4.2.	One first experiment with foreign single-country versions of IMACLIM.....	50
3.	On energy-economy models, their uses and that of their results	50
3.1.	Four modelling priorities at the time of the Kyoto Protocol.....	51
3.2.	On hybrid modelling	51
3.3.	On the polysemous notion of “policy cost”	52
3.4.	Low-carbon policy modelling vs. low-carbon policymaking.....	54
	Research project.....	57
	Introduction	59
1.	Turning the lights towards neoclassical blind spots.....	59
1.1.	Investigating alternative closure rules	60
1.2.	Generalising policy analysis in ‘second best’ settings	63
1.2.1.	Modelling regulated prices	63
1.2.2.	Addressing factor allocation inertias.....	65
1.2.3.	Designing policy packages under constraint of pre-existing distortions.....	65
2.	Advancing the capacity to model households’ energy behaviour	67
2.1.	Designing trade-off functions focused on households’ energy choices.....	68
2.2.	Developing the micro-simulation alternative	69
3.	Furthering the combination of models and analyses.....	72
3.1.	Pushing back the frontier of TD/BU coupling	73
3.2.	Combining geographical scales of analysis	73
3.3.	Investigating circular economy potentials	74
4.	New settings of applied analysis and research collaboratives	75
4.1.	Developing BRICS capacity and analyses	76
4.1.1.	Russia	76
4.1.2.	China	77
4.1.3.	India.....	78
4.2.	Reaching beyond the BRICS	78
4.2.1.	Saudi Arabia	78
4.2.2.	Argentina.....	80
4.2.3.	Moving to one Least Developed Country.....	80
4.3.	Structuring the emerging IMACLIM Network	81
4.3.1.	Network objectives and organisation	81
4.3.2.	Organisation of further transfer efforts	84
	References.....	86

Annex 1	
Macroeconomic consistency issues in E3 modelling: the continued fable of the elephant and the rabbit	95
Annex 2	
Carbon tax and equity. The importance of policy design	115
Annex 3	
Low-carbon policy making vs. low-carbon policy modelling: State-of-the-art and challenges	133
Annex 4	
The IMACLIM Network Manifesto	159

Curriculum Vitae

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- 1997-1998 **Diplôme d'Études Approfondies**, programme doctoral Analyse et Politique Économiques, EHESS. Mémoire sous la direction de Jean-Charles Hourcade : *Modèle IMACLIM : une évaluation macroéconomique du domaine de validité de l'hypothèse d'un double dividende*.
- 1994-1997 **Hautes Études Commerciales**. Majeure de troisième année en Économie.
- 1992-1994 Classes préparatoires aux grandes écoles de commerce et de gestion. Lycée Masséna, Nice.
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Parcours professionnel

- 2011-2014 CMA - Centre de Mathématiques Appliquées, ENSMP, Sophia-Antipolis, France.
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- 2010-2011 FEEM - Fondazione Eni Enrico Mattei, Venise, Italie.
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- 2001-2003 CIRED, UMR 8568
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- 1999-2000 *Resources for the Future*, Washington D.C., États-Unis
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- 1997-1998 CIRED, CNRS-EHESS (UMR 8568).
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Publications et travaux

Thèse de Doctorat

Changement technique et double dividende d'écotaxes : un essai sur la confluence des perspectives énergétique et macro-économique. EHESS, Paris (2003). 289 p.

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Publications dans des revues à comité de lecture et chapitres d'ouvrages

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The Macroeconomics of Energy Transitions. Energy Foundation China, Pékin, 27 mars 2018.

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A macro-micro outlook on fuel poverty in 2035 France. Association Française de Sciences Économiques, Nice, 21 juin 2017.

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Contenu emploi des prospectives énergétiques. Portée et limites des méthodes. Chaire European Electricity Markets, Université Paris-Dauphine, Paris, 26 octobre 2015.

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Précarité énergétique future. Un jeu à plusieurs variables de commande. Séminaire EDDEN-PACTE, Grenoble, 5 mars 2015.

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https://www.iea-etsap.org/workshop/copenhagen_nov2014/wc11-ghersi%20etsap%2019nov14.pdf

Gestion des précarités. Un jeu à plusieurs variables de commande. 3ème journée autour du Débat National sur la Transition Énergétique, CNRS, Paris, 20 mars 2014.

<http://transen3.sciencesconf.org/36121>

Modèles économiques et politiques climatiques. État de l'art et perspectives. Centre Cournot, Paris, 17 mars 2014.

<https://vimeo.com/91932325>

Paradigm shift modelling and innovative approaches: A French case study. European Commission, Bruxelles, 15 octobre 2012.

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A contribution to the Necessary Dialogue between Bottom-up and Top-down Analysis, International Association of Energy Economics (IAEE), Zürich, 2 septembre 2004. Actes du colloque, CD-ROM : 23 pp.

IMACLIM-POLES : A Tentative Bridge across the Bottom-up/Top-down Gap in Climate Policy Modelling. Policy Modelling Workshop, EcoMod Network, Bruxelles, 6 juillet 2002. 23 p. Publié in Bayar, A., Dramais O. (éd.) *EcoMod2002 International Conference on Policy Modelling.* Actes du colloque, CD-ROM.

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Encouraging Ratification of the Kyoto Protocol. Policies for Greenhouse Gases Reduction and Pollution Control in Asian-Pacific Countries, Academia Sinica, Taipei, 1^{er} décembre 2000. 19 p. En collaboration avec R. Kopp, B. Pizer et R. Morgenstern.

Modelling Challenges in Analyzing Greenhouse Gas Trading. Understanding the Design and Performance of Emissions Trading Systems for Greenhouse Gas Emissions, Resources for the Future, Washington, 15 janvier 1999. 17 p. En collaboration avec M. Toman.

Participation à des programmes de recherche

2017-2018	Impacts distributifs de la transition énergétique. Projet d'étude lauréat d'un appel d'offre ADEME concernant les impacts distributifs de la Stratégie Nationale Bas Carbone.
2013-2016	RISKERGY. Projet de recherche financé par la région Île-de-France sur la constitution d'une méthodologie de notation des risques souverains prenant en compte la dimension énergétique.
2011-2012	EV-STEP. Programme européen sur les conséquences énergétiques et économiques de la pénétration du véhicule électrique en Europe.
2011-2012	GT Précarité Énergétique. Groupe de Travail EDF R&D (ICAME).
2009-2012	PASHMINA. Programme européen de modélisation de changements de paradigme de croissance.
2006-2008	TranSust.Scan. Programme européen de modélisation de la transition vers un développement durable.
2004-2007	Scénarios sous contrainte carbone. Étude en collaboration avec l'Institut du Développement Durable et des Relations Internationales (IDDRI) et l'association Entreprises pour l'Environnement (EPE).

- 2004-2006 *Hybrid Energy Modelling*.
Groupe de travail international rassemblé par le CIRED et l'EMRG¹ autour de la publication d'un numéro spécial de l'*Energy Journal* dédié à la modélisation hybride *bottom-up/top-down*.
- 2003-2006 ENEC 2050 - Confluence des Prospectives Énergétique et Macroéconomique dans la Perspective d'un Développement Durable.
Action concertée incitative Énergie 2003, CNRS - Ministère de la Recherche.
- 2003-2005 TRANSUST - Modelling the Transition to Sustainable Economic Structures.
Programme européen de développement de la modélisation du développement durable.
- 2003-2005 BD EMAD - Base de Données Énergie, économie, environnement pour la Modélisation et l'Aide à la Décision.
Action concertée incitative Énergie 2003, CNRS - Ministère de la Recherche.
- 2002-2004 Renforcement des capacités de scénarisation à long terme : maîtrise des données, couplage des modèles.
Programme GICC, Ministère de l'environnement et du développement durable, APR 2001, projet 3.
- 2000-2002 Des scénarios économiques internationaux à l'évaluation des coûts sectoriels et macro-économiques de la réduction des émissions de GES.
Programme GICC, Ministère de l'environnement et du développement durable, APR 1999, projet 6.

Activités d'enseignement

- 2015-2018 **École des Ponts Paristech**, Marne-la-Vallée.
Cours d'introduction aux modèles macroéconomiques de transition énergétique, parcours *Modélisation* du Master EEET-EDDEE, 5 heures.
- 2004-2006 **École Polytechnique**, Palaiseau.
Suivi académique du Master ParisTech *Transport et Développement Durable*.
- 2003 **École Nationale du Génie Rural, des Eaux et des Forêts (ENGREF)**.
Intervention sur la *Modélisation des Politiques Climatique*, 1h30.
- 2003 **École Nationale de la Statistique et de l'Analyse Économique (ENSAE)**. Direction de quatre mémoires d'Économie Appliquée, sur le thème *Modélisation Macro-Économique du Changement Climatique*. 16 heures.
- 2002 **Université de Marne la Vallée**. Chargé de TD. Licence d'Économie et Gestion. Cours *Dynamique Économique I*. 33 heures.

Activités de valorisation

- 2004-2012 Société de Mathématiques Appliquées et de Sciences Humaines, Paris.
Orientation de la politique scientifique.

¹ Simon Fraser University, Vancouver, Canada. <http://www.emrg.sfu.ca/EMRGweb/index.php>

Organisation de colloques et séminaires

- Nov. 2017 Second annual workshop of the IMACLIM Network.
CIREC, Paris. 2 journées.
- Avril 2005 International Workshop on Hybrid Energy-Economy Modelling.
CIREC, Paris. 2 journées.
- Avril 2004 Chaire du Développement Durable de l'École Polytechnique - Modélisation Intégrée
École Normale Supérieure, Paris. 1/2 journée.

Completed Research

Introduction

We devoted the more-than 20 years of research that started with an internship at CIRED in January 1997 to the economic assessment of policies aiming at abating greenhouse gases emissions and thus mitigating climate change—in short, of climate policies. We conducted that research under high political pressure on the international scene and in the French and European Union arenas—the United Nations Framework Convention on Climate Change (UNFCCC) process and its European and French avatars, which led us to produce a corpus of applied contributions. However, from the onset of our activity, the pressing question emerged of which methodology to apply to our economy-wide policy assessments.

One paramount methodological requirement was that they should give due attention to the technical realities at the source of greenhouse gases emissions, first of which the energy intensity of human activities and its foreseeable evolutions—the engineers' viewpoint of the climate change issue. But they should simultaneously account for the economic constraints framing such evolutions, i.e. the investment and operating costs of not only energy supply but also energy end-uses, and their retroactions on other markets including that of investment—the economist's viewpoint of the same issue.

At the end of the 1990's, these two aspects of the economic assessment challenge largely remained disconnected. The climate affair had again opposed the engineer's 'bottom-up' (BU) and the economist's 'top-down' (TD) approaches to energy constraints modelling (Grubb, 1993), as the oil crisis had done two decades before. The 3rd Intergovernmental Panel on Climate Change (IPCC) assessment report describes what can be argued the peak of the competition between the two modelling chapels (Hourcade and Shukla, 2001), after which both communities started bridging the gap between them through the development of hybrid models.

The need for hybrid models stems from recognizing the complementary strengths and weaknesses of both approaches.² To put the stress on weaknesses, standard TD models firstly calibrate on money-metric economic flows, from which they infer physical energy flows with little regard for energy statistics. Secondly, whatever their theoretical paradigm, they simulate rather aggregate energy supply and demand by means of mathematical functions that are (1) quite plain, for sheer analytical convenience, but at the cost of maladaptation to observed or expected flexibilities of energy systems; (2) devised and calibrated as first-order proxies valid only in the vicinity of some initial state of the economy, and for a rather vague 'long term' horizon; (3) applied in theoretical frameworks unfit to represent technical change biased towards a drastic reduction of the energy intensity of growth. They are thus structurally incapable of representing the dramatic tension between the temporal inertia of large investments backing energy supply and shaping energy demand, and the profound technical evolutions of energy systems that the conjunction of oil scarcity and the climate alarm calls for in coming years.

Conversely, BU energy-system models build from energy statistics and offer the scope and detail necessary to capture (and aggregate at need) the expected evolutions of the manifold energy supply and end-use techniques, as well as their precise dynamics across time.³ However, they lack the integrative economy-wide framework necessary to evaluate the total economic costs attached to these evolutions—be it only a comprehensive description of investment flows—and thus cannot possibly account for the feedback loops between the macroeconomic constraints and the energy systems shifts.

² We discussed the need for such hybrid approaches in Hourcade et al. (2006), which followed up on our organisation of an international meeting at CIRED in 2005—although it reflected work dating back to the end of the 1990s. We give the complete paper in Annex p. 91.

³ Notwithstanding, bottom-up models have been criticised for their too-naïve representation of investment decisions touching on energy end-use technologies (Sutherland, 1991)—the source of a perceived 'efficiency gap' between the available techniques and those actually implemented (Jaffe and Stavins, 1994), quite unsatisfactorily explained by extremely high private discount rates. The CIMS model provides some answers to this problem (Jaccard, 2009), which we have not specifically explored in the course of our research.

A second methodological challenge was on the theoretical underpinnings of the TD dimension of our analyses. From the late 1970's on, the exponential increase of computational power had prompted a flourish of multisector analyses of economy-wide issues. These 'quantitative' developments came at the expense of 'qualitative' discussions on the underlying theoretical paradigms. Keynesian critiques of perfect market assumptions, inattention to short-term constraints on resource allocation, or the interpretation of gross operating surplus as the rent on some elusive capital stock, were cast aside. 'Computable general equilibrium models' (CGEM) combining optimal behaviours of representative agents to operationalise the theoretical Walrasian equilibrium became dominant. They were eventually applied indiscriminately, even at the shortest time horizons, where all theoreticians agree that their relevance is quite low.

Our methodological objective was thus twofold from the start. It was primarily to reshape the TD modelling framework with a view to open it up to BU expertise on energy matters. Our answer to this challenge is the IMACLIM approach to hybrid energy-economy modelling, to which we devote section 1 below. Beyond energy matters, our objective was additionally to question the too-systematic use of neoclassical assumptions when assessing transitional policies developing in the short term and in 'second-best' settings where the influence of market imperfections or failures cannot be ruled out lightly. We let this second objective drive our implementation of IMACLIM to a series of applied analyses, which we present in section 2. In one additional section 3, we isolate the presentation of four 'positional' papers on energy–economy models and modelling practices, and on the use of their results. The earlier of these papers build up the arguments at the origin of our research project as summarised by section 1. However, they also prescribe research directions to applied analyses of climate policies, and comment upon the interpretation and use of modelling results. The latest paper additionally touches on dimensions of climate policy analysis that go beyond our own focus on the efficiency and equity of policy designs. This prompted to devote one separate section to their exposition.

1. The IMACLIM approach to hybrid energy-economy modelling⁴

In response to the stakes described in our introduction above, we developed the IMACLIM model as a tool of dialogue between the engineer's and the economist's perception of energy transitions, focusing on providing economy-wide consistency to the partial equilibrium results of bottom-up models. We have done so following two distinct methodological avenues, which we successively present in section 1.1 below. In section 1.2, we insist on the data harmonisation necessary to a sound application of both the modelling approaches of section 1.1.

1.1. Two coupling avenues

Our research on hybrid energy-economy modelling builds on a profound dissatisfaction with the extension, in the wake of the 1973 oil crisis, of Solow's take on production functions (Solow, 1957) to energy questions.⁵ That extension simultaneously meant:

- Applying Solow's "wrinkle" (Solow, 1988) to energy, *i.e.* interpreting the observed energy cost shares (either aggregate or indeed sectoral) as the instantaneous results of cost minimization facing a vector of input prices.
- Generalizing the resulting production function(s) at horizons of analysis ranging decades into the future, by simply submitting it (or them) to exogenous technical change. At first, exogenous technical change

⁴ This section heavily draws on [Ghersl \(2015\)](#), which indeed we wrote with this Accreditation report in mind.

⁵ Berndt and Wood are among the first to estimate a Capital, Labour, Energy, Materials or KLEM production function of the aggregate United States manufacturing sector (research leading to Berndt and Wood, 1975). As early as 1974, Jorgenson publishes a multi-sectoral KLEM model of the United States, which he applies to a prospective outlook up to the year 2000 (Hudson and Jorgenson, 1974).

took the form of neutral (uniform) factor productivity improvements, as in Hudson and Jorgenson (1974). In the second wave of models spurred by the climate affair from the 1990s on, it refined into biased productivity improvements including a specific “autonomous energy efficiency improvement” (AEEI).⁶

Under such a modelling framework of energy-economy interactions, a change in energy prices at any point in time, whatever its intensity, only displaces the factor input mix along some pre-determined, exogenous isoquant. This cannot be a proper framework, especially in the shorter temporal terms, to assess the dramatic shifts expected from highly ambitious climate policy action, or for that matter from potential geopolitical instabilities impacting energy trade, under the inescapable constraint of (mostly) strongly inert energy supply and end-use equipment stocks—understood in the broadest of senses extending e.g. to urban forms.

This critique has two main implications. The first one is that any relevant model of energy-economy interactions must work in an induced technical change framework, in the tradition of Kennedy (1964)—⁷i.e., in technical terms, one that guarantees the path-dependency of substitution isoquants. To illustrate this following Ruttan (2002) (Figure 1), let us consider some time t perturbation that shifts the $t + n$ price vector of some economy from p_{t+n} to p'_{t+n} . Standard comparative statics searches the $t + n$ impact of the perturbation on the single pre-determined production function f_{t+n} , thus settling on S_{t+n} . The point is rather to acknowledge that the perturbation induces technical change leading to a specific f'_{t+n} production function, which induces an O'_{t+n} optimum. It is therefore not any unique f_{t+n} function but the ‘dynamic production frontier’ F_{t+n} enveloping all production functions reachable from year t that should structure economic analysis.⁸ In this analytical framework, ‘path-dependency’ is the dependence of the instantaneous production function f_{t+n} actually prevailing at any $t + n$ point in time, to the effective path of price vectors $\{p_t, p_{t+1}, \dots, p_{t+n}\}$.

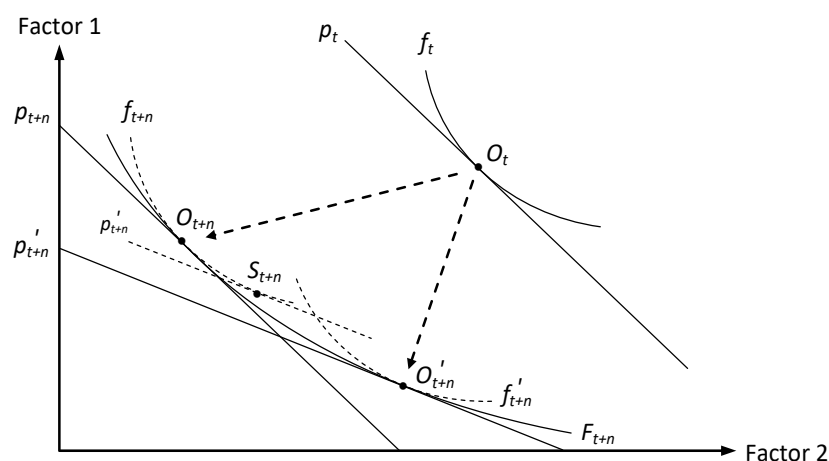


Figure 1 Induced technical change as a dynamic production frontier

The second implication of our critique is that any economy-wide model of energy-economy interactions must turn to energy systems expertise if it is to describe with any relevance the evolution of the techniques that supply energy and convert it into service (heat, light, motion, information and communication), particularly in the short term. This has the unfortunate precondition of requiring modelling ‘capital’ in a way closer to the physical capital actually mobilized in the processes of energy supply and demand, rather than as the ambiguous residual of value-added, labour costs subtracted, of the standard neoclassical approach.

⁶ Löschel (2002) reviews technical change in economic models of climate or energy policy of the 1990s.

⁷ Kennedy explicitly builds on Hicks: “A change in the relative prices of the factors of production 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” (Hicks, 1932, p.124). The work of Kennedy spurred much literature up to Magat (1979), which includes a thorough review of it.

⁸ We draw Figure 1 from Ghersi and Hourcade (2006), where we further comment upon it (see Annex 1 p. 91).

Both implications ultimately echo the Cambridge controversy on capital, i.e. the unsettled neoclassical confusion of the economic productivity of investments for the technical efficiency of equipment.⁹ Solow's own improvement of his initial model by the embodiment of technical progress in successive capital vintages (Solow, 1959) only partly addressed this critique: it introduced path-dependency but did not settle the conceptual gap between flexible, continuous investment and discrete physical capital. Manne (1977) also contributed by focusing on a bottom-up representation of energy supply, thereby explicitly modelling physical capital of energy sectors; but he resorted to an aggregate, abstract KLE production function to project the energy demand of non-energy activity. For the same latter reason, the many subsequent CGE models that substituted some bottom-up representation of factor combinations (in various shapes and hues) to the standard cost-minimizing energy producing sectors only partly improved on the initial KLEM model as well.¹⁰ In the two following subsections, we present our own two methods to try to overcome both identified shortcomings of the KLEM abstraction.

1.1.1. Calibration of reduced forms of bottom-up, technology-rich models

Our first two attempts at improving on the KLEM extension to Solow's model are literal applications of the 'dynamic production frontier' interpretation of technical change. One early construction is applied work on the international climate negotiations covering 2030 projections of 14 major economies (Gherzi et al., 2003, see section 2.2.2 p.44 below). A few years later, we published our improved method with illustrative projections of the global economy, also to 2030 (Gherzi and Hourcade, 2006). In both endeavours, our bottom-up source is the POLES model of energy systems.¹¹ Focusing on climate policy, we purposely use POLES runs for a range of carbon prices broad enough to capture the 'asymptotic' behaviour of energy systems, i.e. the expected floor to energy intensities resulting from equipment inertia at the explored temporal horizon. To reveal 'dynamic production frontiers' in the sense exposed above, we interpret the results of POLES policy runs as the partial price derivatives of the static trade-off functions generated by each sequence of relative prices (Figure 2). We do so under the notable assumption that all prices not explicitly modelled in the partial equilibrium framework of POLES, including capital and labour prices, are constant.¹² We limit our exposition to a two-sector economy of energy and a composite, non-energy remainder of economic activity.

In most economies, the labour content of energy production is too small to have its variations significantly affect aggregate economic activity. However, the labour content of non-energy production has a strong influence on cost assessment, especially under the assumption of imperfect labour markets. We must therefore reveal a set of functions f to compute the labour content, and as a matter of fact the capital content, necessary to the calibration of the envelope of these functions. We do so assuming that:

- All policy-induced $t + n$ economies are on a steady equilibrium path, guaranteeing to each function f the first-order conditions of relative marginal productivities equating relative prices (for any set of two production factors).
- For a given output and a given energy price p_E , the price elasticity of energy demand is derived from POLES considering a marginal increase of p_E .

For a carefully selected functional form, there is one single f making these assumptions compatible with the no-policy prices and factor-demand vectors. The same mathematical property holds successively for every pair of equilibria separated by a marginal increase of the energy or carbon price.

⁹ Cohen and Harcourt (2003) sum up the controversy from a viewpoint similar to our own.

¹⁰ See e.g. Böhringer, 1998; McFarland et al., 2004; Laitner and Hanson, 2006; Sue Wing, 2006; Schäfer and Jacoby, 2006; Schumacher and Sands, 2007; Böhringer and Rutherford, 2008; Fujimori et al., 2013; Karplus et al., 2013; Cai et al., 2015.

¹¹ The POLES model is a joint development of CNRS, IPTS and ENERDATA. See <https://www.enerdata.net/solutions/poles-model.html>.

¹² In the implicitly 'constant' (deflated) currency of POLES.

In [Gherzi and Hourcade \(2006\)](#) we assume, considering their widespread use in the energy-economy-environment (E3) modelling community,¹³ that Constant-Elasticity-of-Substitution (CES) functions of capital K , labour L and energy E approximate each real f at the neighbourhood of the corresponding equilibrium.¹⁴ We calibrate CES_0 the CES prevailing at the (K_0, L_0, E_0) point of the no-policy projection by imposing (1) the linear homogeneity condition, (2) the first-order conditions at the no-policy equilibrium and (3) the energy demand E_1 resulting from a marginally higher energy price p_{E1} under constant other prices and output, as computed by POLES. CES_0 then yields the optimal K_1 and L_1 induced by the marginally higher energy price. We iterate this method on the newly defined (K_1, L_1, E_1) equilibrium, considering the impact of a further marginal energy price increase, as again computed by POLES. This allows the successive identification of equilibrium (K_i, L_i) compatible with POLES information on (p_{Ei}, E_i) couples over the whole spectrum of analysis. Note that, even though we assume a CES function at the neighbourhood of each equilibrium, the resulting envelope has no reason to exhibit constant elasticity of substitution of one factor to another, unless in the implausible case of a constant price elasticity of E over the range of policies explored. We use the resulting set of prices (p_K, p_L, p_E) and factor demands (K, L, E) to adjust functional forms of conditional demands of the three factors (Figure 2).

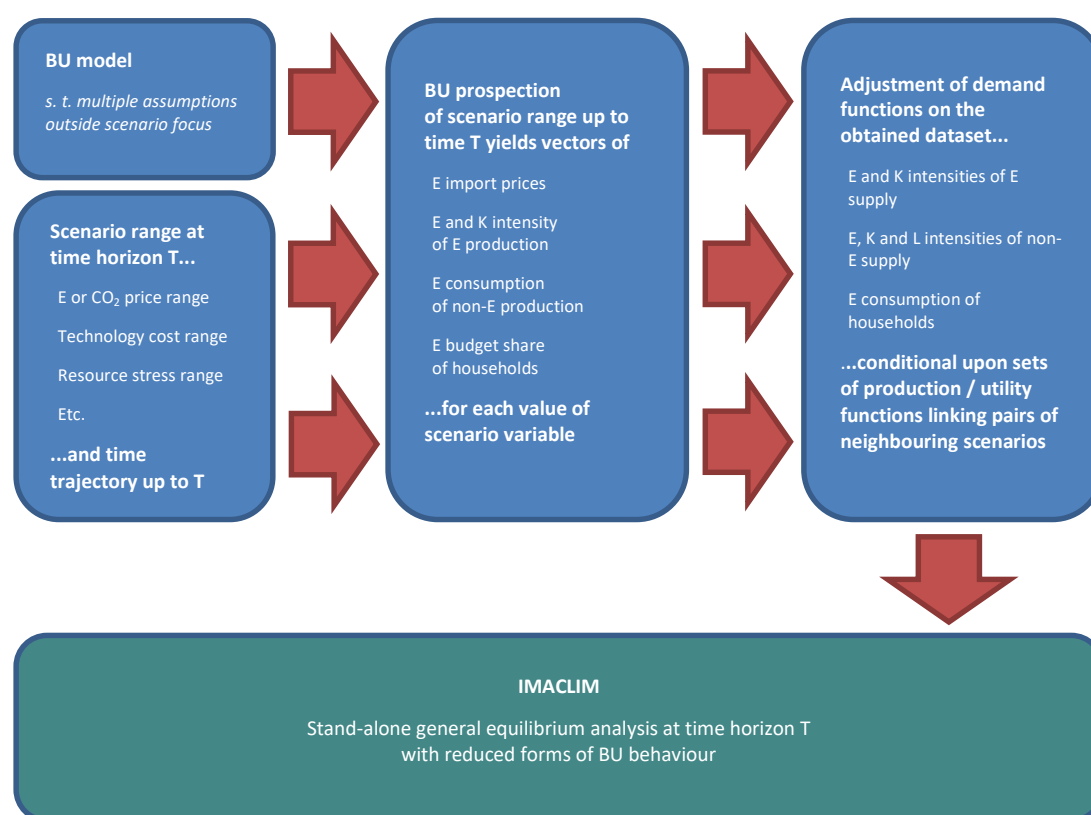


Figure 2 Calibration of reduced forms of bottom-up behaviours¹⁵

Turning to household behaviour, POLES does not systematically report on the proper arguments of utility functions, i.e. energy services (heating, lighting, passenger-kilometres, etc.) whose variations may differ from those of energy consumptions because of efficiency gains. Our method consequently focuses on Marshallian

¹³ In models like G-Cubed (McKibbin and Wilcoxon, 1995), MS-MRT (Bernstein et al., 1999), SGM (Fisher-Vanden et al., 1993) or EPPA. (Babiker et al., 2001).

¹⁴ At this stage of our research, we assume that the 'materials' (non-energy goods) intensity of productions is constant, as is customary in the first generation of CGE models applied to energy issues.

¹⁵ The box of "scenario ranges at time horizon T" proposes alternatives to carbon tax scenarios, which we have not explored in any of our work so far.

demands without revealing the underlying set of utility functions. To calibrate an envelope of the Marshallian energy demand of households, we first translate in budget-share terms the changes in household energy demand computed by POLES, assuming that POLES implicitly considers constant total household expenditures.¹⁶ We then adjust Marshallian demand functions by linking variations of this share to shifts of the ratio of energy to non-energy prices—again, considering that POLES implicitly considers constant non-energy prices.

Lastly but importantly, we derive the impact of carbon or energy constraints on total factor productivity in the non-energy sector¹⁷ from a comparative-static analysis of an endogenous growth mechanism: we affect all factor intensities with a Hicks-neutral technical progress coefficient that is a function of cumulated investments. Assuming all $t + n$ projections on a steady equilibrium path justifies using variations of the $t + n$ equipment expenditures as a proxy of those of cumulated investment.¹⁸ Under this specification, the crowding-out effect of mobilizing more resources in the production and consumption of energy does not result from the allocation of a fixed capital stock. Rather, firms finance their investments (equipment expenditures augmented by interest payments) under the double constraint of market balances—the non-E sector produces investment goods—and of the ability of households' purchasing power to sustain the resulting price increases. Cumulated investments and the induced productivity of the non-E sector consequently align.

1.1.2. Coupling through iterative exchange of trajectories of linking variables

The ambitious 'reduced form' method of section 1.1.1 suffers from two major drawbacks. First, its extension to a multi-sectoral framework raises conceptual issues regarding the form that the trade-off functions connected by envelopes at each time horizon could take if further disaggregation of inputs or consumption goods were considered. Secondly, it is conditional upon the trajectory of scenario variables surmised in the bottom-up source. For the example of carbon pricing, there is no question that simple options like a constant versus a linearly increasing versus an exponentially increasing tax yield contrasted 'response surfaces' for identical values at the explored horizon. This implies that the calibration of reduced forms must be performed again for each specific pricing trajectory.

For these reasons, we developed a second avenue of coupling IMACLIM to bottom-up modelling. Rather than aiming at a standalone version of IMACLIM embarking bottom-up expertise (Figure 2 above), this alternate method consists in a systematic joint running of IMACLIM and the linked bottom-up model (Figure 3). Consistency between the two models builds on an iterative exchange of the largest possible set of shared variables or parameters, up to convergence of all elements of this set.¹⁹

¹⁶ Note that the assumptions of constant expenditures, constant composite consumption and constant composite price are incompatible with variations of the energy expenditures. Given necessarily constant non-energy prices, we prefer to consider constant income (more compatible with the fixed GDP assumption of POLES) rather than constant consumption of the composite good.

¹⁷ Because energy models increasingly account for the impacts of learning-by-doing and R&D efforts on the costs of energy technologies, the envelope of energy production functions is assumed to embody such effects and is therefore not subject to productivity adjustments.

¹⁸ We calibrate the specification to allow a doubling of cumulated investment triggering a 20% cost decrease, based on 1978 to 2000 time-series for France and OECD. Sensitivity analyses demonstrate that variations of the elasticity of total factor productivity to real investment do not qualitatively affect the model.

¹⁹ The approach is similar to that of Dai et al. (2015) but with data exchange extended to prices; or to that of Fortes et al. (2014) or Labriet et al. (2015), although energy prices, rather than exogenously taken from the bottom-up source, remain largely endogenous variables of IMACLIM (see below). The idea of coupling economic and energy models via iteration of linking variables exchanges up to convergence dates back at least to Hoffman and Jorgenson (1976). It was picked up throughout the years to present times (see, e.g., Messner and Schratzenholzer, 2000; Schäfer and Jacoby, 2006; Martinsen, 2011) when it appears to flourish (see the above three recent papers but also Igos et al., 2015).

More precisely, the method consists in:

- Harmonizing all the exogenous parameters common to both models, typically demography, but also possibly international energy prices, if these are exogenous to the bottom-up model as they are in the open-economy, single-region versions of IMACLIM.²⁰
- Forcing, in the input-output framework of IMACLIM, bottom-up simulation results on (1) the international price of energy commodities, if endogenous; (2) the energy consumptions of households and the energy intensities of productions; (3) the capital, operation & maintenance and energy intensities of energy supplies and, as far as possible, some information on the capital intensities of energy end-uses; (4) the volume of energy imports from and exports to foreign markets.
- Running IMACLIM under constraint of these exogenous data to compute various economic indicators (such as GDP, output at various aggregation levels but also possibly variations of relative prices on non-energy markets), which are sent back to the bottom-up model to serve as drivers of energy demand in an updated simulation.
- Iterating the exchange of inputs and outputs between the two models up to convergence, in both modelling systems, of the exchanged data.

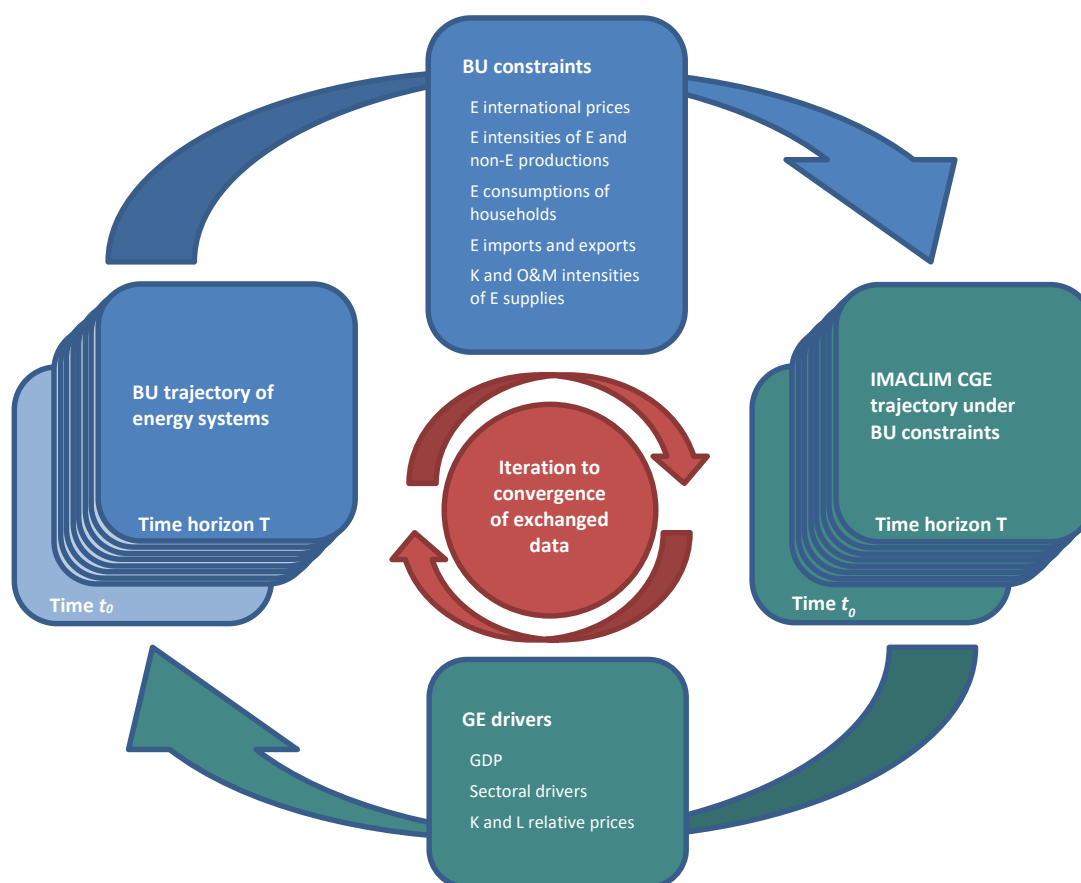


Figure 3 Coupling of IMACLIM to some BU model through iterative exchange to convergence of linking variables trajectories

²⁰ Contrary to the endogenous markets of primary resources of the global multiregional version of IMACLIM, IMACLIM-R (Sassi et al., 2010). Bottom-up models, even global ones, tend to consider exogenous global commodity prices, with very few exceptions as the POLES model (referenced in footnote 11 above).

The outcome of this procedure is a consolidated set of variables consistent with both the economy-wide framework of IMACLIM and the detailed energy-system modelling of the linked bottom-up model. The method naturally calls for a dynamic recursive implementation of IMACLIM rather than for the static comparative approach of the reduced forms of section 1.1.1: it would be pointless to feed back a deviation of real GDP and other energy demand drivers at some unique time horizon of the initial bottom-up trajectory, while maintaining the initial trajectory up to that horizon. The exchanged data is thus in fact a set of time trajectories of the various linking variables, from some common initial year (the later of the two models' first simulation years) to some common outlook horizon (Figure 3). Looking back at the interpretive framework of Figure 1, any envelope F_{t+n} now remains implicit and it is the whole path of O optima, from O_t to O_{t+n} , that the iterative convergence reveals—conditionally upon some parameterized context (regarding policies, technologies, resources, etc.) that changes from one run to the other.

However, contrary to the reduced-form option, the iterative method does not benefit from multiple bottom-up runs that could allow settling all non-energy inputs trade-offs. One central question is again that of end-use capital, *i.e.* the supplemental investment in machinery, home equipment, building insulation and transportation vehicles at the source of energy efficiency. This energy-efficiency investment is increasingly explicit in bottom-up models and we can eventually feed it into IMACLIM alongside energy-demand data and energy-supply investment data.

Notwithstanding, the question of the dynamics of labour demand in non-energy sectors, together with the broader impact of relative-price variations on trade-offs of non-energy goods and factors, for non-energy sectors, remains unsettled. In recent applied work, we have thus resorted to conventional behavioural functions, as indeed the CES function, to settle all trade-offs but those imported from the linked bottom-up model.

Concerning the non-energy behaviour of producers left uninformed by the bottom-up source, we can thus assume that their output Y (whatever our level of disaggregation) is a function of inputs of the primary factors K and L , aggregate energy E and the composite non-energy good M ,²¹ which combine in a nested structure echoing recent literature.²² At the bottom of the structure (Figure 4), capital K and labour L trade off to produce a KL aggregate. At the second tier of the input structure, the KL and E aggregates combine into a KLE aggregate—which allows inferring KL intensity from the E intensity imported from BU modelling.²³ At the third tier of the input structure, the KLE and $\alpha_M Y$ aggregates combine into output Y .

²¹ In disaggregated versions, the composite M is an aggregate of non-energy goods, whose composition we must again settle resorting to some behavioural assumption. In so-far applied work based on model coupling, we have fallen back on the Leontief assumption of fixed intensities.

²² Van der Werf (2008) and Okagawa and Ban (2008) econometrically establish the superiority of the chosen structure over other possible choices (including substituting K to E then the KE aggregate to L). They are also precious sources of estimation of the elasticities of substitution of CES functions at each tier of the structure.

²³ In disaggregated versions, this E intensity is a vector of energy intensities reflecting some energy mix.

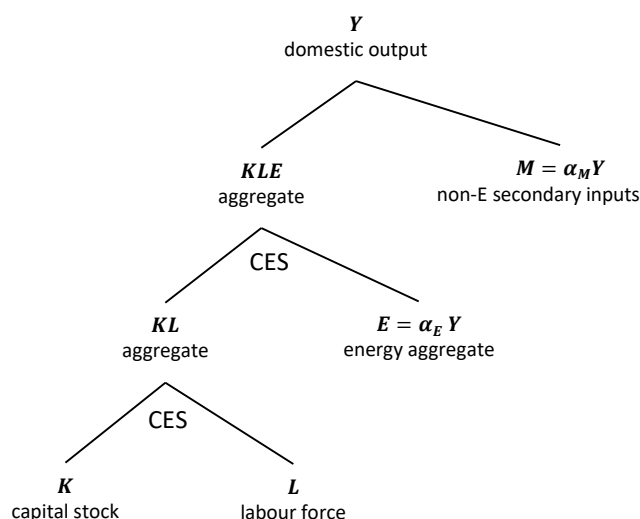


Figure 4 Nested production structures in IMACLIM versions iterating to convergence with BU models

We must underline that such ‘path-independent’ treatment of non-energy input substitutions contradicts our induced-innovation take on technical progress as far as non-energy substitutions are concerned. Besides, simple analysis of the CES function reveals that deducing KL from maintaining KLE as a CES of KL and E is only relevant for moderate E savings, all the more so as the elasticity of substitution of KL to E is low in the circa 0.1 to 0.8 range of estimates reported by the literature (see e.g. Okagawa and Ban, 2008, or van der Werf, 2008). We therefore limit our use of this concession to applied CGEM standards to scenarios that envisage little decoupling of energy consumptions from growth. In ambitious scenarios, we fall back on the assumptions of exogenous KL - and M -intensities of output Y and limit substitution possibilities to capital and labour in the production of value-added KL , for those sectors whose investment is not informed by our BU source.

Turning to households, we directly import the volume(s) of energy consumption(s) from BU modelling and devote the remainder of the consumption budget to non-energy goods. In disaggregate versions, we must surmise some behavioural function to settle the competition between components of the aggregate non-energy good, similar to what we do for production—although we will see below (section 2.3.1 p.45) that more than energy consumptions can be inferred from bottom-up modelling.

Regarding energy trade, which we never properly addressed in the reduced form alternative, one difficulty is that most bottom-up approaches only compute net imports as the difference between domestic output and consumption. We consequently have to disaggregate an evolution of gross exports and imports from the reported evolution of net trade.²⁴ We then force the resulting exports and imports volumes and let domestic production balance demand. Work-in-progress on major oil and gas producers (reported in section 4.2.1 of our Research Project, p.78) also incites us to control the price of energy exports, to reflect surmised rent variations on international markets. In our approach to production, prices build up from costs—although we still consider, as we did in the reduced forms method, a fix mark-up stemming from the differentiation of capital depreciation and profits in value-added. To account for the state of international energy markets as depicted by the linked BU model, we simply adjust a specific margin (rent) on energy exports.

Similar to export prices, we want the production prices of energy to mirror variations computed in the technology-explicit framework of the linked BU model. These variations mainly reflect the capital intensification of energy supply resulting from increasingly costly conventional resources, the higher costs of the 3rd (and 4th)

²⁴ In applied work, we have so far assumed an inverse evolution of imports and exports, which we apply to gross imports and exports volumes of the calibration year as reported by IEA balances.

nuclear generation, stronger environmental constraints, the penetration of renewables, the capital requirements of ‘smart’ distribution networks, etc. They could also reflect increased “operation and maintenance” (O&M) costs induced by shifts of technology mixes. In the economy-wide framework of IMACLIM, the latter costs should translate into an increase of the labour and ‘material’ intensities of energy production—although the split between labour costs, materials, and indeed possible genuine capital expenses in the O&M aggregate attached to BU technologies, is generally unknown.

Considering the minor share of O&M expenses in total energy costs, in applied work so far, we translate all energy costs variations in capital intensity shifts. To do so we develop an original additional iterative method:²⁵

- Along the trajectory computed by IMACLIM, we reveal an approximation of BU energy costs by combining base-year prices and intensities of non-energy factors (capital, labour and materials) with current-year energy price(s) and intensity (intensities). Maintaining non-energy prices at base year level reflects the fact that BU analysis implicitly considers constant non-energy costs.
- We compare the resulting energy cost trajectory with that computed by the bottom-up model.
- We compute what changes of capital intensity allow both trajectories to match, all other things equal.
- We exogenously adjust the capital productivity of energy production to reflect this trajectory of capital intensity changes.
- We iterate IMACLIM runs computing all adjustments to the updated capital intensity trajectory until our IMACLIM approximation of BU energy costs evolves as the genuine BU trajectory.

1.2. Data harmonization requirements Building hybrid energy/economy accounting tables

The first experiments of linking IMACLIM to bottom-up analysis did not mechanically lead us to compare the aggregate energy volumes and prices common to both modelling systems. The reason was our initial use of the standard CGE modelling assumption of normalized production prices. Without loss of generality, we could set the ‘producer’ (net of trade & transport margins and of sales taxes) prices of all goods and services to 1 at our base year,²⁶ thus forbidding any comparison of the consecutive selling prices and sold volumes with corresponding energy data.²⁷

However, despite the mask of normalization—and indeed that of differing monetary units—, massive discrepancies rapidly caught our attention. A first one regarded energy expenses, which varied between IMACLIM and the connected bottom-up model by more than acceptable statistical discrepancies either in their total or for those economic agents similarly aggregated in both systems. Reasons for such discrepancies are that the energy expenses of national accounts build on data that

- Are, for many years but a few reference years, the products of surmised energy-intensity gains and output volume indexes, without guarantee of matching the explicit energy consumptions reported in energy balances.

²⁵ We embed this iteration in the larger iteration of linking variables exchanges between models, i.e. we perform it for each run of IMACLIM under updated constraints from the linked BU model. In the case of our applied work on electric vehicles (section 2.3.1), convergence of cost trajectories at a 10^{-3} precision requires in the order of five iterations of capital productivity changes.

²⁶ The year at which we calibrate the model to match national accounts statistics.

²⁷ We consequently resorted to ‘base 1’ trajectories to translate bottom-up results into the framework of IMACLIM.

- Are collected as expenditures of branches of activities, which are corrected, in turn, to yield expenditures of products produced by branches.²⁸
- Undergo some statistical treatment to add up to an equilibrium of uses and resources.

A second, more subtle discrepancy regarded the distribution of volumes of energy consumptions among economic agents, which substantially changed the consequences of carbon or energy policies focused on some of them—e.g., targeting households emissions would mean targeting a quite different percentage of total carbon emissions in IMACLIM than in the linked bottom-up model. In IMACLIM, this distribution of volumes across agents univocally followed from the assumption of a unique producer price, which implied selling prices differentiated by taxes only. This strongly contradicted energy price data in many countries where the average energy price of firms is quite below that of households, and masks indeed a wide variety of prices faced by producing sectors, depending, among others, on the average size of the firms they aggregate.

The threat of strong biases to our policy analysis thus prompted us to envisage basing our modelling on hybrid matrixes reconciling national accounts with energy-specific data. Over the course of our applications of IMACLIM, we developed two distinct methods to that effect, which the two following subsections detail. A third subsection addresses the important connected question of modelling agent-specific energy prices, and a fourth one presents some numerical demonstration of the importance of hybridising data.

1.2.1. Building from IEA energy balances and energy price data²⁹

Our most extensive energy/economy data hybridizing method builds on disaggregated energy balances and energy price data, typically that available from the International Energy Agency (IEA). It is a 3-step procedure that starts with reorganizing the energy balance into an input-output format compatible with that of national accounts. This is a time-consuming, data-intensive first step that entails, for dozens of energy products:³⁰

- Correcting, when working on an IEA region that aggregates different countries, the reported imports and exports. For both accounts, the IEA indeed only sums up the data of each country within the region, without subtracting intra-regional trade. For e.g. the European Union (applied work of section 2.3.1 p.45), this is a quite necessary step.³¹
- Absorbing statistical discrepancies, by e.g. a homogeneous adjustment of all uses in one direction and of all resources in the other, to bridge the gap between the two totals.
- Reallocating international bunkers and internal transport fuel consumptions to exports and domestic consumption. The IEA treats energy consumptions from a geographical perspective, whereas input-output data aggregate the economic accounts of resident businesses—two quite orthogonal perspectives. This is indeed one of the biggest data treatment challenges, considering how difficult it is to obtain the data required to perform it. The stakes are however high, with the energy intensity of transports recognized as one of the main deadlocks of energy transition.
- Vertically integrating, (1) the energy consumptions motivated by the auto-production of electricity—which only appear as primary energy consumptions in national accounts. (2), the product transfers from the refining industry: IEA balances detail how refineries recycle some of their outputs as inputs; this is

²⁸ Surprisingly enough, the French national statistics institute (INSEE) indicates that “product transfers” impact but a few sectors, mainly related to agriculture. The four energy sectors of the 88-sector INSEE IO table are indeed barely concerned by product transfers corrections, and in a positive way only (which means that some firms mainly involved in non-energy activities have a minor share of their activity on energy markets). This implies that energy firms do not sell anything but energy products strictly speaking, an arguably questionable statistics from an engineer’s point-of-view.

²⁹ This section draws on [Combet et al., 2014](#).

³⁰ In their most disaggregated format IEA energy balances detail 71 resources and uses for 60 energy products.

³¹ We addressed a similar international trade aggregation issue concerning the GTAP input-output table database in [Hamdi-Cherif and Ghersi, 2011](#).

irrelevant from a national accounts perspective, which only record what refineries actually buy on markets, and eventually sell back to markets.

- Absorbing stock variations by adjustment of resources or uses (depending on their signs), similarly to our usual practice on national accounts—one alternate solution being to aggregate stock variations to investment, but this has the undesired consequence of immobilizing energy flows into productive capital.
- Distributing among productive sectors (including those producing transportation services) and households the energy consumptions of transportation activities, one stand-alone end-use of energy balances. This is the second most delicate operation. It suffers from too-rare statistics on business vehicle fleets and particularly the attached fuel consumptions.

One particular difficulty regards the energy consumptions of energy sectors. The input-output tables of many economies report auto-consumptions of the electricity or the natural gas sector that imply volume consumptions flagrantly above those reported in energy balances.³² These auto-consumptions are dominantly commodity trade on liberalized markets, and only quite marginally genuine consumptions. In applied work so far we have hesitated between stripping down auto-consumptions to genuine energy consumptions and consequently moving the value-added of commodity trading to non-energy sectors when re-balancing our hybrid national accounts; or acknowledging energy trade, but this implies breaking the link to energy balances and falling back on national accounting data only.³³

The second step of our hybridising procedure consists in complementing the resulting table of energy flows in IO format with a table of corresponding prices. This is again a delicate step, as the IEA provides energy price statistics with limited disaggregation and must therefore be augmented with other data sources.³⁴ Notwithstanding, the precise average price applying to some 'cell' of the constructed IO table of volume consumptions often remains unavailable. However, the market prices of primary energy products are readily available and can be applied uniformly across (mostly industrial) agents with some confidence. Besides, gas and electricity statistics usually report prices dependent on the volume of consumption, which offer ranges for assumptions—or which can confirm, in last resort, the average price resulting from crossing national accounts expenses and the IO table of energy flows. There is no denying that this step leaves room for judgment, but at the very least, it forces to make explicit, educated choices on the prices of the energy expenditures of all economic agents.

The third step of our hybridizing method is to substitute the disaggregated energy expenses obtained by the term-by-term multiplication of the volumes and prices tables, to that pre-existing in the system of national accounts. We consequently adjust other components of the system to maintain the accounting identities, under constraint of not modifying any of the cross-sectoral totals of uses or resources in the economy—which notably implies that we maintain the total value-added of domestic production. We do so:

- On the side of uses, for the intermediate consumptions of sectors, household consumption and exports,³⁵ by compensating the difference between recomputed energy expenses and original statistics

³² For example, the 2010 IO table of France by INSEE reports a 45 billion Euro auto-consumption of the gas and electricity production and distribution sector. This is incompatible with the ca. 8 million ton-of-oil equivalent (toe) consumptions of said industries reported by the IEA energy balance—which cannot be valued at more than €1,000 per toe on average.

³³ In our applied work on the European Union (see section 2.3.1 p.23), sectoral disaggregation has prompted us to move commodity trade from the energy sectors to the composite sector (which includes trading activities). Conversely, in the sectorally aggregated but geographically extensive framework of our RISKERGY work (see Box 2 p.34), we have decided to rather adjust the auto-consumption of our aggregate energy sectors prorata the adjustment of other energy uses by the hybridising process.

³⁴ CIRED makes frequent use of the ENERDATA database at <http://www.enerdata.net>.

³⁵ National accounts treat the energy consumptions of public administrations as these of an aggregate public service sector, whose uses focus on the final consumption of public administrations. For this reason, the direct final energy consumptions of public administrations are nil. Understandably, gross fixed capital formation does not consume (immobilise) any energy flow either, at least notwithstanding stock variations (see above).

through an adjustment of the expense on the most aggregated non-energy good—a composite remainder of unspecified economic activities, usually encompassing all service activities in E3 models.

- For the resources of energy sectors, by adjusting all non-energy expenses (including value-added components) *pro rata* the induced adjustment of total energy expenses;
- For the intermediate consumption of sectors, labour and capital costs, input and product taxes and imports, by compensating the difference between the recomputed resources of the energy sectors and the original statistics through an adjustment of the resource of the same most-aggregated non-energy good.

The heavy data collection and treatment effort attached to hybrid matrices building led us to supervise their application in the framework of the PhD thesis of Gaëlle Le Treut at CIREC (Le Treut, 2017).

At the time of writing, CIREC has treated France, Brazil, South Africa, the European Union (the 28-Member State aggregate), Russia, India, China and Saudi Arabia at such level of precision. Section 4 of our Research project (p.75) reports on our personal involvement in these endeavours.

1.2.2. Building from BU model variables at base year

As underlined in the preceding section, the construction of detailed prices and volumes tables of energy consumptions compatible with national accounts is both time-consuming and data-intensive. In the course of recent applied work, faced with the necessity to articulate an aggregated IMACLIM to a large number of countries, we consequently came up with an alternative, much simpler method of hybridizing IMACLIM with BU data.

This method bypasses the tedious data collection and treatment effort aimed at recomposing a BU-consistent table of energy expenses by constructing this table directly from aggregate variables of the linked bottom-up model. We implemented it to reconcile the base years of aggregate, 2-sector models initially calibrated on the GTAP database with data for the corresponding year of, again, the POLES model.³⁶ The procedure is similar but not identical to that of section 1.2.1 above.

- A first step similar to section 1.2.1 is to substitute to GTAP energy consumptions of the composite (non-energy) sector and of households, the corresponding price x volume statistics that can be aggregated from POLES data for the relevant year.
- A second, quite specific step is to adjust the energy expenses of the energy sector *pro rata* the adjustment of the sum of other uses induced by the first step. This rough procedure is prompted by the quite specific issue of commodity trading, which we introduced section 1.2.1 above (see also footnote 33).
- A third and a fourth step, both identically shared with the approach of section 1.2.1, consist in adjusting all non-energy resources of the energy sector *pro rata* the adjustment of its energy expenses induced by the second step, and in compensating all induced changes of the uses and resources of the energy sector by adjusting the corresponding uses and resources of the non-energy sector. This warrants conservation of all cross-sectoral accounting totals: intermediate, household and public consumption, investment and exports on the side of uses; intermediate consumption again, labour costs, capital costs, input and product taxes and imports on the side of resources.

Note that this alternate method is all the more relevant as the linked bottom-up model has a description of energy markets compatible with that of IMACLIM. It is the case of the POLES model, which is closer to an

³⁶ In the 8.1 version we used, GTAP details harmonised 57-sector input-output tables for 134 countries or regions covering the globe, see <https://www.gtap.agecon.purdue.edu/databases/v8/default.asp>.

economist's view of energy matters than e.g. models of the MARKAL family, such as the TIMES PanEU model with which we worked on the EU28 economy (see section 2.3.1 p.45). In addition, one shortcoming of the method is that the sectoral disaggregation of the resulting hybrid matrix is limited to that explicitly available in the linked bottom-up model. Lastly, even at the highest possible 2-sector aggregation of energy vs. non-energy goods, the question of households' transport fuel expenses is not easily settled.³⁷

1.2.3. Calibration of agent-specific prices through specific margins

Nothing forbids applying the standard uniform (normalised) pricing rule of CGE models to the hybrid accounts resulting from either one of the two methods above. As we already implied, this has the joint consequences of limiting, for each energy good in the model, consumer price differences to differentiated taxes, and of biasing the distribution of energy volume consumptions. The only advantage of hybridizing data would therefore be to have pinpointed the economic value of the energy sectors and their actual cost shares in productions. It might appear counterproductive to thus discard all the collected information on the actual distribution of consumption volumes and on agent-specific prices. However, this is indeed what modellers do when exploiting the hybrid matrices derived from the widely used Global Trade Analysis Program (GTAP) database in standard CGE approaches. In our instance, having produced the hybrid tables ourselves naturally lead us to fully exploit them by departing from standard CGE modelling practice and introducing agent-specific prices.

The question of how to model agent-specific prices should of course be linked to the reasons why prices faced by different economic agents for an identical volume of some energy good actually vary. Two main reasons prevail. One reason is that aggregation masks the heterogeneity of energy goods. This is obvious in models where energy is one single good, within which the volume mix of natural gas, electricity, petroleum products, *etc.* may vary substantially from one consumer to the next. Because the prices of all vectors *per* energy unit are not aligned (for interesting practical reasons beyond our scope here), the average price of the energy consumption of agents varies too. But this holds too in models where energy is more disaggregated. Not mentioning primary forms, E3 models typically distinguish coal products vs. natural gas vs. petroleum products vs. electricity. The plural in coal and petroleum products betrays product heterogeneity, which prices generally reflect—see simply the contrasted prices of diesel and gasoline fuels in many countries.

A second reason for agent-specific energy prices is that strictly identical energy goods, as typically a kWh of electricity or a cubic meter of natural gas, face distribution costs that sharply increase from centralized (*e.g.* large firms) to decentralized (*e.g.* small commercial or residential customers) consumptions. These increasing costs are a complex blend of equipment costs, maintenance costs and even harder-to-assess specific costs attached to varying contractual commitments. It is doubtful that any data outside undisclosed corporate data could allow a meaningful distribution of these extra costs on the cost structure of energy production.

Faced with this lack of information, in our applied work addressing this issue (the post 2007 analyses of section 2 below) we decide to introduce a set of 'specific margins' aggregating, for each economic user category, deviations from the average producer price emerging from energy cost structures. By construction, the aggregate margins compensate and thus do not alter the balance of each energy sector resulting from the hybridizing processes of either section 1.2.1 or section 1.2.2 above.

1.2.4. Impact on policy modelling

In **Combet et al. (2014)**, we devote a section to demonstrating the consequences of hybridisation and the consecutive accounting of agent-specific prices on policy assessment. To that end, we implement a quite

³⁷ In the applied work of the RISKERGY programme (see Box 2 p.34), we crudely attribute to households all fuel consumptions of light duty vehicles. Firms pay for a non-negligible part of such consumptions, though. Conversely, households pay for some fuel consumptions attached to light trucks but also to boats and even airplanes—although the latter expenses are statistically negligible.

standard static 2-sector (energy and non-energy) CGE model with production and utility functions of constant elasticities of substitution (CES functions) drawn from the available literature. With this model, we compute the welfare costs of cutting down energy consumptions of firms, households, or both agents simultaneously, *via* lump-sum-recycled energy taxes, for both the 2010 French and 2005 Brazilian economies.³⁸

For households the welfare cost differential of using conventional (conv.) vs. hybrid data is small, in line with the statistical adjustment performed on households' energy expenses. For firms, however, cost assessments based on the conventional matrix turn out several times higher than those based on our hybrid datasets (Figure 5)—convergence of the two assessments for larger energy cuts is a mere artefact of the CES functional form, which systematically tends towards 100% welfare costs when approaching a 100% cut. We still have to sustain these results with some analytical exploration, especially of the cost gap amplification *via* the input-output matrix, to properly publish what is yet but a discussion paper.

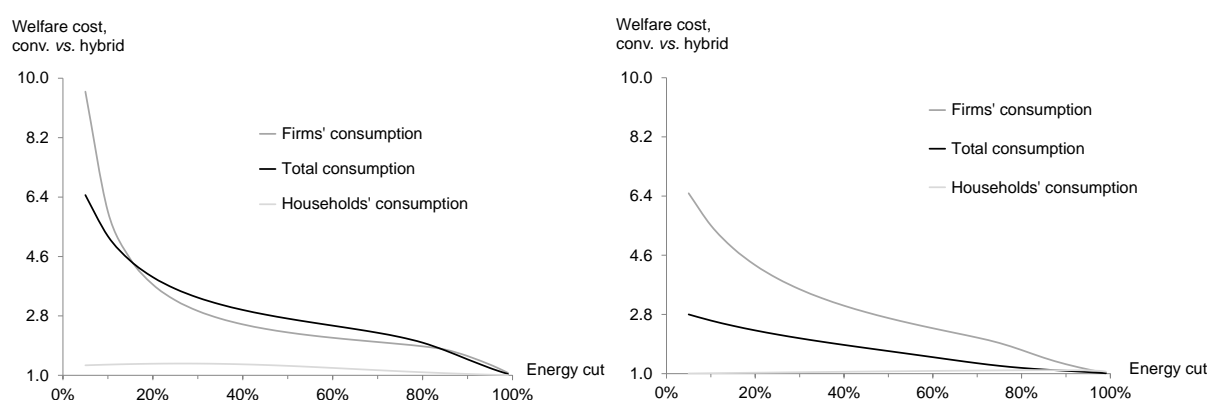


Figure 5 Cost differentials of energy conservation measures, 2005 Brazil (left panel) and 2010 France (right panel)
Source: Combet et al., 2014

2. Applied analyses

The methodological developments that section 1 summarises span from 1997 to the present day. Applied analyses across the same years therefore integrate them in various degrees. The very first pre-2000 analyses rest on preliminary versions of IMACLIM, calibrated on raw (non-hybridised) national account and implementing the reduced-form coupling methodology on bottom-up expertise rather than actual modelling. Conversely, the most recent work on the European Union (see below) rests on hybrid matrixes and coupling with bottom-up modelling of the TIMES family, an open-source, widely used modelling architecture maintained by the ETSAP programme of the IEA.³⁹ Notwithstanding, for the sake of concision, we will only briefly qualify the methodological framework in which the below results were computed and rather focus on the main conclusions of each research effort.

We present our main research results by themes, starting with economy-wide analysis on France, moving to analysis of the international climate negotiation stakes, then to sectoral analyses focused on the residential and the transportation sectors—although still systematically set in the economy-wide framework of IMACLIM. In a fourth “*Varia*” subsection, we present two additional pieces of research: one isolated but interesting effort produced during our stay at Fondazione Eni Enrico Mattei in 2010-2011, and a recent effort on implementing a South Africa version of IMACLIM, which is really the embryo of a significant part of our Research Project (see below).

³⁸ In Combet et al. (2014) we only report on France for the sake of concision.

³⁹ See <https://iea-etsap.org/>.

2.1. Climate policies in the French context

Implementation of a domestic carbon tax has come on and off the political agenda in France since the mid-1990s. Every attempted reform failed at a sooner or later stage up to 2014, when the French government finally defined reform particulars that could conquer or outmanoeuvre all oppositions:

- An exemption of all firms with carbon emissions covered by the European Union Emissions Trading System (EU-ETS).
- A recycling of much of the tax proceeds of initial years (up to 2017) into a tax-credit mechanism supporting private research.
- The complementary measure of a “green check” in direction of 4 million poor households, which can be spent to face energy expenses or engage into energy-efficiency investments.
- Last, but not least, a mere, partial change of label of already-high fossil energy excises, which could then follow specific, rapidly growing trajectories in further years. For jurisdictional reasons out of our scope here, this allowed to bypass the obstacle of the *Conseil Constitutionnel*, which had barred two previous reforms (2000, 2010) on the ground that they breached the constitutional principle of equality before the tax system (*égalité devant l'impôt*), because of numerous tax exemptions not sufficiently aligned with the general purpose of the reform.

These features mirror the two main causes of opposition to the carbon tax reform: fears of negative impacts on the competitiveness of French productions (first and second points) and of highly regressive impacts of the reform, which would hit poor households harder than richer ones (third point). Our research addressed both concerns in several journal articles that we sum up in the following subsections.

2.1.1. Earlier exploration of the double dividend hypothesis

At the time of the Kyoto Protocol and attached first national commitments to carbon emissions abatement, our first journal articles assess the possibility of a ‘double dividend’ of French carbon policies: that a carbon pricing reform could not only benefit the environment but also the economy (Hourcade and Gherzi, 1997; Hourcade and Gherzi, 2000; Gherzi et al., 2001).⁴⁰ In these papers, we test various particulars of the reform under contrasted assumptions regarding the flexibility of energy consumptions, the rigidity of the labour market and the consequences on total factor productivity of the induced crowding-out of investment and shifts of relative prices.

We conclude that there exists a plausible ‘domain of validity’ of the assumption of a double dividend if carbon-tax or emission-permit auction proceeds are recycled in a decrease of labour taxes. Hourcade and Gherzi (2000) is the most thorough of these three papers. Notably, its implementation of a static IMACLIM calibrated on 1997 France reveals ‘bell-shaped’ curves of the impacts of a carbon tax recycled in labour tax cuts. The reform all the more favourably affect households’ consumption as behavioural elasticities (ability to adapt to relative-price shifts) of the consumers and producers are high, and crowding-out of non-energy investment by energy investment is low (Figure 6). These results only echo, in the French context and leaning on our specific IMACLIM numerical tool (although in a much preliminary, little hybridised form), the well-known analytical conclusions of Bovenberg, de Mooij, Goulder or Parry about the opportunity of recycling any climate policy proceeds in a reduction of the most distortionary taxes hampering economic activity.

⁴⁰ The 2000 and 2001 papers form the sixth and seventh chapters of our PhD thesis (Gherzi, 2003).

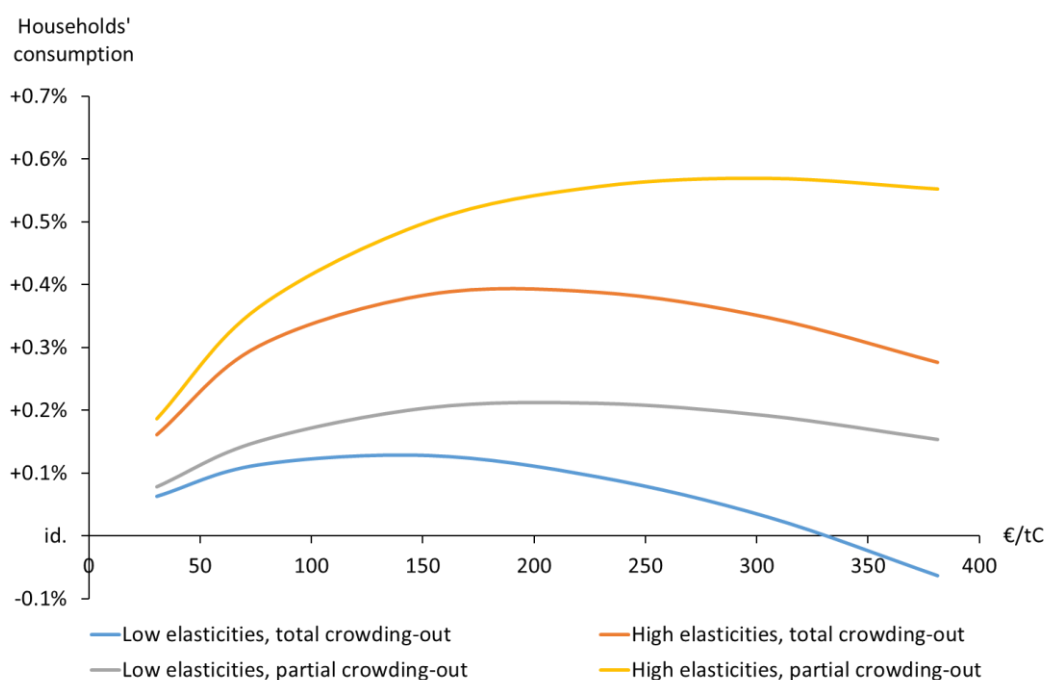


Figure 6 Impact of a carbon tax on households' consumption in 1997 France
Source: Hourcade and Gherzi, 2000

In [Hourcade and Gherzi \(1998\)](#), we extend our range of analysis to a crude assessment of the impact across 35 French activity branches of a carbon tax triggering an abatement effort similar to that required under France's Kyoto Protocol commitment.⁴¹ Resting on implementation of our very first version of IMACLIM calibrated on 1996 France, our 1997 paper had estimated this economy-wide tax at 850 French Francs per ton of carbon (€35 per ton of CO₂), inducing a 13.8% drop of national CO₂ emissions ([Hourcade and Gherzi, 1997](#)). Recycling the proceeds of this tax into lower labour taxes and accounting for moderate input substitution allows a net decrease of the production costs of 28 out of 35 branches (Figure 7). The seven negatively-impacted branches register cost increases below 0.7%, with the only exception of petroleum industries (branch T05), who see their costs increase by 1.8%. Altogether, these 'losing' branches only sum up to 9% of distributed output and 4% of labour payments. The conclusion is that a well-designed carbon tax reform can preserve the competitiveness of much of the French industry. In fact, the seven 'losing' branches could be exempted without much consequence on the environmental efficiency of the reform: their emissions are largely 'fatal', in the sense that they are impossible to abate by the implementation of alternative technologies—the case of refining industries is particularly clear. Taxing them would only cause carbon leakage without any benefit to the global environment, i.e. displace to foreign countries whatever level of supply remains necessary to meet the level of demand dragged down by the new price regime.

⁴¹ The Kyoto Protocol required from France that its average annual carbon emissions would remain at their 1990 level over the 2008 to 2012 period.

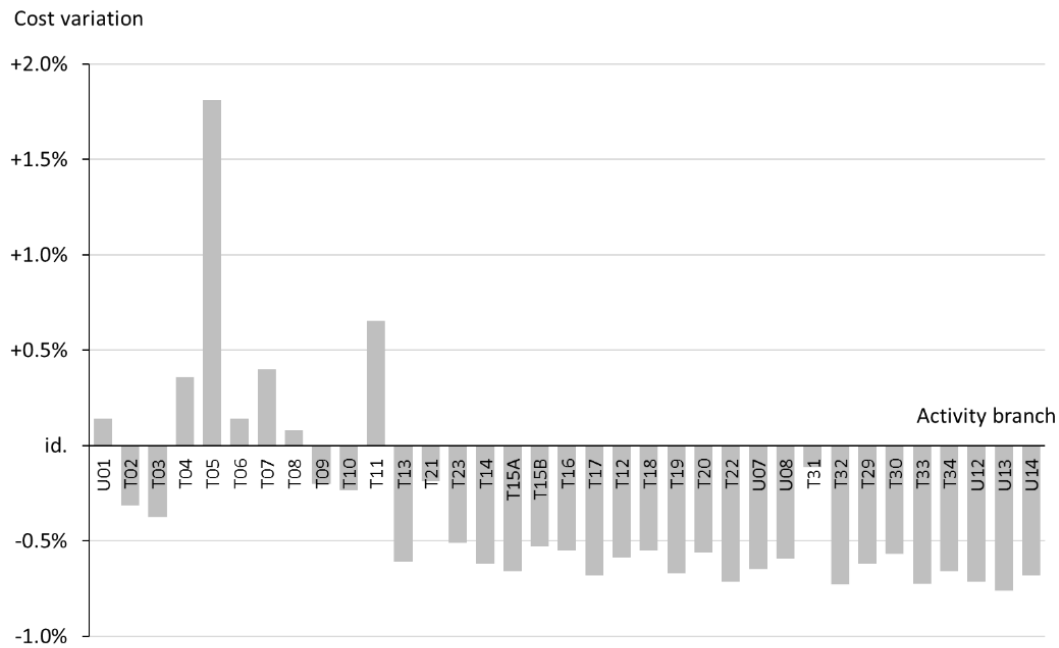


Figure 7 Impact on output costs of a €35/tCO₂ carbon tax recycled in labour tax cuts, for 35 activity branches in 1996 France
 Source: Hourcade and Gherzi, 1998⁴²

2.1.2. Later analyses extended to distributive impacts

We picked up research on climate policies in the French context to produce expertise sustaining the Rocard commission of July 2009. This commission was yet another attempt at building consensus around carbon pricing in France, under governmental impulse. This was the occasion of a major update of IMACLIM, **benefitting from the PhD research of Emmanuel Combet (Combet, 2013) and Camille Thubin (Thubin, 2012), under our partial supervision**. We thus extended our modelling framework to the secondary distribution of income between households, firms, public administrations and foreign agents (the ‘rest of the world’), and indeed to a disaggregation of the ‘representative consumer’ in five income classes. This allowed us to produce an extensive report (Combet et al., 2010) revisiting our numerical assessment of a French carbon tax reform, including a thorough scrutiny of its distributive implications, in a still static (counterfactual) framework, but updated to the 2004 French economy.

⁴² Branch nomenclature is available in the article at http://www.persee.fr/doc/rei_0154-3229_1998_num_83_1_1697, p.40 (in French).

Public debt assumption	Constant debt-to-GDP ratio				10% lower debt-to-GDP ratio			
	None	None	Total lump-sum ¹	Partial lump-sum ²	Targeted income credit ³	Partial lump-sum ²	Targeted income credit ³	Targeted income credit ³
Direct compensation to households	None	None	No remainder	Lower social contributions	Lower social contributions	Lower social contributions	Lower social contributions	Lower social contributions
Use of remainder of proceeds	Lower social contributions	Lower VAT	Increased lump-sum	Lower social contributions	Lower social contributions	Lower social contributions	Lower social contributions	Lower social contributions
Use of budget surplus	Lower social contributions	Lower VAT	Increased lump-sum	Lower social contributions	Targeted measures ³	Lower social contributions	Targeted measures ³	Targeted measures ³
Total CO ₂ emissions	-15.9% / -41.5%	-15.9% / -41.4%	-16.4% / -42.2%	-16.1% / -41.8%	-16.0% / -41.7%	-16.8% / -42.1%	-16.6% / -42.0%	-16.6% / -42.0%
Real Gross Domestic Product	+1.0% / +2.1%	+0.1% / -0.2%	-0.2% / -0.8%	+0.5% / +1.0%	+0.7% / +1.4%	-0.3% / +0.3%	+0.1% / +0.9%	+0.1% / +0.9%
Job creation (thousand full-time equivalents)	407 / 1,016	56 / 112	54 / 94	259 / 666	317 / 784	34 / 479	174 / 665	174 / 665
Oil imports (billion current euros)	-2.2 / -4.3	-2.2 / -4.3	-2.3 / -4.5	-2.3 / -4.4	-2.2 / -4.3	-2.5 / -4.5	-2.4 / -4.5	-2.4 / -4.5
TOGETHER	+0.9% / +1.8%	+0.3% / +0.4%	+0.3% / +0.4%	+0.7% / +1.3%	+0.8% / +1.5%	-0.5% / +0.2%	-0.3% / +0.5%	-0.3% / +0.5%
Effective consumption with energy efficiency gains	+0.8% / +1.5%	+0.1% / +0.2%	+2.5% / +6.2%	+1.6% / +3.6%	+1.6% / +4.0%	+0.4% / +2.6%	-0.3% / +2.4%	-0.3% / +2.4%
Living-standard %ile 1-5	+0.8% / +1.7%	+0.1% / +0.0%	+1.4% / +3.4%	+1.1% / +2.5%	+1.3% / +3.3%	-0.1% / +1.5%	-0.4% / +1.8%	-0.4% / +1.8%
Living-standard %ile 5-35	+0.7% / +1.3%	+0.1% / -0.1%	+0.4% / +0.6%	+0.5% / +1.0%	+0.7% / +1.3%	-0.6% / +0.1%	-0.4% / +0.4%	-0.4% / +0.4%
Living-standard %ile 35-65	+1.0% / +2.3%	+0.5% / +1.0%	-0.2% / -0.8%	+0.5% / +1.1%	+0.5% / +0.9%	-0.6% / +0.1%	-0.1% / +0.3%	-0.1% / +0.3%
Living-standard %ile 65-95	+1.9% / +4.8%	+1.4% / +3.4%	-0.0% / -0.4%	+1.1% / +2.7%	+1.1% / +2.7%	-0.3% / +1.4%	+0.4% / +2.0%	+0.4% / +2.0%
Living-standard %ile 95-100								

In each cell: left: figures for a €100/tCO₂ tax; / Right figures for a €400/tCO₂.

¹ All proceeds, whether levied on households or firms, equally distributed to households depending on household size and composition (lump-sum assumption).

² Proceeds levied on households handed back to households as lump-sum (see above); proceeds levied on firms used to cut down social contributions (labour taxes).

³ Compensation measures limited to percentiles 1 to 80: income tax credit matching carbon tax payments on energy basic needs estimated at 56% of average consumption of percentiles 1 to 5; increase of *per capita* social transfers other than unemployment benefits and pensions.

Table 1 Impacts of carbon tax reforms in 2004 France
Source: Combet et al., 2010.

One first conclusion of this report is an update and development of our earlier analyses, that a carbon tax leads to similar CO₂ emissions abatement, but has contrasted socio-economic consequences, depending on the mode of recycling of its proceeds and on the public budget context. For a tax that would have reached €400/tCO₂ in 2004, we thus compute fairly robust 41.4% to 42.2% lower carbon emissions and €4.3 to €4.5 billion lower oil imports; but GDP variations ranging from -0.8% to +2.1%, job creations between 94 thousand and more than 1 million, aggregate household consumption gains between 0.4% and 1.8% and consumption gains for the 5 poorest living-standard percentiles between 0.2% and 6.2% (Table 1). As in earlier papers, the economic efficiency of recycling carbon tax proceeds into labour tax cuts comes out higher than that of other recycling options like lump-sum transfers to households or VAT cuts (Table 1). We refine our explanation of why this is so, by highlighting how a reform with labour tax cuts effectively transfers part of the fiscal charge from firms to non-wage incomes like land and property rents—or social transfers, including pensions. The consecutive cut in output costs improves the competitiveness of French exports, which launches a virtuous circle of activity and income gains.

Furthermore, our extended framework of analysis reveals that the more efficient recycling option of cutting social contributions is regressive. It benefits the higher living-standard percentiles more than their lower counterparts (see lower part of Table 1). This is because it raises capital income more than labour income and indeed than transfers—which remain at constant *per capita* levels in real terms, while the budget share of energy is on average higher for the lower percentiles.

‘Lump-sum’ recycling is one blunt way of redressing this undesirable equity impact, but at the efficiency cost of substantially lower GDP and employment creation. A compromise between economic performance and social justice is attainable by a mixed recycling option that uses the carbon tax payments of firms to reduce their social contributions and hands back to households their own payments as lump-sum transfers (columns 3 and 5 of Table 1). This compromise may be further refined by turning the lump-sum transfer into a tax credit balancing out carbon tax payments on basic energy needs, complementing it with financial measures targeting the more vulnerable households, and limiting both benefits to the lower 8 living-standard deciles (columns 4 and 6 of Table 1) to rather target further labour tax cuts. With such refinements, the reform can indeed accommodate the additional objective of reducing public debt while remaining both efficient and progressive (column 6 of Table 1).

A third dimension of [Combet et al. \(2010\)](#) regards the consequences of the reforms on the output costs of activity sectors. It is an update of our 1998 analysis (Figure 7 p.23) with a similar, rough methodology, although at a higher level of disaggregation (Figure 8). It confirms our former estimates that a high proportion of activities—88 out of 107 = 82%, compared to 28 out of 35 = 80% in our 1998 analysis—see their unit output costs decline when considering all general equilibrium effects, even though part of the proceeds are dedicated to compensation measures in direction of households and public debt alleviation. These activities form an even higher 92% of total national value-added (91% in our 1998 analysis). The stability of these estimates, despite the approximately 3-time higher carbon tax compared to the 1998 analysis (€100/tCO₂ versus €35/tCO₂), is the consequence of labour tax cuts homothetically increasing with tax payments. The activities recording cost increases above 1.25% are chemical industries (2 sectors), iron ore mining, transport services (3 sectors) and fishing. For the 3-time higher tax, the +6.2% largest cost increase is 3.4-time higher than the +1.8% largest increase of the 1998 analysis.

Interestingly, carbon abatement with the 3-time higher tax in a 2004 context is only 20% higher than in the 1996 context (-16.6% versus -13.8%). This is for a small part because of inflation, which erodes the real value of 2004 euros compared to 1996 euros (13% only between 1996 and 2004 according to the World Bank data), for another part because of the convex nature of abatement costs, and also simply because of model recalibration.

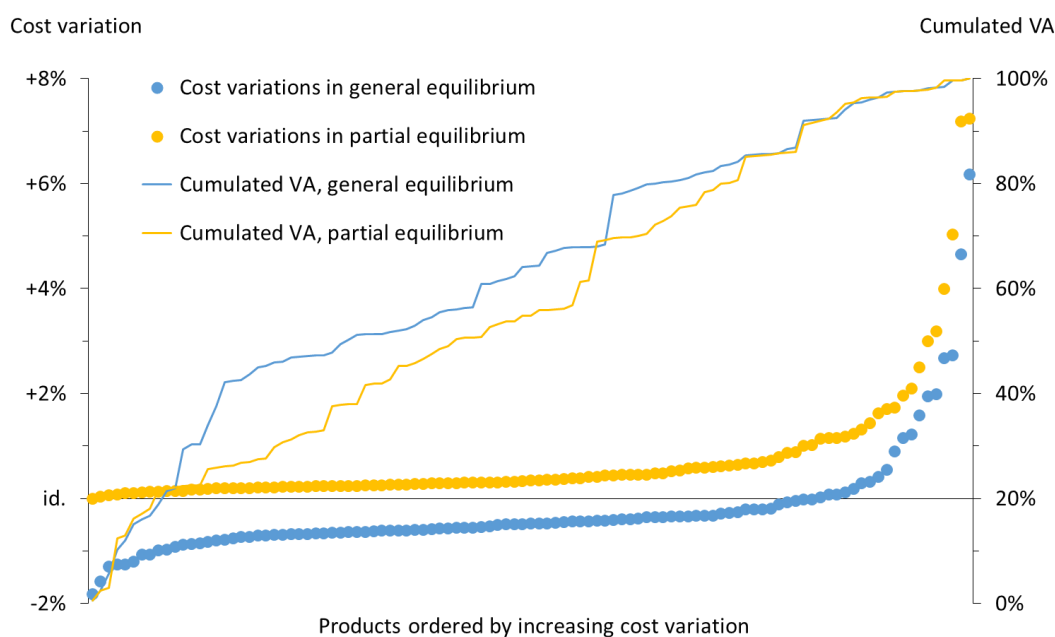


Figure 8 Impact on output costs of a €100/tCO₂ carbon tax reform with mixed recycling including 10% public debt cuts (Table 1, column 6)
Source: Combet et al., 2010⁴³

At the time of our report publication, we take up its novel insights regarding the distribution of the costs or gains of carbon reforms on living-standard groups in two different journal papers. One paper focuses on demonstrating how carefully-designed recycling schemes, some of them not in the initial report, allow improving both the efficiency and equity outcomes of an identical tax—with marginal impact on its environmental efficiency (Hourcade et al., 2010a). The other paper is a more straightforward transposition of the report but adds the additional angle of money transfers neutralising the distributive impacts between household groups (Hourcade et al., 2010b, in Annex to this report p.117). From a policy point-of-view, this is a somewhat abstract, normative stance compared to the implementation-oriented but ad hoc schemes of the report.

2.2. International climate negotiations

The natural complement to our carbon policy analyses in the French context are some analyses on international climate negotiations. These started in the wake of the Kyoto Protocol of 1997, at a time when the “burden sharing” of global mitigation efforts between large economies was a debated issue that echoed in the negotiating stances of, particularly, ‘Annex B’ countries—those countries with quota commitments under the Protocol.

2.2.1. Meta-modelling of the Kyoto Protocol consequences

During a stay at Resources for the Future (1999-2000), we developed a meta-model simultaneously considering the marginal abatement cost curves (MACCs)⁴⁴ of 6 world regions from 12 global climate-economy models

⁴³ The 107 points plot the cost variations of the 107 branches, ordered from the smallest to the largest, according to ex ante computation (partial equilibrium) or ex post computation (general equilibrium).

⁴⁴ MACCs plot the cost of abating one additional ton of carbon in one specific economy, from the first to (theoretically) the last ton of carbon emitted at one point in time. They are often used to report the direct investment costs of technical options allowing additional abatement. However, they can also report marginal social costs, i.e. the welfare or GDP cost of incremental abatement, all feedbacks and consequences

embodying various degrees of optimism and pessimism about key assumptions underpinning international climate negotiation stances. The meta-model computes global carbon quotas market equilibria for the 12 sets of MACCs. Lending equal probability to each of the 12 reduced models' outcomes provides some rough assessment of the uncertainty surrounding the consequences of various market design options.

We applied this meta-model to an in-depth analysis of the missed opportunity of COP6 (sixth Conference of Parties to the UNFCCC) at The Hague in November 2000 (Hourcade and Gherzi, 2002).⁴⁵ International negotiations on implementation of the Kyoto Protocol (KP) collapsed at The Hague around four main issues:

- The issue of compliance costs, both the total cost of action and the politically sensitive marginal cost of action, generally interpreted as the price of carbon to be imposed on economic agents.
- The level of domestic action, considering the provisions of emissions trading, Joint Implementation (JI) of abatement actions by agents of one Annex-B country in another one, and Clean Development Mechanism allowing Annex B countries to acquire emission credits by abatement actions in non-Annex B countries.
- The environmental integrity of the Protocol, with particular fears regarding the amount of 'hot air', i.e. excess emission quotas resulting from the post-1990 collapse of former soviet economies, when 1990 is the reference year of quota allocation.
- The involvement of the developing world i.e. of non-Annex B countries, who by definition of Annex B escaped any quota commitment at Kyoto, despite their rapidly growing weight in the world economy— and hence global emissions.

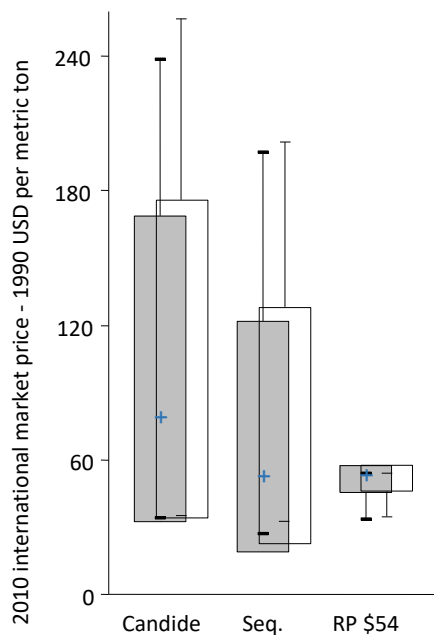


Figure 9a Marginal cost ranges under the Seq. and RP options
Source: Hourcade and Gherzi, 2002

Our meta-modelling endeavour meant to demonstrate that some room for compromise between these four, partially contradictory objectives, existed at The Hague. We built our demonstration on the assessment of policy options such as concrete ceilings to or levies on carbon imports; 'environmental restoration payments' to be made on excess emissions; and credits for sequestration activities in Annex B countries.

The restoration payments devised with our RFF colleagues (Kopp et al., 2003) were meant as a 'safety valve' warranting a cap on total compliance costs. They consisted in an unlimited additional supply of permits at an agreed-upon ceiling price, whose proceeds would be reinvested in additional abatement action during a true up period. Our numerical analyses confirmed that they were a superior means of addressing the cost uncertainty issue, much more effective than the extended sequestration option (accounting of 'carbon sinks' from forestry activities and land-use management, which we assessed at 183MtC) promoted by United States negotiators to control marginal costs (Figure 9a).⁴⁶

of the reform on the broad economy considered. Confusion between technical and social costs is frequent in carbon policy discussions (see our summary of Hourcade and Gherzi, 2009 section 3.3 p.50).

⁴⁵ This 2002 paper forms the first chapter of our PhD thesis (Gherzi, 2003).

⁴⁶ Figure 9a displays 2-standard-deviation likelihood intervals (shaded boxes centred on the mean of 12 estimates), extreme bounds (dashes) and median values (crosses) of marginal cost estimates across the 12 reduced-form models forming the meta-model. It reports on a 'Candide'

They would also substantially improve the environmental integrity of the Protocol implementation when duly accounting for actual limits to the willingness to pay (WP) for mitigation (Figure 9b)⁴⁷—while other compliance mechanisms, by effectively pricing carbon above the marginal cost at which action had stopped, were bound to induce defection.

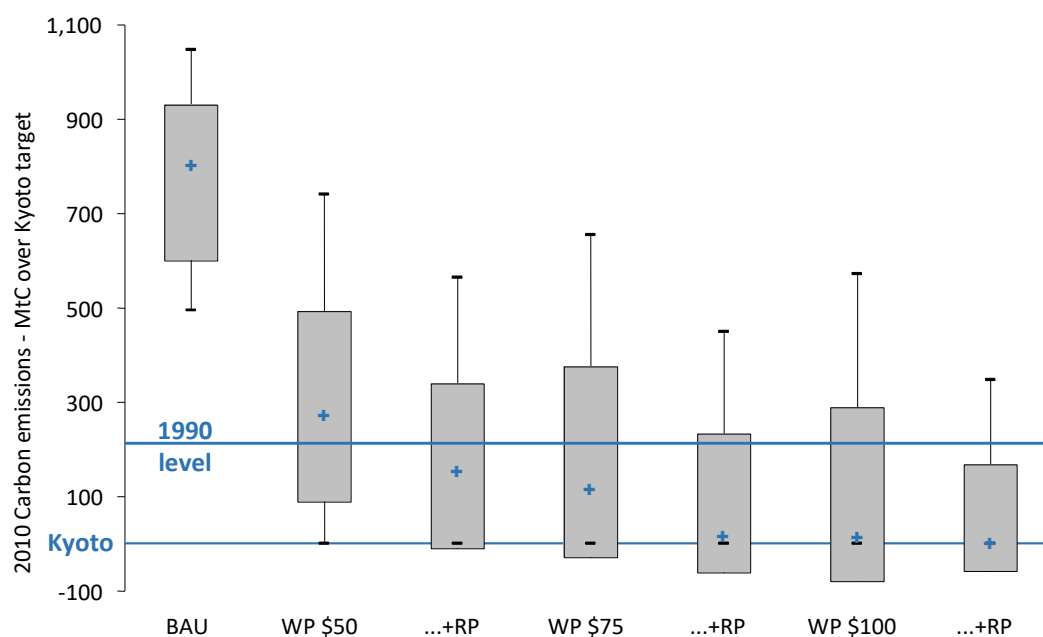


Figure 9b Carbon-emission ranges under limited Willingness to Pay (WP) without and with Restoration Payment (RP)

Source: Hourcade and Gherzi, 2002

In 2008, we publish another application of this same meta-modelling tool with a focus on the consequences of the United States rejecting the Kyoto Protocol (Hélioui et al., 2008). The ‘hot air’ excess quota allocation to transition economies becomes a stringent problem as it could cover the entire abatement commitments of the remaining Annex B country, thereby depriving the protocol of any effective impact on global emissions. The collapse of the international market price of carbon quotas testifies of the extent of the threat (Figure 10). It is particularly strong for the higher estimates of hot air supply—1,470 MtCO₂ per year under our ‘HA+’ assumption versus 550 MtCO₂ per year under our ‘HA-’ assumption.

The organisation of an oligopoly by hot air suppliers could support prices and, consequently, abatement action in Annex B countries. Policy design can however not be left at that. We thus further estimate a ‘green fund’ proposal of systematically investing in additional abatement any proceeds from hot air sales. At the time of our writing, the World Bank is supporting a proposal in that sense, as well as some hot air suppliers including Russia, who express interest in the technology transfers that could underpin it. Our meta-modelling results favourably assess its impact on prices, which rise to a range where a negotiation compromise seems attainable, with very little sensitivity to the volume of hot air eventually available (Figure 10)—one major advantage of the green fund mechanism.

(full implementation regardless of total and marginal costs) scenario, a ‘Seq.’ scenario considering extended sequestration options reaching 183 MtC globally, and a ‘RP \$54’ scenario considering a \$54 cap on marginal costs implemented as a restoration payment.

⁴⁷ The shaded box plots of Figure 9b report the same information on the distribution of reduced models’ results as those of Figure 9a. The additional light box plots apply in the event of ‘hot air’ providers acting as Stackelberg leaders, i.e. controlling their sales to raise market prices with a view to maximise their profits.

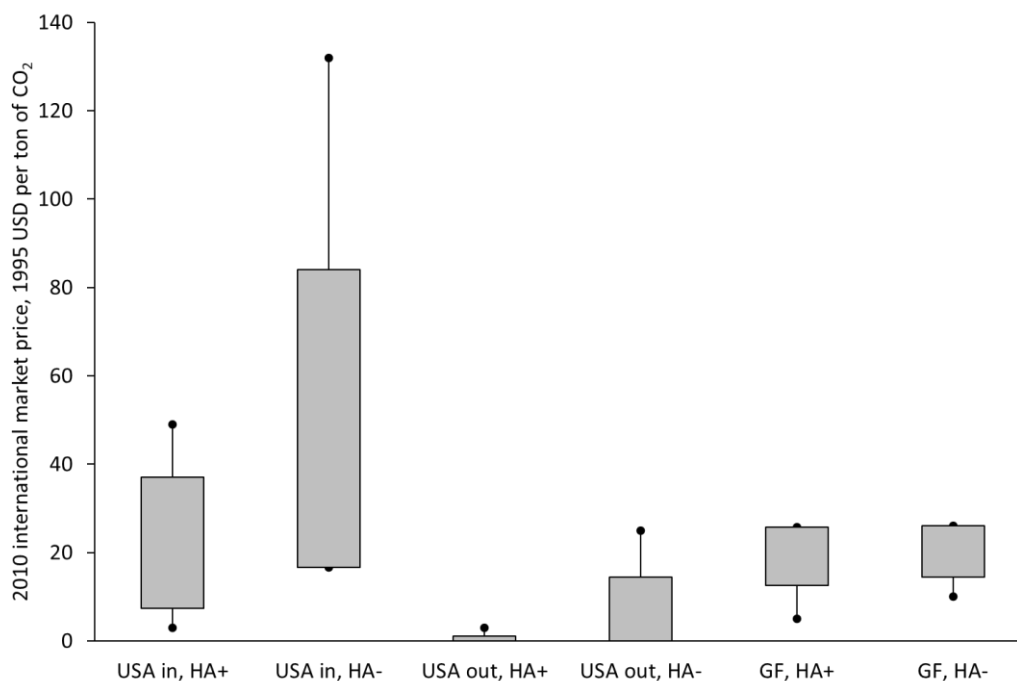


Figure 10 Impact of USA drop-out and Green Fund provision (GF) on marginal cost ranges for high (HA+) and low (HA-) hot air assumptions
Source: Hélioui et al., 2008

2.2.2. An IMACLIM-POLES assessment of post-Kyoto burden sharing

In 2003, we published our first systematic attempt at coupling IMACLIM to bottom-up modelling outside CIREC (Gherzi et al., 2003).⁴⁸ In this paper, we present applied work on the equity and efficiency of post-Kyoto international climate mitigation burden-sharing agreements. We explore the 2030 consequences of two contrasting carbon-quota allocation rules: a “Soft Landing” rule extending the Kyoto protocol approach to burden sharing and a “Contraction and Convergence” rule progressively departing from the Soft Landing burden sharing to arrive at a global common per-capita emissions endowment in 2050. Our numerical assessments lean on runs of 14 IMACLIM models embarking reduced forms of POLES modelling outputs for 14 countries or regions covering the globe, according to the method described in section 1.1.1 above—an important step in the early methodological developments of our research.

As regards policy analysis, we set the global emission reduction objective of both rules at 20% from baseline in 2030, a conservative target seen from today. Notwithstanding, both the “Soft Landing” approach, more favourable to developing economies, and the “Contraction and Convergence” approach, more favourable to developed economies, seem bound to engage the international negotiation into deadlocks (Table 2), even when carbon pricing reforms strive to minimise their aggregate social costs by recycling pricing proceeds into lower labour taxes (the ‘auctioned allocation’ row of Table 2).

In the face of such deadlocks, the conclusion of our paper is literary only: we stress the need to shift from an approach framed in terms of burden sharing to an approach framed in terms of leverage effect on development. Among others, the ‘burden sharing’ point-of-view has the strong disadvantage of negating any possibility of a Pareto-improving accord that would concretise at the benefit of all parties. Interestingly, we barely flesh out the ‘leverage effect’ stance that we call for, at the level of our conclusion only. It is as if our assessments were foreboding the ultimate failure of the ‘top-down’ policy approach of global cap & trade at the Copenhagen

⁴⁸ This research provides the material of the fifth chapter of our PhD thesis (Gherzi, 2003).

Conference of Parties to the UNFCCC, and the consecutive rise of the ‘bottom-up’ policy approach of Nationally Determined Contributions (NDCs).

	Contraction and Convergence rule		Soft Landing rule	
	Without international emission credit market	With international emission credit market	Without international emission credit market	With international emission credit market
Free allocation	High marginal—private—costs for the OECD and transitional economies. Exceedingly high consumption losses for the US, Japan and transitional economies.	Exceedingly high marginal—private—costs for the developing world. High consumption losses for the transitional economies and India.	Exceedingly high marginal—private—costs for sub-Saharan Africa. High consumption losses for Japan, India and Other Asia.	Exceedingly high consumption loss for India. High consumption losses for Other Asia. High foreign transfers from Other Asia, and to China.
Auctioned allocation	Exceedingly high marginal—private—costs for the OECD and transitional economies. Exceedingly high consumption losses for the US and Japan.	Exceedingly high marginal—private—costs for the developing world. Exceedingly high foreign transfers from the US and FSU.	Exceedingly high marginal—private—costs for sub-Saharan Africa, Brazil and Other Asia. High marginal—private—cost for Japan.	Exceedingly high marginal—private—costs for the developing world. Exceedingly high foreign transfers from Other Asia, and to China.

Table 2 Political barriers to global post-Kyoto quota allocation rules
Source: adapted from Gherzi et al., 2003

2.3. Sectoral analyses

On top or aside of our research on French and international climate policies, two of our research themes focus on sectors whose emissions’ control is of particular concern, considering their current trends and high technical inertias: the transportation and the residential sector.

2.3.1. The transportation sector

At the occasion of a project funded by the European Commission, we had to mobilise the global, recursive version of IMACLIM developed at CIRED by colleagues (Sassi *et al.*, 2010) to analyse the compatibility of transport-specific and overarching mitigation objectives of the European Union (Gherzi *et al.*, 2013). Our numerical assessments reject the hypothesis that even stringent 2020 and 2050 overarching CO₂ mitigation targets dominate (i.e., necessary imply compliance with) short-run objectives in the transportation arena regarding biofuel penetration and the carbon efficiency of light-duty vehicles (LDVs) (Table 3). This implies that the policies targeting transports’ emissions come at some extra cost that is not necessitated by climate mitigation up to 2050. Notwithstanding objectives other than climate mitigation like local pollution or congestion issues, the extra cost might be justified, though, to counter the high inertia of vehicle fleets and especially transportation behaviours (linked among others to urban forms, of particularly slow dynamics) in a longer term. This assumption however remains to be tested in proper research.

Target (EU reference)	Year	Objective	Reference scenario	Overarching Carbon Constraint scenario
Share of biofuels (EC 30/2003)	2010	5.75%	0.19%	0.19%
Share of biofuels (CEU, 2007)	2020	10%	2.95%	4.02%
LDV CO ₂ emissions, bench-test vintage average (SDS target)	2012	120 g/km	134 g/km	127 g/km
LDV CO ₂ emissions, bench-test vintage average (EC 443/2009)	2015	120 g/km ^a	134 g/km ^b	127 g/km
LDV CO ₂ emissions, bench-test vintage average	2020	95 g/km	132 g/km	120 g/km

^a The target is more precisely defined as 130g/km on average for the total sales of each carmaker (with derogative provisions for very small producers), complemented by an extra 10g/km reduction from “additional measures”, see regulation EC 443/2009.

^b Bench-test vintage averages of the REF and OCC scenarios are systematically estimated 18% below the projected on-road vintage averages.

Table 3 Status of transport objectives under two scenarios
Source: Ghersi et al., 2013

We turned again to transportation issues at the occasion of an ERA-NET European project on the penetration of electric vehicles in the European Union (EU). Our part in it was to provide the economy-wide framework into which to embed the BU outlooks of German colleagues. We thus developed the coupling of a fully hybrid EU28 IMACLIM with the TIMES PanEU model of the University of Stuttgart. This coupling experiment is our most thorough so far: we implemented the iteration-to-convergence method of section 1.1.2 above, eventually forcing in IMACLIM 39 different trajectories either directly taken from TIMES or inferred from its runs (Ghersi, 2014a, 2015b).

Preliminary results⁴⁹ indicate that the EU development of electric personal mobility has a small GDP impact, which could be compensated by a strong trade performance of the EU electric-car industry. Under pessimistic trade performance of EU electric cars (nil exports, 35% to 50% reliance on imports), in a factor 2 mitigation context,⁵⁰ a penetration of electric cars (ECs) up to a fourth of total car sales in 2050 comes at a moderate GDP cost peaking at 0.17% along the trajectory to 2050. In a factor 5 mitigation context, an increased penetration of ECs leading to an additional 2.8 million vehicle sales in 2050, induces GDP losses peaking at 0.22%. However, under optimistic trade performance of EU electric cars (exports twice as high as sales to households, reliance on imports similar to that of conventional vehicles i.e. below 10%), the same EC developments induce small GDP gains peaking at 0.15% in a factor 2 context and at 0.10% in a factor 5 context.

Interestingly, under pessimistic trade performance the two peaks of GDP losses happen at years when EC penetration has a maximum impact on electricity prices, rather than at years when electric car sales peak in market share or sheer volume. This implies that the impact of EC penetration on electricity generation costs is one major driver of its economic costs.

The second conclusion of this research is that EC penetration only marginally affects tax collection. At the restricted level of fuel sales, the cuts in oil products sales imply losses of both excise and VAT income, but these are substantially compensated by the increase of the excise and VAT levied on electricity sales—considering calibrated average tax rates levels in the EU. Under pessimistic EC trade assumptions, cumulated excise and VAT proceeds net of vehicle purchase subsidies only drop by 1.4% in a factor 2 context and 1.0% in a factor 5 one. At

⁴⁹ The iteration process with the TIMES PanEU model is yet to be completed for this research to be published. The description of preliminary results is taken from Ghersi (2015b) with only slight editorial changes.

⁵⁰ A reduction of EU emissions to half their 1990 level in 2050. Similarly, a factor 5 context is a reduction of emissions to 20% their 1990 level in 2050. The marginal cost of fuelling electric vehicles is highly sensitive to the mitigation context.

a comprehensive macroeconomic level, the corresponding tax savings fuel household consumption anyway, which in turn raises taxes that fuel public budgets. Consequently, whether in a factor 2 or in a factor 5 context, total (modelled) tax proceeds net of vehicle subsidies register a negative impact lower than 0.25% across time. Notwithstanding, in the short run up to 2020, our assumed vehicle sale subsidy makes up a significant share of the lost public income.

2.3.2. The residential sector

Our research on residential energy consumption focuses on the issue of fuel poverty in France. It follows from an invitation of *Électricité de France* (EDF) to take part in an expert group on the matter, which led to develop a prospective outlook on the prevalence of the phenomenon in influential macroeconomic scenarios for France (Gherzi and Ricci, 2014). This outlook leans on two methodological improvements to IMACLIM.

The first improvement regards a systemic modelling of households' demand with a specific focus on residential energy consumptions (Gherzi, 2014c). This modelling distinguishes 8 household consumption goods: housing, housing maintenance and repair (to record retrofit expenses), public transports, automotive fuels, electricity, natural gas, domestic fuels and a composite good remainder. Public transports and automotive fuels further disaggregate in 'constrained' vs. 'leisure' varieties. Similarly, electricity breaks down in specific and non-specific (*i.e.* substitutable) uses. All goods enter an extended utility function, which centrally exploits the conclusions of urban economics on the long-term choices regarding housing, and the transportation demands induced by such choices.

The second improvement is a 'macro-micro' extension of the model that performs disaggregation of its 5 income quintiles into 10,240 household types with updated statistical weights. The method is that of "micro-accounting with reweighting", a micro-simulation method favourably described by Agénor et al. (2004) or Herault (2010). It allows re-creating the diversity of household situations at the projected horizon, which is a *sine qua non* condition to numerically assessing fuel poverty prevalence—and has the potential of innumerable other applications.

Our outlook on energy poverty is still at the stage of a working paper, although currently under evaluation by a peer-review journal.⁵¹ Under two fuel-poverty indicators and for four influential macroeconomic scenarios of 2035 France, we compute an increase of both the number of fuel-poor households (absolute measure) and the prevalence of fuel poverty among households (relative measure). Detailed quintile results show that the increase strongly concentrates on the poorer income quintile (Q1), while Q2 to Q5 see their fuel poverty rates, and in many instances even their absolute numbers of fuel-poor households, decrease. The particular brunt borne by Q1 households reflects their sensitivity to

- One public policy assumption common to all our scenarios: that of a containment of public deficits (at their share of GDP of 2006, the calibration year of our analysis) through a general cut in social transfers including pensions and unemployment benefits.
- Another generalised assumption of a convergence of *per capita* specific electricity consumptions, which affects them all the more so as it is posited independently of price variations—although, conversely, our simulations fix the share of labour income accruing to each quintile at its 2006 level, despite some evidence of and concern on an increase of wage inequalities.

It is also caused by Q1's households lesser capacity to adapt to energy prices hikes by changing their fuel mix or resorting to insulation or more-efficient heating equipment—this reduced capacity is however our own exogenous assumption, for lack of quintile-specific behavioural data, although it reflects concerns widely expressed in the literature.

⁵¹ We draw the following description of our results from Gherzi and Ricci (2014) with only marginal editorial changes.

On a more optimistic note, despite the aggregate increase of the phenomenon, the aggregate social cost of fuel poverty, which we measure by the ratio of the residential energy expenses of the fuel poor to GDP, remains stable at its 2006 value of ca. 0.21% of GDP in all 2035 scenarios (under the more focused Low-Income High Cost definition of fuel poverty). The particular increase of Q1 fuel poverty shows in the fact that Q1 shifts from concentrating half this cost in 2006 (0.12% of GDP) to three quarters of it in 2035 (0.16% to 0.17% of GDP). This concentration should be of concern to policymakers. However, our macroeconomic results demonstrate that public budgets preserve room of manoeuvre to consider some socialisation of Q1 fuel-poor expenses, even under the double constraint of contained public debt ratio and fiscal pressure.

2.4. *Varia*

2.4.1. Free-time preference and its global carbon emission impacts

During our stay at the Fondazione Eni Enrico Mattei (FEEM, 2010-2011) we worked on one application of the WITCH model⁵² around the ‘beyond GDP’ issue of free-time preferences (Bosetti and Gherzi, 2012). We formalise the trade-off between ‘free time’ (time off the labour market) and labour in the Ramsey framework of WITCH, and calibrate it for the 12 regions of the model. We then compare the consequences of convergence of the free-time preferences coefficients of all world regions to the contrasted Western European (WEU) vs. United States value. We call the corresponding scenarios the ‘US way-of-life’ (USWL) and the ‘Western-European way-of-life’ (WEWL) scenarios.

In a nutshell, the ‘US way-of-life’ (USWL) scenario induces substantial discounted GDP impacts, which range across regions from -6% (KOSAU region) to +20% (MENA, EEURO regions),⁵³ as well as labour supply impacts ranging from -5% (KOSAU) to +15% (MENA). In the Western European way-of-life (WEWL) scenario, these impacts range respectively from +2% (EEURO) to -27% (SSA), and from 0% (WEURO, EEURO) to -24% (SSA) (Table 4). However, discounting the impacts mechanically lends more weight to the earlier years, when regions only gradually drift from their BAU trajectories by converging to one or the other foreign preference. Detailed modelling results reveal indeed that GDP variations symmetrically reach +32% (EEURO, USWL, 2095 and 2100) and -32% (SSA, WEWL, 2075 to 2100), while labour supply ones range from -34% (CHINA, WEWL, 2025) to +32% (EEURO, USWL, 2080 to 2100).

As a side note, it is worth mentioning that because of the varying shares of each region in the total global GDP and person-hours, the global aggregation of the two scenarios delivers results that are not easily derived from the disaggregated ones. In the USWL scenario, global discounted GDP increases by 4.2%, while global discounted person-hours decrease by 0.3%—the regions that increase their labour supply are on average more productive than those who decrease it. In the WEWL scenario discounted person-hours fall by 13.8% and GDP by 11.7%.

⁵² <http://www.witchmodel.org/>.

⁵³ For the explanation of region names, see footnote 54.

	USWL scenario		WEWL scenario	
	Disc. GDP	Disc. person-hours	Disc. GDP	Disc. person-hours
USA	-0%	-0%	-15%	-14%
WEURO	+16%	+14%	+0%	+0%
EEURO	+20%	+13%	+2%	-0%
KOSAU	-6%	-5%	-19%	-17%
CAJAZ	+3%	+2%	-11%	-11%
TE	+5%	+3%	-11%	-10%
MENA	+20%	+15%	+1%	-1%
SSA	-12%	-10%	-27%	-24%
SASIA	+13%	+10%	-6%	-5%
CHINA	-13%	-11%	-28%	-21%
EASIA	-4%	-3%	-19%	-16%
LACA	-2%	-2%	-18%	-16%
WORLD	+4.2%	-0.3%	-11.7%	-13.8%

Table 4 Impact of 2 time-preference scenarios on the discounted 2005 to 2100 GDP and worked person-hours

Source: Bosetti and Gherzi, 2012⁵⁴

Beyond GDP and labour market time, the use of WITCH allows tracking and translating differences in GDP into differences in total primary energy demand and the resulting greenhouse gas emissions (Table 5). The impacts of the two scenarios are broadly in line with the GDP gains or losses they induce, but at scrutiny reveal some more counter-intuitive mechanisms: compared to BAU, the USWL, despite a significantly higher GDP growth, induces both a lower energy and carbon intensity, while the WEWL increases them both. The reason for this is the contrasted impact of both scenarios on global energy markets. The 4.2% increase in discounted GDP caused by the USWL implies increasing tensions on fossil fuel markets, which translate in substantially higher prices that induce improvements in energy demand management and decarbonisation. Conversely, the dramatic 11.7% slack in GDP caused by WEWL considerably eases those tensions and cuts down the incentives to invest in energy efficiency or decarbonisation. The mechanisms at play are most visible in the case of the two central regions of the US and Western Europe for those scenarios that generalise their free-time preferences: despite unchanged GDP, both their energy consumptions and emissions evolve in quite illustrative ways.

⁵⁴ Countries or regions in row order are the USA; Western Europe; Eastern Europe; Korea, South Africa and Australia; Canada, Japan and New Zealand; Transition Economies; Middle-East and North Africa; Sub-Saharan Africa; South Asia; China; East Asia; Latin America and the Caribbean.

	USWL scenario		WEWL scenario	
	Cum. 1 ^{ary} E cons.	Cum. emissions	Cum. 1 ^{ary} E cons.	Cum. emissions
USA	-0.7%	-0.4%	-14.2%	-13.4%
WEURO	+19.1%	+17.3%	+3.4%	+3.5%
EEURO	+21.3%	+17.5%	+6.8%	+5.5%
KOSAU	-5.6%	-4.4%	-16.5%	-13.3%
CAJAZ	+3.4%	+3.3%	-9.8%	-9.0%
TE	+5.5%	+4.1%	-7.4%	-5.2%
MENA	+18.9%	+16.8%	+5.9%	+4.9%
SSA	-11.1%	-4.2%	-20.4%	-7.9%
SASIA	+13.2%	+9.8%	-3.1%	-2.4%
CHINA	-11.3%	-10.4%	-22.9%	-21.5%
EASIA	-4.0%	-3.2%	-15.8%	-14.1%
LACA	-2.4%	-1.3%	-15.8%	-9.1%
WORLD	+2.5%	+1.7%	-10.7%	-9.1%

Table 5 **Impact of two scenarios on cumulated 2005 to 2100 primary energy consumption and CO₂-equivalent emissions**
Source: Bosetti and Gherzi, 2012

2.4.2. One first experiment with foreign single-country versions of IMACLIM

In 2015 and 2016, we became strongly involved in the supervision of the PhD of Jules Schers at CIRED, devoted to the implementation of a South African version of IMACLIM, IMACLIM-ZA. This research, funded by the French development agency (AFD), preliminarily concretised in a substantial report assessing the impact of climate mitigation on the South African economy, with a particular focus on the labour market segmented in 3 skill levels (Schers et al., 2015). The consecutive PhD thesis, with many improvements over the rough, first versions of IMACLIM-ZA, is currently at the very last stage of completion.

It opened up a new research agenda that we will elaborate on in section 4 of our Research Project p.75 below.

3. On energy-economy models, their uses and that of their results

As mentioned in our Introduction, we dedicate this final section of our *Completed Research* synthesis to the presentation of four ‘positional’ papers on energy–economy models, modelling practices and the use of modelling results. To some extent, these papers, and especially Hourcade et al. (2006), provide blueprints of desirable model characteristics, which largely echo some of our own developments under section 1 above. However, they also prescribe research directions to applied analyses of climate policies, and comment upon the interpretation and use of modelling results. The latest paper additionally touches on dimensions of climate policy analysis that go beyond our own focus on the efficiency and equity of policy designs. Articulating its presentation with that of the former papers (rather than reporting more fully on them in the course of section 1) testifies of the broadening, along the years, of our perception of the stakes attached to modelling practices and the use of modelling results in policy debates.

3.1. Four modelling priorities at the time of the Kyoto Protocol

The earliest of the four papers dates back to our stay at Resources for the Future in 1999-2000 (Gherzi and Toman, 2003). It is a survey of the strengths and weaknesses of 15 models of greenhouse gases emissions trading available in the literature at the time of writing, most of them applied to the analysis of the Kyoto Protocol on a global cap-and-trade greenhouse gases mitigation effort. It highlights four directions of research that required exploration.

- Distributive issues, in the broadest of senses covering the international distribution of mitigation costs across world regions, and their domestic distribution across both productive sectors and household groups.
- Endogenous technical change, to overcome the use of autonomous energy efficiency improvements (energy efficiency improvements modelled as exogenous energy productivity gains) or backstop technologies (zero-carbon technologies available at fixed supply costs beyond some temporal horizon).
- ‘Second best’ dimensions of international emissions trading, including policy constraints on global access to the cheaper mitigation options (“where flexibility”) or on the ability to bank or borrow emission permits across quota periods (“when flexibility”), but also mere transaction costs, quite systematically overlooked by available analyses at the time.
- A better understanding of the implications for international carbon trading of international commodity trade and financial flows, and the consecutive ‘carbon leakage’ (relocation of carbon-intensive industries into countries with more lenient or inexistent carbon control).

Although our paper did not discriminate between the four sets of questions, the second one stands out as properly methodological, while the others rather relate to model coverage and implementation. With hindsight, we devoted much subsequent research effort to the first (see sections 2.1 and 2.3 above) and the second (the focus of our methodological contributions, see section 1 above) of these required developments, while we only barely touched upon the third and fourth points in our few analyses outside ‘open economy’ settings (see mostly section 2.2 above).

3.2. On hybrid modelling

Our second ‘positional’ paper is the introduction to a special issue of *The Energy Journal* that gathered contributions to an international workshop on hybrid energy-economy modelling, which we organised at CIREN in 2005 (Hourcade et al., 2006). It is a landmark of our research trajectory that concentrates the arguments in favour of combining the engineer’s (bottom-up) and the economist’s (top-down) viewpoints of energy constraints in ‘hybrid’ models of energy-economy interactions. Our Introduction above (p.21) gives the essence of the argument of addressing each approach’s limitations by capitalising on the strengths of the other approach.

In the paper, we summarise this argument in a graphical representation that interestingly adds “microeconomic realism” to the “macroeconomic completeness” and “technological explicitness” criteria (Figure 11). As we already hinted (see our critique of the behavioural assumptions of both top-down and bottom-up approaches in our Introduction and footnote 3 p.21), none of the two complementary approaches performs satisfactorily in this dimension. On the one hand, standard top-down models offer too crude representations of energy demands and the underlying technologies to produce meaningful insights. On the other hand, standard bottom-up models duly attach explicit technology options to each energy end-use but settle technology choices on the too simple criterion of cost minimisation, thus disregarding subtle differences between technologies serving the same purpose, limitations to the financial capacity to invest, etc. Besides, they compute levels of energy-service

demands based on rough econometrics typically expressing them as simple functions of GDP per capita. They rarely take into account price elasticities and fail to offer a comprehensive, systemic description of energy consumptions—e.g. to connect the demand of transportation services to urban density and thus the size of lodgings, which in turn determines heating, cooling and lighting requirements. We pick up this critique at the opening of the second section of our research agenda, which focuses on addressing such limitations (see section 2 of our Research Project p.67).

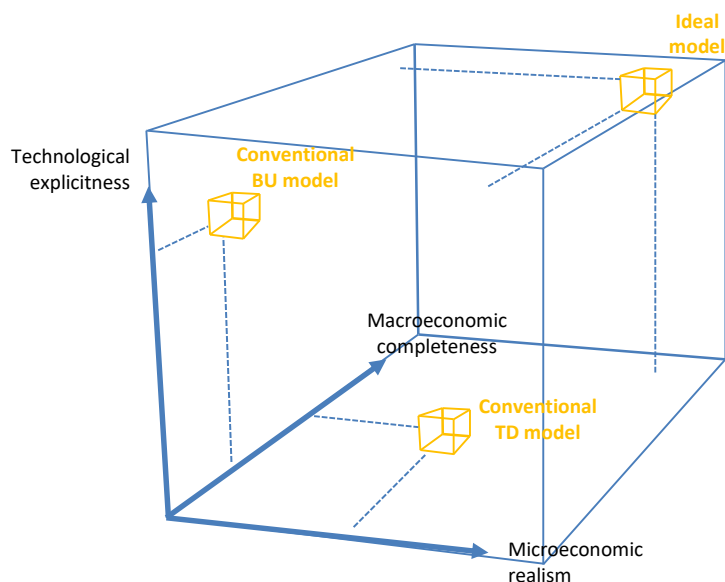


Figure 11 Three-dimensional assessment of Energy-Economy models
 Source: Hourcade et al., 2006

3.3. On the polysemous notion of “policy cost”

In **Hourcade and Gherzi (2009)**, we address the confusion raised in scientific and political discussions by the quite distinct realities that the same terms of ‘abatement costs’ can convey. One central distinction is the very nature of reported mitigation costs. They can be the technical costs of the portfolio of energy supply and end-use equipment necessary to mitigation; the macro-economic GDP, consumption or unemployment costs induced by the financing of such technical costs and their impacts on relative prices; or the welfare costs assessing these macroeconomic costs via some aggregate social utility function. Confusion stems from the fact that the three notions, although quite distinct, can be expressed in identical units: dollar per abated ton of carbon, aggregate monetary amount or ratio of this amount to GDP or income, etc. The assessment gap is particularly wide between the former and the two latter measures, because of, in a closed economy:

- The structure of the input-output (IO) matrix, or inter-industrial relationships, which determines how the direct price increase induced by technical costs spreads throughout the production system and results in a new set of relative prices.
- The impact of this shift of the price vector on the trade-off between factors in production—and the looping of these two first effects to equilibrium.
- The pre-existing tax system, which both distorts carbon price signals, and offers the opportunity to coordinate climate and fiscal policies so as to minimise the marginal welfare losses of a given climate objective—the ‘double dividend’ issue.

- The functioning of the labour market: the degree of wage flexibility determines how policy-induced changes in the relative price of labour affect the level of employment and ultimately real wages. Real wages in turn affect disposable income and households' consumption.
- Public budget constraints, i.e. the manner and extent to which complementary policies compensate the impact of the mitigation policy on public budgets.
- The costs of redirecting technical change: to some extent, the investment in abatement activities crowds out general investment and has a negative impact on general productivity.

In an open economy setting, interactions with international markets, including those for fossil fuels and in some instances carbon itself, further complicate the interplay between these factors. The reactions of oil, gas and coal prices to carbon pricing and the general shift in regional relative prices affect terms of trade and consequently macroeconomic indicators or welfare. Last, but not least, international financial markets constrain the investment decisions to build carbon-free energy capacities.

A second source of ambiguity of policy cost assessments is their level of aggregation across the two dimensions of space and time. The degree of precision of their tools, if not the expectations of policymakers faced with the necessities of the policy debate, drive carbon-policy modellers to produce aggregate estimates of policy costs, which masks their distributions across economic agents and time. Two policy packages with contrasted distributive impacts can thus coincide on one aggregate technical, macroeconomic or welfare cost assessment. Similarly, two policy packages can have contrasted cost trajectories that coincide at one or several points in time, or even when discounted to their net present value. There is however little argument that one policy package resulting in lower inequalities than another one, for some identical cost (whatever the cost notion), is preferable to that other one. Similarly again, one policy package implying a smooth investment trajectory is probably preferable than another one requiring unbalanced efforts across time.

The disaggregation across sectors, households or regions of technical or macroeconomic costs is a matter of data availability—and, from our own experience, of a substantial additional research effort. However, welfare costs raise conceptual issues because the aggregate welfare measure can proceed from individual ones following contrasted viewpoints on social justice, from the utilitarian viewpoint interested only in the maximisation of total welfare, to the Rawlsian viewpoint targeting maximisation of the minimum welfare. For the policy modeller concerned with distributive issues, reflecting this diversity of viewpoints boils down to weighing the vector of welfare impacts in specific ways when summing it up. The first reflex, common for non-economists, is to use the same weights for all household types or regions, as would appear ethically legitimate. However, minimising the aggregate welfare cost of any environmental policy (in fact of the provision of any public good) on such a basis results into placing its burden on the richer households or regions only, as long as per capita incomes have not equalised. Another possibility is to resort to Negishi weights, which are roughly inversely correlated to *per capita* incomes at each point in time. Most multiregional optimal control models retain that approach to aggregate the welfare of regions—see e.g. the description of RICE in Nordhaus and Yang, 1996. Doing so imposes a form of ‘no redistribution constraint’, but at the cost of considering the current and projected distributions of income of no-policy scenarios as either optimal or immovable.

In fact, most policy-assessment models do not directly address distribution issues. It is therefore important to consider that any one of their numerical results prevails under two important conditions. The first one, rather conservative but politically realistic, is that the welfare of individuals and/or countries forming aggregates is implicitly weighted in function of their income. The second one, more problematic, is that appropriate complementary policies moderate their distributive effects. In the absence of such policies, aggregate cost measures may mask significant shocks on some portions of the population or of the productive activity, potentially great enough to undermine the political acceptability of the reforms under scrutiny.

On the time dimension, the inability of discounted sums to discriminate between a cumulated constant difference between two balanced growth pathways over some extended time-period and a ‘point’ shock on growth at some point in time means that it is important to supplement any discounted costs assessment with

some information on the cost profiles. Many models are not suited to the in-depth study of such profiles. Static general equilibrium models can only report them in a limited way, assuming a smooth and steady transition from the supposed date of the policy implementation to the computed equilibrium. Recursive models often exogenise the time profile of either the price signal or the emission constraint to assess policies. Optimal control models are intrinsically suited to studying cost profiles. Their inter-temporal decision framework allows shifting focus from emission constraints to concentrations or temperature increases derived from simplified climate modules. They thus endogenise both the abatement efforts and the corresponding marginal cost constraints. It is consequently intriguing that they should not be more often applied to richer thought experiments, for example climate policies delayed until some time threshold where additional information allows informed policy developments (as in Ambrosi et al., 2003).

Two additional sections expand the reach of [Hourcade and Gherzi \(2009\)](#). In the first one, we further qualify cost assessments depending on how the models that produced them represent techniques. We distinguish between the mutually exclusive explicitness of technology-rich models and the comprehensiveness of economy-wide models, in a discussion that largely echoes the arguments already developed in our Introduction (p.21) and section 3.2 above. In the second of these two additional sections, we question the tendency of modellers and policy makers alike to interpret the marginal cost of any mitigation action as the price signal required to trigger it. The confusion is obvious when the technical and social costs of mitigation do not coincide, as is the case in all economy-wide analyses except the most aggregated ones. This is a point that we take up again in the most recent of our four positional papers, which we now turn to.

3.4. Low-carbon policy modelling vs. low-carbon policymaking

We reproduce in Annex the latter paper ([Gherzi, 2014b, see Annex 3 p.135](#)) because it develops arguments very close from our current views on modelling developments and practices, in a context of strong expectations from policy circles faced with an ever more daunting ‘decoupling’ (of economic growth and emissions) challenge. The paper originally builds on a survey of the literature devoted to low-carbon scenarios and its uses and misuses—or indeed total lack of use—of models or modelling results.

Its first section bears on carbon pricing and partially echoes the last section of [Hourcade and Gherzi \(2009\)](#), as we already mentioned. It stresses uniform carbon pricing as the condition to the minimisation of technical costs, while acknowledging the implausibility of political agreements on one single value of carbon at the global scale and over one century. Even at the politically integrated level of the European Union, the coexistence of the European Union Emissions Trading system (EU-ETS) covering large emitters and of national commitments on other emission sources implies at least two different carbon prices in each economy. Therefore, governments only promote carbon value trajectories as normative assessments of the theoretical least-cost options. Influential governmental reports by the UK and France employ similar methods to pinpoint such trajectories: from heteroclite modelling experiments on exogenous emission trajectories, they derive carbon values for pivotal years, then interpolate or extrapolate based on Hotellings’ rule (value of carbon growing at a rate equal to that of discount) or on even simpler linearization.

However, they do not discuss the consistency of these interpolations and extrapolations with the trajectories outlined by the modelling exercises that framed their choices of pivotal values—indeed, neither report details the latter trajectories. In the case of the French report at least, the abstract model that supports adopting Hotelling’s rule is obviously incompatible with the dynamics of those models from which the pivotal 2030 value derives. The challenge of reconciling such contrasted trajectories should have been highlighted rather than masked.

More fundamentally, both the French and UK reports lack a minimal discussion of the exogenous emission trajectories imposed to the models to compute carbon value estimates beyond 2020. They do discuss targets in

terms of both CO₂-equivalent concentrations and cap on temperature increase. However, the crucial question of how these targets translate into emission trajectories accommodating 2020 and 2050 commitments is unclear. The French report graphically presents its constrained emission trajectories and laconically indicates deriving them from the fourth IPCC report. The British report does not print its own and only mentions their source, some SimCap model. Regrettably, the optimality of these trajectories is unaddressed.

Moving from the normative stance of carbon value trajectories to positive policymaking raises again the paramount question of the wedge between the private and social costs of mitigation—whose causes we already detailed in section 3.3 above. There is no contention that minimisation of the technical cost of mitigation by equalisation of the marginal abatement costs of all emitters is one necessary condition to policy optimality. It is however not sufficient, because the various sources of discrepancy between the technical and social costs—some of them ‘second best’ features common to many economies—affect activity sectors and households differently. Striking the least-cost option consequently requires organising a set of transfers of the technical costs amongst economic agents. The question is not to be confused with that of the equity of the reform. It is indeed that of minimising its aggregate social cost by mitigating, e.g., the contrasted impact of the uniform carbon price on the competitiveness of sectors of production or on the propensity to consume of households. However, it may prove more complicated and costly to minimise costs by fine tuning downstream compensating transfers via various complementary policies, than to reduce them by acting upstream via some differentiation of the carbon price. This may indeed be some ex post justification of the fragmented European policy process.

From a modeller’s perspective, the consequence is that the challenge of policy assessment cannot anymore be the simple question of moving the cursor of one uniform carbon price applying to all emission sources indifferently, considering some standard assumption about the recycling of the pricing proceeds—typically, that of a lump-sum transfer to households. It is rather to explore the *terra incognita* of policy action under constraint of second best features of economies, in the several dimensions of the policy signal, its potential differentiation across emitting sources and the complementary measures necessary to minimise its ultimate economic impacts.

Besides, pricing is not always the least-cost policy option because of market failures or imperfections, which drag both innovation efforts and technology adoption below their socially optimum levels. Peer-reviewed articles that present comprehensive assessments of policy packages confronting this reality are rare. ‘Grey’ literature, on the contrary, abounds with studies and reports that insist on the necessity to combine a wide range of policy instruments to achieve high rates of decarbonisation, and propose such combinations. We survey the latter literature in a section of Ghersi (2014b) to produce a long catalogue of climate policy measures concerning energy supply and demand and indeed complementary measures beyond energy markets. However, we stress how the range of advocated measures and the precision in their description contrast with the paucity and crudeness of modelling support.

Faced with the above panorama, our last section of Ghersi (2014b) proposes a research agenda. We purposely limit it to cost-efficiency analysis, thereby both acknowledging current EU policymaking and shunning from the debates surrounding cost-benefit analysis (Box 1). In this latter choice we follow Dietz (2012) or Yohe and Hope (2013), who react to the persisting if not increasing failure of damage assessment to reach any form of consensus.^{55,56} As Kopp and Mignone (2012) establish (without formally endorsing it), this shift is a transcription to climate affairs of Baumol’s prescription to degrade the Pigouvian policy principles when faced with too-elusive externality costs (Baumol, 1972).

The 2007 Stern review (Stern, 2007) and the 2010 United States Interagency Group on the Social Cost of Carbon (IWGSCC, 2010) successively fuelled an escalating controversy on cost-benefit analysis, including three recent

⁵⁵ Dietz observes that the gap of about one order-of-magnitude between the plausible ranges of the social cost of carbon and the corresponding marginal abatement costs that he estimated in 2010 (Dietz, 2010) has likely been amplified by more recent publications.

⁵⁶ Ackerman and Stanton (2012) also advocate focus on cost-efficiency analysis, not only because the social cost of carbon is highly uncertain, but also because they reassess the corresponding uncertainty range to values confidently greater or equal to the estimated range of the marginal costs of the total global abatement potential up to 2050.

special journal issues—those introduced by Kopp et al., (2012b), Marten et al. (2012) and by Guesnerie and Stern (2012) (only partly for the latter). The most debated points are:

- Climate sensitivity, i.e. the long-term impact of CO₂ concentration on average global temperature, and particularly the consequences of considering a ‘fat’ rather than a ‘thin’ tail to the probability distribution of that central parameter (Weitzman, 2012; Pindyck, 2013; Pycroft et al., 2011; Stern, 2013; Nordhaus, 2012).
- The damage function linking temperature change to economic impacts. The quadratic form introduced by Nordhaus (1992) is suspected not convex enough, and alternatives explored (Weitzman, 2012; Pindyck, 2013; Stern, 2013; Ackerman et al., 2010; Dietz, 2012; Kopp et al., 2012). Besides, the available damage estimates are criticised as incompletely covering the many impact channels (Dietz, 2012; Kopp and Mignone, 2012; Marten et al., 2012; Stern, 2013). Kopp and Mignone (2012) also stress how inappropriate a social cost of carbon is if measured off a baseline already beyond some ‘tipping point’ of the climate system (i.e. when the damage function is only piecewise convex).
- The discount rate, which in the standard Ramsey framework dissociates in the rate of pure time preference and the constant relative risk aversion. Prescriptive vs. descriptive approaches to discounting lead to markedly higher vs. lower assessments of the social cost of carbon i.e. the optimal mitigation requirements (Nordhaus, 2007; Kopp and Mignone, 2012; Anthoff and Tol, 2013; Stern, 2013).

Uncertainty on these three dimensions dramatically increases the range of plausible social costs of carbon. Fearing that this uncertainty is in part irreducible, some recent papers more or less openly question the ultimate contribution of cost-benefit analysis (Dietz, 2012; Weitzman, 2012, Yohe and Hope, 2013; Stern, 2013).

Box 1 Controversies on cost-benefit analysis up to 2013
Source: Ghersi, 2014b

In a nutshell (see Annex 3 p.135 for the full text), our research agenda recommends:

- The assessment of cost-efficient trajectories to point-in-time targets free of any preconception concerning either emissions or pricing pathway.
- The exploration of the *terra incognita* beyond uniform pricing, with due account of pre-existing distortions or inertias of abatement options.
- A systematic elicitation and questioning of incentive overlaps.

... As well as stresses the necessity to develop the integrated capacity to address these three questions in some consistent, comprehensive modelling framework.

Research project

Introduction

Our research activities will remain driven by our conviction that economy-wide modelling is a necessary tool of aggregation of beliefs, expert views and forecasts into consistent energy/economy outlooks. It will thus naturally build on the effort invested in the development of the IMACLIM approach. Capitalising on our surveys of both low-carbon futures modelling (Gherssi, 2014b, see Annex 3 p.135) and our own coupling experiments with IMACLIM (Gherssi, 2015) as well as on recent experiences of developing new country-versions of IMACLIM, laid the foundations of a renewed research agenda.

One first objective of this agenda is a further exploration of some blind spots of analysis outside the reach of neoclassical paradigms. This objective branches in two directions. One direction is to investigate alternatives to the savings-driven macroeconomics of the standard neoclassical model. Another one is to improve our attention and ability to model ‘second-best’ features of economic systems. Both directions will allow better discrimination of our model implementations through time (the time horizons of our analyses) and space (the specifics of economies under scrutiny).

A second axis of our further research will concern specific methodological developments on the modelling of households’ energy consumption behaviour. This has been devoted much less research than energy supply and the energy consumption behaviour of producers. However, the control of both residential and private transportation emissions is one acknowledged key of deep-decarbonisation pathways.

A third axis will regard improvements of our ability to combine IMACLIM to other models and analyses. Our coupling methods to bottom-up models of energy systems still have limitations that we intend to work on. We will also pursue the integration of energy-economy models of different geographical scales at different levels of aggregation—one major research challenge of coming years to our global community of climate and energy policy modellers.

We successively detail these three research directions in three sections below. We then devote a fourth section to the new research fields where we plan to implement our extended analytical capacity. This leads us to present ongoing and planned developments of further country versions of our IMACLIM model in the framework of a growing international network, and to some elements of organisation of our research activity to sustain that effort.

1. Turning the lights towards neoclassical blind spots

In response to the diagnosis opening section 1.1 above (p.22), IMACLIM was from the onset developed in the tradition of Johansen (1960), i.e. as the extension of an input-output model to endogenous prices and quantities, rather than in that of Scarf (1967), i.e. as an operational Walrasian equilibrium combining optimal behaviours of representative agents.⁵⁷ Comfortingly, we find this choice endorsed by Solow (2000), who advocates a combination of limited optimisation behaviour and pragmatic rules of thumb in the matter of behavioural specifications. More recently, Krugman, in various editorial papers, expressed the view that the inability of neoclassical economics to explain, let alone anticipate, the financial crisis of 2008 has lastingly undermined its methodological leadership. In our field of energy-economy modelling, as early as 1997, Schneider (1997) picks up the telling metaphor of ‘lamp-posting’—looking under the comforting lamppost’s light for things that have

⁵⁷ In the distinction we follow Thissen (1998) or the polemical but quite thorough analysis of Mitra-Kahn (2008).

been lost outside its reach—framed by Ravetz (1997) to question the indiscriminate use of the neoclassical paradigm.

Endorsing these critiques, we will continue to apprehend modelling in the broad sense of a comprehensive representation of economic flows, in both money and physical terms, and avoid narrowing it down to one specific theoretical framework. We particularly accept that this more generic take on modelling can induce to renounce eliciting micro-foundations to our analyses and to favour, to some extent, ‘structuralist’ approaches acknowledging ‘stylized facts’ *à la* Kaldor suggested by statistical observation. We deem such approaches all the more relevant as our research shifts focus from developed economies to developing economies, where the assumptions of perfect markets and information further lose plausibility.

Our research ‘beyond the neoclassical circles of light’ will take us in two directions, which we address in two subsections below.

1.1. Investigating alternative closure rules

This research axis emerged from the convergence of several research threads in recent years. At the origin, our first experiences of exporting the IMACLIM framework to allied foreign institutions in the developing world (see section 4.1 below) highlighted the need of a simplified structure mimicking the macroeconomic behaviour of the model, which could be controlled and altered at need.⁵⁸ At the time when we convinced ourselves of that, we came to develop a standard 2-sector CGE to illustrate the utility of hybridising energy and economy accounts (see section 1.2.4 of our Completed Research p.34). Shortly thereafter, we recycled this 2-sector model into the starting RISKERGY research project (Box 2), which raised theoretical macroeconomic questions converging with those opened by the Brazilian and South African studies (see section 4.1 below).

For the most part, these questions revolve around the ‘closure rule’ of the IMACLIM model. Sen (1963) first formalised the fact that specifying independent constraints on all elements of the resource and use sides of GDP was bound to over-determine economic models, because the balance of resources and uses was an additional, unescapable constraint warranting accounting consistency. The ‘closure rule’ hangs on how to solve this over-determinacy, i.e. on the choice of what resource or use not to define by any constraint other than that of balancing aggregate accounts. Questions immediately follow on the appropriateness of the different closure options and on their influences on modelling results.

Sen’s intent was to contribute to a body of literature concerned with ‘income distribution’ in the sense of the split of value-added between labour and capital payments. Our numerical energy-economy modelling is far more disaggregate than the stylised one-sector, one-agent and closed-economy model that he had devised for that purpose. We operate in a multi-sector, open-economy setting with, for the more recent versions, a description of secondary income distribution extending to the modelling of net debt positions and the attached net interest payments. This mechanically adds dimensions to the closure rule issue: the trade balance (foreign savings) and the specific savings versus investment balances of all agents effectively disaggregate both the investment and savings variables of Sen’s original model.⁵⁹

⁵⁸ In fact, we came to identify the absence of such reduced model as one shortcoming of the CIRED PhDs dedicated to both the Brazilian (Lefèvre, 2016) and the South African economies. In the case of Brazil, the inoperability of the French model’s take on secondary income distribution and the consecutive computation of self-financing capacities of agents (see Ghersi, 2014) prompted to renounce modelling debt accumulation. We comment on the case of South Africa further below.

⁵⁹ For a clear exposition of the additional closure options allowed by modelling open economies, see Dewatripont and Michel (1987).

From 2013 to 2016, the RISKERGY research project gathered seven French research teams and small businesses around the aim of developing a method of sovereign risk rating taking account of energy issues. CIREC's role in this endeavour was the development of a macroeconomic modelling capacity able to connect to the BU model of another project partner, the familiar POLES model (see above). Project requirements prompted us to favour the dynamic framework of the iteration-to-convergence method of section 1.1.2 of our Completed Research (see p.26). The purpose was indeed to test the resilience of economies to, and the impact on public debt accumulation of, short-term energy shocks along the growth trajectory to 2020.

One key constraint of this research was that our modelling should apply indistinctly to the entire set of countries individualized by POLES, *i.e.* to 54 economies with sharply contrasted economic and energy characteristics. As a consequence, we worked on aggregate 2-sector economies and were careful to systematically resort to international datasets covering a large number of countries (at the World Bank, the IMF, the IEA, etc.), to parameterise our modelling framework. Parameters include recent statistical trajectories of GDP growth, labour supply, labour productivity, unemployment but also the trade balance and prevailing exchange rates.

We calibrated our multiple IMACLIM country models at a 2007 base year on hybrid matrixes resulting from the combination of the extensive GTAP database with POLES data, following the synthetic method of data hybridisation presented in section 1.2.2 of our Completed Research (p.33). In this instance, shortcutting the alternate extensive method of section 1.2.1 appeared particularly relevant, considering the daunting task of extending this method to several dozen countries, many of which suffering from poor statistical apparatus. As we stressed in section 1.2.2, this came at the cost of some approximations, particularly in the split between the transport fuel consumptions of households and firms.

We delivered our final report to the RISKERGY research project at the end of 2016 (Gherzi, 2016).⁶⁰ The document contains (1) a minute description of how we combined national accounting (GTAP) and energy systems modelling (POLES) data to produce the hybrid matrices sustaining our analysis; (2) a description of our 'KLEM' model (2-sector IMACLIM model) insisting on its specific short term features (imperfect labour and capital markets) and its extended calibration to main macroeconomic data of the 2007 to 2013 period; (3) an outlook at 6 energy scenarios for 50 economies, with detailed public debt trajectories for 44 of them.

Box 2 The RISKERGY research project

In open-economy versions of IMACLIM,⁶¹ the trade balance has been systematically used as the endogenous variable closing the resources and expenditures equality, via adjustment of the real effective exchange rate (REER, which in economy-wide models is usually defined as the ratio of some domestic price index to some international price index). This is a choice that stems from the original IMACLIM models forcing both exogenous savings and investment rates following 'structuralist' Johansen (1960) practice, rather than endogenising investment facing an exogenous trade balance assumption—the standard CGE practice. That choice is of little consequence under 'stable' economic conditions, when the structure of GDP is little changed by whatever external shock is hitting the model. Indeed, if the GDP shares of households' consumption C , direct public expenditure G and investment I only slightly vary, then by way of the aggregate definition of GDP on expenditures' side (Equation 1) the share of the trade balance $X - M$ in GDP will remain stable as well. Depending on the specifics of exports X and imports M formulations, striking the right trade balance should not require dramatic variations of the REER.

$$GDP = C + G + I + X - M \quad (1)$$

If, however, one of the expenditure shares other than that of trade varies significantly, the trade balance will be forced to adjust, as significantly, to offset this variation. This is precisely the issue that emerged in our exploration of the South African economy (Schers et al., 2015, see section 2.4.2 p.50). In preliminary runs, surmised gains in

⁶⁰ Available at http://www2.centre-cired.fr/IMG/pdf/riskergy_cired_16dec16.pdf.

⁶¹ By opposition to the global multi-regional version of the model, IMACLIM-R (Sassi et al., 2010).

capital productivity affected investment demand from producing sectors, to result in a significantly lower investment share of GDP. As a consequence, the trade balance had to improve substantially. This required a significant downward adjustment of the REER—under constraint of our precise specifications and elasticities for both exports X and imports M .

However, the plausibility of such an adjustment, not merely conjunctural but structural to the outlined growth trajectory, is low. It could have two causes: a drop of the nominal exchange rate of the South African Rand, and a slower pace of nominal inflation in South Africa than in its trading partners' economies. Neither of these is expected from a 'catching-up' economy—one growing faster than its trading partners, thanks to faster productivity gains—as South Africa. The question is therefore whether some other closure rule would be more adapted to the South African economy. An immediate corollary question is whether this more adapted rule would substantially change our estimation of the impact of a carbon tax on South African economic activity and carbon emissions. In more general terms, this line of research means to explore the modelling of alternative macroeconomic closure rules, in the spirit of e.g. Robinson (2006), with a view to consolidate or indeed nuance the policy assessment conclusions derived from the standard neoclassical model or the Johansen alternative implemented in IMACLIM so far.

In fact, literature provides evidence that alternative closure rules can qualitatively change policy conclusions. For example, Taylor and Lysy (1979) demonstrate how significantly the choice of a closure rule bears on CGE modelling results, concluding on the quite explicit caveat that “both the politics and the economics of the rules by which a policy oriented economist's implicit model is closed bear close scrutiny before he can be taken seriously”. To the best of our knowledge, none of the prominent modelling teams engaged in carbon- or energy-policy assessment have touched upon this important subject so far.

For the convenience of a greatly reduced running time, and to warrant control of our experiments, we will heavily rely on implementation of the compact 2-sector models developed at the occasion of the RISKERGY project (Box 2 above) to explore alternative closures. In this, we will in fact follow the example of Johansen himself as favourably reported by Rattsø (1982): “To understand the macroeconomics involved in these large-scale computable general equilibrium models, it is convenient to construct an aggregated representation of the model. In fact, in 1960 Johansen cleared up some of the economic controversies by building a one-sector version of the model.”

The specific relevance of each closure rule should not be misinterpreted as a choice between schools of economic thought. It rather depends on the temporal and geographical setting of analysis. There is no question that the neoclassical model is more adapted to the long term than to the short term. An authority as Solow is of the opinion that it is best suited to analyse macroeconomic equilibrium at decadal intervals, whereas 'Keynesian' alternatives (in the broadest of senses) should apply to year-by-year studies (Solow, 2000). One major area of research is how to bridge the gap between the two temporal horizons in dynamic analysis. It is possibly beyond our reach but we may also address it at the occasion of some specific applied exercise.

Similarly, there is little debate that the standard neoclassical model is more adapted to developed and liberal economies where both market imperfections and regulations are limited. In other settings, alternative closure rules may be far more relevant, as testifies the vast literature devoted to CGE modelling of developing economies. A survey by Robinson (1988) extensively covers the seminal contributions of the 70's and 80's on such issues, from a theoretical viewpoint stressing the importance of closure.

The fact that model closure has particular bearing on investment supply relates to the central policy question, in energy matters, of how to finance dramatic energy transitions over a limited number of years. Under neoclassical closure and in a recursive framework,⁶² investment supply results from exogenous domestic and foreign savings, and any additional energy investment requirement will mechanically crowd out some of the investment supply

⁶² Considering our focus on applied, descriptive analysis, the normative framework of intertemporal optimisation is and will remain out of our research scope.

dedicated to general economic activity. In the so-far Johansen framework of IMACLIM, foreign savings increase to meet the additional investment demand at the cost of a deteriorated trade balance, which accumulates in an increased national debt to the rest of the world. However, many developing economies maintain exchange control policies that forbid the REER adjustments necessary to induce the required levels of foreign capital inflows—and effectively constrain the contribution of the latter to domestic investment.

Again, the literature on development economics provides numerical methods to explore such constraints, as the Robinson survey testifies (Robinson, 1988). However, to the best of our knowledge, these methods have not found their way into the numerous CGE applications of climate policy analysis to developing countries. Bridging this conceptual gap opens the opportunity of significant contributions to the energy-transition policy debate.

1.2. Generalising policy analysis in ‘second best’ settings

The qualification of ‘second best’ has a large variety of meanings and interpretations. We use it here to cover departure from three ‘first best’ assumptions of general equilibrium theory: the clearing of markets by the unconstrained adjustment of prices; the homogeneity and perfect mobility of factors across sectors of activity; and the absence of any market distortions pre-existing energy transition policies. In the following subsections, we briefly argue how these assumptions conflict with actual economic settings, particularly at shorter temporal horizons, and present how we plan to acknowledge that fact in our future research via adjustments to our model and its implementation.

1.2.1. Modelling regulated prices

We already touched upon regulated prices in our section about closure rules when alluding to fixed exchange rates. Price control shapes other markets in most economies, in ways that we cannot ignore if we are to warrant the policy relevance of our applied analyses. It can come in the weak form of price boundaries, typically that of a minimum wage on the labour market—which exists in close to all economies, even in the most market-oriented ones as the United States. It can operate via constraints on the evolution of prices, with or without reference to that of other prices, e.g. the price of electricity or housing services in many economies (including France). Finally, it can come in the stronger form of publicly set prices, typically for basic commodities as energy goods and in developing countries.

Our price control examples deliberately centre on the energy and labour markets. The reasons are obvious as regards the former, considering our research focus. We draw attention to the latter because of its implications for policy assessment. The corollary of price control on the labour market is indeed a mismatch between labour demand and labour supply. Because the control is in effect a floor price, the mismatch takes the form of excess supply, i.e. unemployment. Considering price rigidities on labour markets therefore prompts allowing unemployment variations, which significantly magnify the assessed macroeconomic impacts of transition policies.

IMACLIM has long paid attention to involuntary employment via the simple artefact of a wage curve forcing an isoelastic correlation of the real wage and the unemployment rate (Blanchflower and Oswald, 2005).⁶³ We do not plan specific improvements in this regard, although we will keep on devoting due attention to wage setting issues in various institutional and economic contexts, including globalisation. However, we have so far not put the model to the test of exogenous consumer prices. From a mathematical viewpoint, exogenising one variable

⁶³ Other economy-wide models use the wage setting / price setting (WSPS) model and the closely related Philips curve approach. Both approaches produce results similar to the wage curve by essentially indexing wages on consumer prices, to a more or less direct extent. Pissarides (1998) analytically explores the consequences of labour tax cuts in four theoretical models of equilibrium unemployment, which could inspire new developments.

of the model as a consumer price requires either dropping one equilibrium constraint, or endogenising another variable. The consumer price equations are necessary to the accounting balance of resources and uses of each activity sector singled out in the hybrid input-output matrix on which the model calibrates. However, a set of natural resource rents, mark-up rates, taxes & excises and trade & transport margins form a wedge between output costs and consumer prices. All the elements of this set are parameters when considered per unit of output. We can therefore choose one of these elements to endogenise its variations. It becomes the variable that the model adjusts to meet the consumer price constraint.

Which element to choose depends on the specific design of the price-control policy. If it does have a counterpart in the form of output-based public support, tax or excise rates can be set free—one or the other without consequence on modelling results, because their adjustments identically produce the exact aggregate strain on public budgets that allows price control. If it has not, and the cost of warranting the consumer price falls on the private sector, then the ‘specific margin’ original feature of IMACLIM (see section 1.2.3 p.34) can be played on. In many countries, where public authorities operate the utilities that sell at fixed consumer prices, the distinction will not play and the cost of the control will weigh on public budgets anyway, via either subsidy expenses or a reduced operating surplus.

These reflexions point at the need for quality data on the public subsidy system and its precise mode of intervention, as well as on the public participation to economic activity, and ultimately on budget deficit policies—will the increased strain on public budgets accumulate in public debt? Will it rather be compensated by higher taxes or lower expenses? Which tax is most probably going to adjust? Under what precise constraint of ‘budget neutrality’? In some countries, these questions may find ready answers in public policy plans, to which collaboratives with local researchers will grant us access (see section 4 below). In others, we will have to explore them via scenario variants.

Of course, the relevance of that level of detail in the description of public policies will depend on the time horizon of our explorations. It is for example at the centre of the *Vision 2030* policy discussions in Saudi Arabia (see section 4.2.1). More generally, substituting a ‘fixprice’ approach to the standard ‘flexprice’ approach (in the terms of Robinson, 1988 and the literature it surveys) is particularly relevant in the very short term. It was required in the framework of the RISKERGY research project (see Box 2 above), which aimed at a yearly prospective outlook up to 2020 only. For each of the countries modelled, application was eventually limited to two ‘stress tests’ meant as unanticipated shocks: an international oil price shock of a geopolitical nature (closing down of the Ormuz straight), and a domestic shock reducing electric capacity (a catastrophic event). The principle of flexible prices clearing markets is not relevant to address the short-term unbalances expected from the shocks. We mean “market” in the broadest of senses here, covering primary factor markets (labour and capital), where price rigidities could cause unemployment and underutilisation of productive capacity. But we also mean the trade balance, which should not be allowed stability by unconstrained adjustment of the real effective exchange rate (REER); or public budgets, which will be hit by the shock with limited ability to absorb it *via* adjustment of tax rates.

For each of the three sorts of balances there is in fact a continuum of possible specifications between the ‘flexprice’ and ‘fixprice’ extremes. We can numerically explore this continuum by endogenising the ‘market’ imbalance (unemployment, capacity underutilisation, trade deficit, public budget deficit) and introducing one additional constraint specifying isoelasticity of that imbalance to the underlying price (the wage, the capital rent, the REER, the vector of tax rates).⁶⁴ We can then test any negative elasticity. Under such extension, the ‘flexprice’ model is the particular case when the elasticity is infinite, the ‘fixprice’ model that when it is nil. This method opens up a range of scenario variants that may be of particular interest to replicate statistically observed structural relationships in some country settings, as our ongoing work on Saudi Arabia testifies (see section 4.2.1).

⁶⁴ This is the precise conceptualisation of the wage curve that settles unemployment levels in current IMACLIM versions. It also applies to capital underutilisation in IMACLIM-R, which that model links to a wage premium affecting output costs.

1.2.2. Addressing factor allocation inertias

A second departure from first best conditions with a potentially high impact on policy assessment regards factor mobility. The standard CGE approach considers perfect factor mobility between sectors. One corollary of this stance is equalisation of marginal factor payments, which standard models enforce by specifying one single wage or one single level of capital payments applying to all sectors indifferently. Primary factor endowments allocate across sectors following sectoral cost minimisations. There is therefore an implicit ‘normative’ quality to this allocation, in the sense that it defines how factors ‘should’ allocate to activities to maximise output. Our concern is more with the descriptive question whether factors ‘can’ effectively move so easily between sectors.

Similar to the closure rule and ‘flexprice’ versus ‘fixprice’ alternative, answer to this question hangs on the time frame of applied analyses. We already quoted Solow as advocating decadal intervals between neoclassical equilibriums (Solow, 2000). This may indeed provide sufficient time for most of labour supply to reallocate, although the question of labour skills immediately emerges. For low-skill labour as well as for some cross-sectoral business skills underlying management and administrative tasks, at all possible qualification levels, unconstrained reallocation is plausible. For the more technical skills as some of those involved in transition technologies, among others thermal renovation and solar panel installation, this is more debatable.

Another questionable consequence of perfect labour mobility is that it implies that full-time equivalent (FTE) labour units moving from one sector to another see their marginal productivity instantly adapt to that prevailing in the new sector.⁶⁵ However, statistical observations reveal higher wage losses from changing jobs between industries than within industries (Figura and Wascher, 2010; Fallick, 1996). The recent literature offers various methods addressing such productivity adjustments, which effectively constrain labour mobility. Lofgren and Cicowiez (2017) propose one such contribution and offer a synthetic literature review of other model specifications addressing imperfect labour mobility. This is a source of IMACLIM developments with potential high impacts on policy assessment—Van der Mensbrugghe (2007) demonstrates that in the case of trade liberalisation. We already touched upon the subject in the framework of our South Africa model implementation (Schers et al., 2015), where we introduced segmented skill markets. We will adapt future model implementations (see section 4) accordingly, as warranted by their economic settings and time horizons.

Perfect capital mobility over a decadal period is an even stronger assumption than it is for labour in energy transition analysis. The inertia of capital stocks is one acknowledged obstacle to a rapid change of both energy supply and end-use technologies, with equipment lifetimes varying from a few years (appliances and vehicles) to a few decades (conventional power supply units) and possibly centuries (buildings, dams).⁶⁶ Accounting for such inertias is one purpose of our coupling to bottom-up analyses, which explicitly models them. Other inertias, however, regard the allocation of the capital stock across sectors of activity. They are particularly relevant to countries, whose transitions imply structural change at paces incompatible with investment flows. Similar to labour, the CGE literature offers alternatives to perfect capital mobility (see Islam, 1999, for a survey) that we can lean on to develop future IMACLIM implementations.

1.2.3. Designing policy packages under constraint of pre-existing distortions

In our review of low-carbon policy modelling (Gherzi, 2014, see section 3.4 p.54 and Annex 3 p.135) we comment on the *Terra Incognita* of policy analysis in ‘second best’ settings. Focused on the issue of technical change, literature has indeed broadly explored the simpler pricing instruments of a uniform carbon tax or a system of emission permits trading—which are in fact fully symmetrical pricing versus quota-enforcing instruments under

⁶⁵ Standard CGE approaches dispense from calibrating FTEs on satellite accounts of sectoral labour. They rather calibrate the effective labour content of sectors by assuming uniform wages across sectors.

⁶⁶ Building retrofit only partially allows circumventing building inertia because the more efficient insulation options are not accessible via renovation but only at the time of construction.

a set of additional assumptions. As we reported, there is some lasting confusion on the ability of these instruments to minimise the *social* costs of the carbon reform, all feedbacks accounted for, when they only guarantee minimisation of the *technical* cost of abatement—at least theoretically,⁶⁷ and hence in most modelling frameworks.

Böhringer et al. (2009) stumble on this complexity in a paper assessing the 2020 climate commitments of the European Union. In two out of four variants developed to analyse sensitivity to alternative baseline growth, they find that uniform pricing induces higher compliance costs than the differentiated prices of segmented efforts on concentrated versus other carbon emitters. They identify, as reasons for these seemingly heterodox results, that the private and social marginal abatement costs do not match in their modelling framework, on the simple ground that it accounts for the pre-existing distortions embedded in tax and tariff systems and in international trade. Deviating from uniform pricing can be welfare improving, if the increase in private abatement costs caused by differential pricing is more than offset by terms-of-trade gains, or the alleviation of initial tax distortions.

Boeters (2014) devotes a thorough numerical analysis to the question of differentiated pricing. He establishes that in the case of the EU at a 2020 horizon, and in a CGE framework distinguishing 16 activity sectors based on GTAP data, the efficiency of differentiated pricing allows abating 27% of the emissions that remain when cutting down emissions by 20% through uniform pricing, for an identical welfare cost. He also identifies market power in export markets and taxes on consumption, intermediate inputs and domestic output as the main causes of the sub-optimality of uniform pricing.

We must again qualify these conclusions with a *caveat*: there is no question that equating private technical costs through uniform pricing is the first step to hitting the overall least-cost option. This first step must however be followed by that of optimising the recycling of the pricing proceeds, be they tax income or auction revenue. What Böhringer et al. and Boeters effectively demonstrate is that their shared modelling assumption of a lump-sum rebate to the ‘representative agent’ is not welfare-maximising in an economy exposed to international competition, and with pre-existing tax distortions.

It remains that, in a ‘second best’ world—even one as close to a first-best optimum as the fairly standard computable general equilibrium models of Böhringer et al. or Boeters, we cannot explore optimal abatement policies by moving the cursor of a uniform carbon price along its monetary axis, at least under the basic assumption of a lump-sum rebate to households. In fact, Lipsey and Lancaster (1956) have long established that the smallest departure from ‘first best’ conditions forbids any preconception on the optimal pricing policy—*e.g.*, that sectors with identical *ex-ante* tax burdens should have their emissions priced identically.

What this calls for is an extension rather than a radical shift of the policy analysis process. We must consider carbon pricing under the constraint of several initial distortions. The further policy design challenge develops in two competing directions: to identify these distortions and adapt the pricing policy to them, versus to maintain the technical efficiency of uniform pricing but to thoroughly explore recycling options of the pricing proceeds in second best economic conditions. The former option is that of Boeters (2014). The latter is indeed the one we have followed in the case of France (see section 2.1.2 p.38), although without formalising it as we do here.

Our future applied analysis of carbon mitigation reforms will give due attention to this alternative. One prerequisite to the relevance of such policy design exploration is substantial work on data collection and treatment, particularly as regards tax systems and subsidies or indeed price-control policies. One simple and fairly universal example relevant to energy commodities is the difference between ad valorem and excise taxes: the former see their fiscal products change with volumes and valuation (prices), the latter only follow volume changes. Research collaboratives with partner institutions in the countries of focus (see section 4 below) are a

⁶⁷ In practice, barriers stand between the price of carbon and some mitigation options. One notorious example is the problem of split incentives between landlords and tenants: landlords have no direct interest in investing in energy efficiency because energy expenses fall on tenants.

guarantee that we will conduct that data mining work with access to local resources (including those in languages other than the English lingua franca) and expertise on data reliability.

2. Advancing the capacity to model households' energy behaviour

Our hybrid modelling method (section 1.1 p.22) purposely ignored the critique addressed by economists to bottom-up modellers for their disregard of potentially significant transaction costs barring the adoption of profitable technologies—the so-called ‘no-regret’ potential (see our footnote 3 p.21). We saw the value-added of coupling to bottom-up models contained all in the explicit description of technologies, and in the unexpected behaviour of consumption aggregates summing up multiple, discrete technological trade-offs. We also had some expectation that improvements in behavioural specifications like those put forward by the CIMS model project at Vancouver University (Jaccard, 2009), which we became familiar with at the time of our preparation of an international workshop on hybrid modelling in 2005, would generalise.⁶⁸ They did not, and it turned out that most of the bottom-up models to which we have coupled or plan to couple IMACLIM resort to standard life-cycle cost minimisation to settle technology choices (see section 4.3 below). Upstream from technology choices, they also tend to correlate household demand for energy services (heating, cooling, lighting, communicating, etc.) to GDP per capita, sometimes to the size of housing, and largely disconnect them from the evolution of relative prices—which they hardly cover in their partial equilibrium settings anyway.

However, the control of households' energy demand is one notorious key to low-transition futures, because of the inertia (low price-elasticity, high income-elasticity) of residential and passenger transportation demands. Energy efficiency gains cannot alone induce the consumption cuts required by deep decarbonisation. Sobriety, in the sense of a decoupling of energy services demand and income growth, is a systematic component of ambitious low-carbon scenarios. We have just seen that bottom-up models treat as exogenous scenario dimensions the ‘energy-service intensities’ of household income. In the framework of our iterative bottom-up/top-down coupling (the option of section 1.1.2 p.26), we could therefore provide to bottom-up models energy service demands based upon trade-offs duly reflecting sobriety options.

The state-of-the-art of top-down models is not up to this task. Because of their historical focus on the description of energy supply technologies, most prominent CGE models applied to climate and energy outlooks still resort to nested CES functions to represent consumer demand—see the DART (Klepper et al., 2003), the EPPA (Paltsev et al., 2005), the PACE (Böhringer, 2002) or the PHOENIX model (Sue Wing et al., 2011). These functions commonly isolate one aggregate energy bundle from all other consumptions and level off both the substitution possibilities among energy goods on one hand, and those between the energy bundle and the bundle of all non-energy goods on the other hand.⁶⁹ They do not explicitly model the underlying energy services, the true sources of welfare.

This level of approximation is probably acceptable for small deviations of the relative prices over a short term, even more so in the framework of analyses focusing on the supply side of economies. It is however quite debatable for the profound changes induced by the starting energy transition, especially if the research question is concerned with how consumers fare. In the face of these shortcomings, we have recently opened up two research directions to advance our capacity to model households' energy demand behaviour, which we intend to consolidate and prolong.

⁶⁸ CIMS calibrates “intangible costs” to bridge the gap between observed adoption rates and the rates that prevail under the only criterion of cost-minimisation.

⁶⁹ In the version referenced the PACE model bundles fossil fuels only and aggregates electricity to non-energy consumptions through a Cobb-Douglas specification. The EPPA model gives automotive fuels a specific, explicit treatment, in line indeed with our recommendations. However, it fails to connect transportation expenses to housing expenses, to account for the role of urban forms in shaping transport needs.

2.1. Designing trade-off functions focused on households' energy choices

One first direction to improve upon the standard practices illustrated in the above introduction is to work on a more appropriate utility function. We followed this direction in the framework of our production of fuel poverty outlooks (Gherzi and Ricci, 2014; see section 2.3.2 p.47), which prompted focus on the dynamic constraints embedded into spatial systems.

The version of IMACLIM that we implemented in Gherzi and Ricci (2014) distinguishes 8 household consumption goods: housing, housing maintenance and renovation (to record renovation expenses), public transports, automotive fuels, electricity, natural gas, domestic fuels and a composite good remainder.⁷⁰ We further disaggregate public transports and automotive fuels in 'constrained' and 'leisure' varieties. Similarly, we break down electricity between substitutable and non-substitutable uses, and its substitutable uses between space heating and other purposes (water heating, cooking). All goods enter an extended utility function, which centrally exploits the conclusions of urban economics on the long-term choices regarding housing, and the transportation activities induced by such choices. Fujita (1989), who synthesises developments dating back to the 1960s, sets a milestone to this research. Bertaud and Malpezzi (2003) provide an extensive survey of its robustness, by applying it to 48 megalopolises around the globe. In summary, our transposition of this research in IMACLIM amounts to:

- Impose a constant budget share to housing expenses—i.e. assume a Cobb-Douglas utility of housing vs. other expenses—outside the constrained transportation expenses attached to the housing expense decision.
- Derive constrained transportation demand as a function of the housing surface, based on the assumption of nil transportation requirements for a minimum housing surface exogenously set at 9 square metres *per* consumption unit.⁷¹

The constant budget-share rule combines nicely with our modelling of the land-use rent in the housing sector.⁷² The high net operating surplus of this sector at calibration year translates into steeply decreasing returns, which raise housing prices enough to contain the increase of housing surfaces well below that of income.

Housing surfaces then determine demand for the energy service of space heating, which induces around 80% of residential energy consumptions. Space heating is the CES product of 'housing maintenance & renovation' consumptions (which include insulation and heating equipment installation) and an energy bundle, which is in turn a CES of the 3 heating options of gas, fuel and electricity. Both CESs have their elasticities calibrated on the RES-IRF model developed at CIRED (Giraudet, 2011).⁷³ We complete these central features with assumptions on the cooking and water heating consumptions, and non-substitutable electricity demand. Following Cayla (2011), we suppose that the two former consumptions are strictly proportional to total population, with energy efficiency gains roughly compensating increased per-capita services. We draw the dynamics of non-substitutable electricity demand from the French power grid authority (RTE, 2011).

⁷⁰ The model also describes an aggregate of crude oil and coal—the two goods are aggregated because of the current quite low level of coal consumption in France, and the little prospect of any pick up considering the role of nuclear energy in electricity production. Households do not consume crude oil and stopped consuming coal in 2007.

⁷¹ The 9 square-metre minimum surface is translated into aggregate constraints on household classes thanks to household survey data. It echoes a French regulation (loi 2000-1208) that bans renting any lodging below such surface.

⁷² To model the land-use rent of the housing sector we assume marginal-cost pricing (nil profits on the last unit sold) and use the net operating surplus of the sector to calibrate isoelastic decreasing returns (Total Factor Productivity negatively elastic to output).

⁷³ RES-IRF models the dynamics of the French residential building stock disaggregated in energy performance classes and its consumptions of fuel oil, natural gas and electricity. It explicitly considers 'rebound effects'—the statistically documented, partial trade-off between lower energy expenses and higher thermal comfort after thermal retrofit (see e.g. Critchley et al., 2007).

It was the primary purpose of this specification to improve the modelling of residential energy consumptions compared to the state-of-the-art, to produce relevant fuel-poverty estimates. Because of their large share in the total, our effort focused on heating consumptions, which prompted addressing the question of the size of housing and its sensitivity to income and relative prices. The urban economics literature gave a ready answer to that, but generalising it from cities to an entire country and also without regard of time (across our 2006 calibration year and our 2035 modelling horizon) is stretching far its interpretation. Recent statistical work at CIRED on household survey material will allow checking if the constant-share rule approximately holds, and for what disaggregation of household groups.

Besides, our demand system only very roughly addresses personal mobility, the other major driver of households' energy consumptions. Constrained transport expenses duly result from the urban economics model, but leisure transport expenses are a crude constant share of all consumption expenses not attached to housing, while the composite good remainder (an aggregate of all goods but energy, housing and transport services) receives the complementary share. Another serious limitation is that we model the modal choice between private and public transport by considering a simplistic constant elasticity of substitution between public transport services and direct automotive fuel consumptions, albeit a low one, in the production of the constrained and leisure transport services. IMACLIM-R, the recursive dynamic multi-regional version of IMACLIM developed by Sassi et al. (2010) proposes far more relevant transport specifications based on an innovative attention to the transportation time constraint (see our own presentation of these in the appendix to [Gherzi et al., 2013](#)). Importing these in our open-economy versions of IMACLIM is one natural improvement that we shall work upon at the occasion of our next applied analysis with household focus.

Beyond personal mobility, [connecting energy consumptions to time use is a research direction that we followed in a micro-simulation framework during the PhD research of Simona De Lauretis under our supervision \(De Lauretis, 2017, see below\)](#). Becker (1965) proposed a seminal contribution on the consumption behaviour of households under time constraint. He introduced the concept of a 'household production function', which combines time to purchased goods to produce services that are the real source of utility. Generalising this concept to the household specifications of IMACLIM is a non-incremental development that would require considerable effort. We may engage it in the framework of a focused research project.

Lastly, but importantly, we shall conduct this line of research on household behavioural specifications with due consideration of aggregation issues. It is quite different to model the choices of one individual or household than it is to model the aggregated behaviour of several million consumption units. The difference is blatant in the case of the common property of equipment goods. Starting with personal vehicles, carpooling and car sharing are means to increase vehicle occupancy, i.e. decrease the average energy intensity of personal mobility. More generally, putting in common little-used equipment goods is a way to decrease the material intensity of welfare, with indirect consequences on the energy intensity of economic growth. By their own natures, these collective behaviours escape the reach of the 'representative agent' paradigm and require specific modelling developments.

2.2. Developing the micro-simulation alternative

A second research direction to improve upon the state-of-the-art of households' behaviour modelling in top-down models is micro-simulation. Our first experience with such methods dates back to our work on fuel poverty ([Gherzi and Ricci, 2014](#), see section 2.3.2 p.47). More precisely, the micro-simulation that we performed at the occasion of this research resorts to the "micro-accounting with reweighting" method favourably described by Agénor et al. (2004) or Hérault (2010). The method rests on the assumption that large household surveys propose sufficiently diverse socio-economic profiles to allow investigating the consequences of any external constraint by a shift of households' representativeness weights.

To illustrate, let us consider some large household survey and the test of a 10% decrease of households' energy expenses. The original representativeness weights of households in the survey commonly warrant that the weighted sums of demographic series add up to national totals, of e.g. total population, total number of households and number of persons of either gender per 5-year age cohort. The reweighting method consists in adjusting the original weights to accommodate the additional constraint of, in our example, a 10% lower households' energy expense at national level. The procedure is obviously over-determined, as an infinity of vectors of weights allow matching the original demographic constraints and the extra energy expense constraint. Minimising the distance between the original vector and the adjusted one allows selecting one specific weight vector. Consequently, the weights of households with energy-intensive lifestyles decrease slightly while those of households with energy-sober lifestyles increase slightly. The weighted sums of all unconstrained survey series adjust accordingly and indicate the economy-wide consequences of the 10% energy expense decrease. Interpretation of the survey is that of a typology of consistent lifestyles between which households get to choose.

In [Gherzi and Ricci \(2014\)](#), we implement the method on a 2006 survey to produce outlooks at a 2035 horizon. The methodological bet is that the 'typology' interpretation of the survey holds between the two dates provided we upscale the income sources and consumption budgets of all households according to the modelling results of IMACLIM. It is comforted, to some extent, by the fact that the earliest available edition of the same household survey describes 1979 households in very similar socio-economic series. The 27 years of behavioural changes, including those induced by the rise of information and communication technologies, only have a quantitative impact on survey series, which we approximate by our upscaling of consumption budgets, but do not qualitatively affect them. Additionally, the purpose of the reweighting is a mere 'distribution around the mean' of the behaviours settled by the utility functions of IMACLIM (see 2.1 above) for 5 living-standard classes of households. We do not use it to characterise behavioural shifts beyond our set of weighting constraints. These substantially frame our reweighting analysis by bearing on demographic composition in 4 groups, income in 6 sources, budget composition in 9 shares and, quite importantly for our fuel poverty focus, the total housing surface.

In recent analysis, however, we inversed the relationship between IMACLIM and the household survey and grounded the modelling of household behaviour on the reweighting results without ex ante constraints on behavioural adjustments. Under such conditions, micro-simulation becomes an actual alternative to the utility-maximising model at the level of household groups of section 2.1 above. This is the second research path on household behaviour modelling that we mean to explore further.

This recent analysis was at the occasion of [the PhD research of Simona De Lauretis, under our supervision between 2014 and 2017](#).⁷⁴ [This research aimed at developing outlooks to 2050 on the consequences of the penetration of behaviours identified as potentially carbon-saving \(De Lauretis, 2017\)](#). From a methodological viewpoint, the contribution of this research is to set up a coupling method between the economy-wide analysis of IMACLIM and the micro-simulation analysis of the household survey. Inspired by our coupling to bottom-up models, the method consists in an iterative exchange of outputs up to convergence of both numerical systems—stable economy-wide conditions in IMACLIM for a stable vector of representativeness weights conditioning all weighted sums of unconstrained series in the household survey.

The IMACLIM outputs that we feed into the household survey are the variations of the same 6 income sources that we worked on in our fuel-poverty simulations, to which we add the investment of households (gross fixed capital formation) and their income and other direct taxes. When warranted, we force these variations in per capita terms, e.g. we force the same variation of the average wage on the activity incomes of all households in the survey, or the same variation of the average pension on the pension benefits of all households in the survey.

We then perform the reweighting of the survey under constraint of national totals of the 6 income sources and 3 investment and tax payments totals, as well as of a number of socio-economic transformations that we assume to frame our analysis. These transformations include structural lifestyle determinants as the occupational status (active employed, active unemployed, retired, other), the distribution of households according to their

⁷⁴ The PhD was formally under supervision of Franck Lecocq, director of CIRED.

composition (4 types of households), their geographical localisation (8 national regions) and its population density (4 density ranges), their type of housing (individual versus collective building).⁷⁵ They notably exclude any constraint on the age or gender of the projected population, with an explicit view to allow behaviours to spread across such frontiers.

The reweighted survey defines budget shares at national level, which we can feed back to IMACLIM as constraints replacing its original utility specifications. We run IMACLIM under these constraints and start the iterative convergence process by feeding updated IMACLIM outputs on income sources, direct taxes and investment, to the household survey again.

There is, however, one important limitation to this method. The iterative process must start from a ‘typology’ of household consumptions that is relevant to the horizon of projection—2050 in the instance of De Lauretis (2017). In particular, this typology must properly account for technical change and its consequences on energy services and their energy intensities at the projected horizon. In De Lauretis (2017), we perform an initial upscaling to 2050 of the household survey based on a combination of exogenous expert views on households’ real consumptions for 17 out of the 18 consumption goods that our version of IMACLIM disaggregates. The 18th consumption is that of a composite good remainder, which we determine via budget saturation considering exogenous savings rates. Consequently, the resulting modelling tool proceeds from a sort of exogenous reference of consumption shifts embodying technical progress and its consequences, and is only able to compute adjustments to supplementary behavioural constraints to this baseline.

Still, there remains ample room for exploitation of the macro-micro architecture as it stands, i.e. a model playing on the weighting of behavioural archetypes to assess aggregate behavioural changes in a fixed technical change setting, with full economy-wide consistency. Considering the effort required to set up the household database and the macro-micro architecture, De Lauretis barely had time to touch upon the exploration of 3 behavioural evolutions (carpooling and car sharing, further e-commerce penetration and cooking habits), which, taken alone as they were, do not produce very significant results. However, one major contribution of De Lauretis is the extension of the household budget survey to dozens of additional series by pairing it with other household surveys on housing, transportation, the breakdown of power consumptions by end-uses and, notably, time use. This wealth of dimensions allows exploring a vast array of more striking scenarios. We are currently discussing options in this regard, with the aim of completing the publication of the thesis’ material in journal articles.⁷⁶

Notwithstanding, we are already working on refinements of our micro-simulation method. This research develops in the context of a contract with the French Environmental Agency ADEME about the distributive impacts of the French National Low-Carbon Strategy (Box 3). We target improvements in two directions, **thanks to coordinated efforts with Franck Nadaud, CIRED’s research engineer specialising in econometric and statistical methods**. One first direction is a standard econometric characterisation of households’ behaviour, but for distinctive household groups, based on a recent pseudo-panelisation by Franck Nadaud of 6 successive French household surveys from 1984 to 2010. We plan to substitute the produced behavioural specifications to the set of aggregate exogenous assumptions that we used in De Lauretis’s thesis to upscale household consumptions before reweighting them. However, it is probable that such econometric treatment will not suffice to assess the impact of rupture technologies like the electric vehicle, which, from an economy-wide perspective, will massively substitute power consumption to gasoline and diesel consumptions. It should also fall short of providing relevant estimates of future building retrofitting options, considering the planned public intervention in that regard.

Our second direction of improvement will therefore be an explicit modelling of the penetration of electric vehicles, building retrofit options as well as the construction of new low-consumption & positive-energy

⁷⁵ This is in fact the set of constraints used by INSEE to estimate the original representativeness weights by minimising deviation from a vector of identical weights (equal to the ratio of the national number of households and the sample size of the survey), see Deville et al. (1993). Part of the PhD demonstrates that these variables indeed structure the time use (‘lifestyles’) of households and therefore their energy consumptions. We published some of these results in [De Lauretis et al., 2017](#).

⁷⁶ Among others, we are thinking of analyses linking to our work with FEEM on the dynamics of free-time preferences ([Bosetti and Ghersi, 2012](#)). Thanks to De Lauretis, our household survey details working times for all individuals in each household.

buildings. We are planning to use the literature on technology adoption to set up logit functions that can sort out households by their probability to adopt one or the other of these technologies, as well as to estimate the induced budget shifts. We can then use our new behavioural specifications to allocate any required budget adjustment (positive or negative) in each household. The number of households that effectively switch to the new technologies will however remain exogenous until we can adapt fully endogenous adoption behaviour from the literature—we do not plan any work on this specific research question.

In the course of 2017, we successfully answered a tender from the French environmental agency ADEME to produce an analysis of the distributive impacts at mid-term horizons of the updated French government's National Low-Carbon Strategy. Work started in January 2018 and will span over the entire year.

The National Low-Carbon Strategy (in French, SNBC) is a set of strategic guidelines to foster the transition of the French economy to a low-carbon economy. Its overarching objective is that of carbon neutrality by 2050. It sets explicit GHG mitigation objectives to the transportation, buildings, industry, agriculture and waste management sectors. The SNBC was first defined at the end of 2015 and is due to update by July 2019, and then every five years. Our contract regards the assessment of some of the complementary measures that ADEME promotes for the 2019 update.

The required quantitative outlooks will rest on the 'macro-micro' framework combining IMACLIM and micro-accounting with reweighting of a household survey (see above), which we initially applied to fuel poverty exploration (Gherzi and Ricci, 2014) and further developed by the supervision of Simona De Lauretis' PhD (De Lauretis, 2017). For each of the tested policy packages and time horizons, expected results are the computation of a collection of distributive indicators covering income inequality (mean income ratios, income threshold ratios, Gini index, Atkinson index), poverty (poverty rate based on UN definition of income below 60% of median income) and fuel poverty (energy effort rate, low-income high-cost indicator).

**Box 3 Distributive impacts of the French National Low-Carbon Strategy
A research contract with ADEME**

3. Furthering the combination of models and analyses

International action on sustainable development took an important turn at the beginning of the 2010s. In our original field of climate mitigation, this was the time when, after failure of attempts to prolong the burden sharing approach beyond the Kyoto Protocol implementation period, action centred again on the voluntary commitment of countries. This move concretised in the acclaimed success of the Paris UNFCCC conference of December 2015 and its Nationally Determined Contributions (NDCs) framework of action. A mere 3 months before the Paris conference, heads of States and Governments had adopted the 2030 Agenda for Sustainable Development under the United Nations umbrella. The Agenda, concluding a process that had initiated at the Rio+20 conference of 2012, defines 17 Sustainable Development Goals (SDGs)—among which “affordable clean energy” and “climate action”—and 169 associated targets.

These evolutions prompted a flourish of research efforts on climate and energy transitions and other SDGs at national levels, which produced such wealth of insights that it is probably beyond the capacity of any single model to cover as a stand-alone tool. However, economy-wide models as IMACLIM can procure the integrative framework in which to bring those analyses in consistency, by working out their interactions on markets and the trade-offs of economic agents, including their investment decisions. We have been following this research path since our first attempts at coupling IMACLIM to bottom-up analyses, and we will continue to research improvements of such methods following section 3.1 below. We will additionally investigate two other directions of models and analyses combinations, to which we devote two further subsections.

3.1. Pushing back the frontier of TD/BU coupling

Despite extensive past developments (see section 1.1.2 p.26), one persisting limitation of our soft-coupling option is that we only feed back demand drivers from IMACLIM to the coupled BU model. As a consequence, the BU model continues settling production and end-use technology competition under the assumption of constant relative non-energy prices, rather than with reference to the relative price adjustments computed in the economy-wide framework of IMACLIM. This introduces a bias into the “merit order” selection of technologies (the minimisation of lifecycle cost of technical options) that persists up to convergence of the coupled models.

Bauer et al. (2008) stress this shortcoming of soft linking approaches—although commenting on a soft linking experiment slightly different from our own. We can readily address it by extending the set of linking variables from IMACLIM to the BU model to the evolutions of capital versus other non-energy costs relative to the price of one energy commodity acting as numéraire in this data transfer. Our aggregation of capital costs on one side and all other non-energy costs on the other side reflects bottom-up practice of opposing “CAPEX”, capital or capacity expenses, and “OPEX”, operating expenses, in their description of technology costs.⁷⁷ The main obstacle of this evolution is a quite trivial one. It is the concentration of technology cost data in large databases that were not designed for easy modification, as our extended procedure would intend to.

However, we may push forward this agenda in the framework of the established global ETSAP community of TIMES bottom-up model users. We have recently engaged in a joint research effort with the Energy Policy and Modelling Group (EPMG) of University College, Cork, whose director also chairs the executive committee of ETSAP. The research effort consists in developing an economy-wide framework to the global 15-region TIAM model (a derivative of TIMES) maintained at EPMG. Over the last two years, we devoted discontinuous efforts to adapting to TIAM the ‘KLEM’ coupling method developed with the POLES model in the framework of the RISKERGY programme (see Box 2 p.61). In recent months, we completed the method by extending it to the constraint of balanced international trade of non-energy goods **and supervised its coding in Python language by one engineer a CIRED**.⁷⁸ The tool resulting from the combination of our multiregional KLEM and the TIAM model is an integrated global multiregional bottom-up & top-down modelling architecture that we plan to put to use shortly to explore international mitigation scenarios, under impulse of our TIAM modeller colleague in Cork.⁷⁹

One important dimension of this collaborative, which we wanted to draw attention to, is the particular level of expertise and influence of Cork modellers in the TIMES community. This opens the possibility that advancements of our coupling method, e.g. via the coding by TIAM modellers of optional shifts of relative CAPEX versus OPEX versus energy costs, could ultimately make their way into the broad TIMES community. We will see below (section 4.1) that we are currently engaging in several other coupling experiments with TIMES models, which could benefit from such evolutions.

3.2. Combining geographical scales of analysis

Another important thread of methodological research prompted by the shift of attention from global climate agreements to national multidimensional transitions is the combination of geographical scales of analysis. The search for that sort of integration is a natural consequence of the necessity to be able to place national efforts into global frameworks. A basic reason to do so is to test their consistency with one another, considering

⁷⁷ Further disaggregation of OPEXes in labour and other expenses seems out of the range of foreseeable bottom-up evolutions.

⁷⁸ In the course of the RISKERGY programme, we lacked the time to integrate the newly built 44 POLES-KLEM country models in a consistent international trade framework and had to accept possible shifts of the aggregate trade balance of these 44 economies with the rest of the world.

⁷⁹ Because it will not be under our lead but only with our collaboration, we do not elaborate on this line of research in our research project.

international economic interactions via trade in goods and services and capital flows—one first attempt at that sort of analysis by Pye et al. (2016) concludes to significant inconsistencies. Another reason to pursue such integration is to assess the compatibility of national commitments with global commitments as e.g. the capping of temperature increase below 2°C. A third reason is to test whether the fragmented approach of independent national actions does or does not induce global efficiency losses—bearing in mind the troublesome results of Böhringer et al. (2009) that uniform (coordinated) pricing does not guarantee social cost minimisation of the climate action (see section 1.2.3 p.65). One corollary to this third reason is to develop the capacity to assess the consequences of connecting again the mitigation efforts of different countries, via e.g. international economy-wide or sectoral emissions trading systems, or ‘Climate Clubs’ grouping countries around mitigation action and penalising outsiders via trade tariffs (Nordhaus, 2015).

Maintenance at CIRED and in partner institutions of a growing number of IMACLIM country models (see section 4 below), as well as of the global IMACLIM-R model and now of the global TIAM-KLEM architecture (see 3.1 above), both increases the interest of such research and facilitates it. At the very least, we can frame our future scenario developments in open-economy settings with insights from the database of global IMACLIM-R scenarios maintained by other researchers at CIRED—although we pragmatically tend to fall back on authoritative sources as e.g. the IEA world energy outlook on the international energy commodity prices exogenous to our scenarios.

However, the TIAM-KLEM architecture offers the prospect of a more ambitious linkage that would embed full-blown national models into an aggregate global model. Because we built TIAM-KLEM up from the separate country models of the RISKERGY programme (see Box 2 p.61), we modelled its closure of international trade on non-energy goods and services via the iteration to convergence of country models solving. Country models solve one after another and the trading price and volume of non-energy goods updates in between each solving, up to convergence. This opens up the possibility to substitute the 2-sector aggregation of multi-sectoral IMACLIM country models results to the results of compact 2-sector KLEM models at each step of the iteration, for one or more countries. The only problem to solve is one of sectoral disaggregation, to feed information back from the 2-sector description of trade by the KLEM framework, to the multi-sectoral framework of IMACLIM country models. Although we have not started researching this issue, we are confident that we can solve it in different ways, from pragmatic solutions aimed at testing our model integration framework to elaborate ones duly reflecting on the structural change issues underlying sectoral disaggregation.

3.3. Investigating circular economy potentials

A third line of research meant to open IMACLIM to additional fields of analysis is a recent PhD project on the potentials of circular economy in the compared contexts of Brazil and France. **The PhD candidate, Antoine Teixeira, is currently working at CIRED as research assistant on two short-term projects bearing on assessment of the French National Low-Carbon Strategy, one of which under our responsibility** (see Box 3 p.72). **The PhD is due to start next October under our supervision**, funding permitting—the Deloitte consultancy group has expressed strong interest and negotiations are close to conclusion.

Recent years have seen a growing interest in the concept of ‘circular economy’,⁸⁰ from governments attempting to set up policies promoting its principles to institutions and academics working on a more precise definition of it and exploring its applicability. The aim of this new economic paradigm is to overcome the linearity of our present economic system, whose growth is strongly correlated with the extraction and consumption of non-renewable resources, both fossil energy resources and mineral and biological raw materials. Solutions to achieve this aim range from the introduction of alternatives to single-use products and resources through the development of recycling and repair channels, to the use of more resource-efficient technologies, and more

⁸⁰ This description of the circular economy concept and induced PhD project is our adaptation of a French PhD project summary by Antoine Teixeira.

generally to the implementation of an economic system of exchanges and circularities where each resource is valued at each stage of its lifecycle. These solutions often refer to existing concepts borrowed from different streams of economic thought.⁸¹ Three types of strategies emerge:

- Reducing the intensity of resource flows through the development and diffusion of new, more resource-efficient production technologies, the orientation of consumption away from material-rich products towards a service economy and the substitution of a sharing economy to the current ownership economy.
- Slowing down non-renewable resource flows by a durable and robust design of goods to increase their lifespan between resource extraction and landfill.
- Creating resource loops involving the substitution of secondary materials from recycling and used products from repair, re-processing and re-use. This lever's potential is all the higher as the first two strategies are activated.

Despite the large diversity of dimensions to the concept, most public policies only address it from the angle of recycling and sustainable waste treatment. Research offers broader coverage in the form of impact analysis in partial equilibrium settings. Some recent economy-wide studies adding to the corpus limit themselves to one or the other dimension of the ensemble. Global level studies neglect the resource-loop question and focus on exogenous behavioural changes in favour of high value-added (i.e. low material-intensity) productions. Country-level analyses mainly consider the impact of recycling in resource-poor developed countries.

Considering these limitations, the purpose of the PhD research is to develop a framework of analysis embracing more dimensions of the circular economy concept and accounting for their interactions. The framework shall be applicable to countries with contrasted levels of development and endowments in natural resources. The input-output representation of economies and its comprehensive coverage of material flows is a natural starting-point for such a framework. However, compared to standard CGE 'animation' of input-output structures, the proposed model will need to integrate:

- Material loops at different levels of the lifecycle of products, to represent new trade-offs of the circular economy at the level of supply, demand and ultimate disposal.
- Production trade-offs between primary and secondary materials and between new and second-hand products.
- Final consumption trade-offs between new and second-hand products as well as between individual equipment and collective services.
- Trade-offs at the end-of-life of products between landfilling, recycling, repair, re-use and energy recovery.

The updated tool will allow producing new insights on the sustainability of growth trajectories, including on the energy and climate dimensions.

4. New settings of applied analysis and research collaboratives

Around 2010, CIRED started using its longstanding relationships with international research centres abroad as a channel of technology transfer of the IMACLIM approach to modelling. In recent years, several PhDs were devoted to the development and implementation of IMACLIM to Brazil, and one to that of IMACLIM to South Africa. Both endeavours included calibration on dully hybridised datasets and linkage to bottom-up models of

⁸¹ Ecological economics, industrial ecology, industrial symbiosis, functional economy, sharing economy, biomimicry, socio-ecological resilience, regenerative or 'cradle-to-cradle' design, localism, reverse logistics, etc.

the TIMES family, in the spirit of our methodological contribution (see section 1 p.22). Although the Brazilian model developed at a time when we were away from CIREC visiting the Fondazione Eni Enrico Mattei (FEEM) and the *Centre de Mathématiques Appliquées* (CMA) of École des Mines, **we were and are still involved in the South African project as co-supervisor of the PhD of Jules Schers (see section 2.4.2 p.50)**. The thesis should be defended shortly.

Reaching to Brazil and South Africa was not fortuitous. The purpose was to extend our modelling capacity to major players of the developing world, simultaneously acknowledging their ever-increasing weight in global energy consumptions and carbon emissions, the drift of international negotiations from a top-down approach of the cap-and-trade type (the Kyoto Protocol) to a bottom-up aggregation of Nationally Determined Contributions (NDCs of the Paris agreement of COP21), as well as the paucity of properly devoted modelling efforts. One additional motivation was to revive research on the tension between environmental and development objectives and their reconciliation, which had been at the heart of CIREC research at the time of its founding in the early seventies (as the CIREC name conveys), but had progressively escaped its focus in later years. The specific choice of Brazil is a consequence of strong historical links between CIREC and the COPPE research centre of the Federal University of Rio de Janeiro. This connexion opened access to a South-South initiative where the Energy Research Centre (ERC) of the University of Cape Town played a prominent role. Winning support from the ERC allowed launching the South African initiative. Opportunities soon arose to extend to the other BRICS countries as well as beyond this group.

4.1. Developing BRICS capacity and analyses

4.1.1. Russia

Work on Russia started under our own impulse considering the paucity of analysis on that country, although a major player of international energy markets for both crude oil and gas, as well as a re-emerging geopolitical power. **In October 2015, we launched the Russian data hybridisation effort via the graduating internship of Lucile Henry from the ESPCI engineering school, under our supervision.** The 3-month internship and its prolongation to June 2016 was the occasion to produce a guide that facilitated subsequent data hybridisation efforts (Henry, 2016). Around the same time, CIREC happened to engage in answering a research tender of the European Commission under its ‘Horizon 2020’ (H2020) funding programme, as leader of a COMMONS proposal.⁸² Although the proposal failed to secure funding,⁸³ its build-up effort led to favourable discussions with Russian and Indian colleagues around the opportunity to build IMACLIM models of their countries. The setting up of both country models eventually entered the proposal. The lack of funding delayed the Russian effort up to this year, when our Russian partner decided to make the development of an IMACLIM-RU model one objective of the PhD thesis of one of his students. The decision was largely the consequence of the success of the second international IMACLIM meeting that we organised at CIREC in November 2017 (see section 4.3 below). In the wake of this decision, **we succeeded in securing a Make Our Planet Great Again funding to finance a 4-month stay of the Russian PhD student at CIREC from September to December 2018.**

In the framework of this PhD, the Russian case study will address several dimensions of the energy transition challenge. One first dimension is sheer compatibility of ambitious global mitigation and economic growth—the common denominator of all our country studies. The case of Russia however stands out for the strong stakes attached to its fossil extraction industry. Less stressed outside Russia, the country is also endowed with a green

⁸² The COMMONS acronym played on two different meanings addressing two dimensions of the H2020 call: COnditions for aMBitious Mitigation in the eurOpean unioN and other regionS and CO-designed Mitigation roadMaps for the eurOpean unioN and other regionS. The “commons” word additionally aimed at conveying the emphasis of the proposal on cross-country and cross-regional interactions.

⁸³ The EU commission evaluation rated at 3.5/5 (between “good” and “very good”) the “Excellence” of the project, a notion that covers its academic quality—the part of the proposal in which we were highly involved.

energy potential at the scale of its immense territory, far beyond the needs of its own, relatively small population. Our analysis will thus consider prospects of shifting from a development model fuelled by the fossil rent to a green growth paradigm, including the possibility that massive exports of biomass at various transformation stages could replace the current oil, gas and coal exports as a foreign currency source and a public budget contributor. Our current effort on the Saudi transition (see the following section 4.2) will offer precious methodological experience in this treatment of structural change for a resource-oriented economy.

In addition, specific competences at our partner the Higher School of Economics (HSE) Moscow will allow extending our analysis in two directions. The TIMES model of HSE—the bottom-up model to which IMACLIM-RU will couple—tracks local pollutant emissions, and this will allow us to investigate the co-benefits of the transition on health. It will be our first incursion in the co-benefits research field and one with high-stakes potential application to India and China (see below). HSE also has specific expertise on industrial technologies that could structure analysis of the dynamics of the Russian inter-industry matrix. What particular research questions can be explored building upon this expertise remains to be discussed with our Russian partner.

4.1.2. China

Work on the Chinese economy started in 2016, in the form of successive 6-month visits at CIRED of two PhD students from Tsinghua University. **Although without formal engagement, we have been involved in the supervision of the PhD research of both students ever since.** The first visit bore on the production of hybrid accounts of the Chinese economy, the pre-requisite to any implementation of IMACLIM. The discrepancy between energy expenses reported by national accounts and energy expenses resulting from the crossing of energy flows and price statistics (from the IEA and national sources) turned out massive, and the hybridisation process is still pending, hanging on supplementary data to settle the dramatic inconsistencies that our work brought to light. However, there is strong probability that our final matrix will substantially depart from official statistics of energy expenses and this could induce our aggregate modelling analysis of the Chinese transition to stand out as an original contribution in the vast available literature on the matter.

The second student visit focused on the collection and statistical treatment of Chinese household survey data, with a view to build up a micro-macro capacity similar to that which we developed in the case of France (section 2.3.2 p.47). This opens the way to analysis of the distributional consequences of the transition on Chinese households. To the best of our knowledge, this sort of analysis is currently unavailable from the literature, despite the high number of papers dedicated to the Chinese energy transition. However, experience of both failed and passed reforms in other countries demonstrates that it is not only the total cost of action but also its distribution among economic agents—including its ultimate impact on public budgets—that governs implementation. From a modeller's perspective, Devarajan et al. (1990) indeed stress that the macroeconomic consequences of external shocks (e.g. shocks on international fossil prices) or tax policies (e.g. the introduction of a carbon tax) have equity consequences quite larger than their efficiency impacts. Exploring such stakes requires at least representing the secondary distribution of income, i.e. the set of taxes, subsidies, social benefits and other transfers that re-distribute parts of the primary factor payments among households, firms and public administrations to shape their budget balances. Further disaggregation of households in income groups allows assessing how energy transitions affect inequalities.

The pace of progress of the Chinese effort is slower than that of our other country projects. Work on a 2-sector IMACLIM-CN, which we now systematically engage in, as a modelling first step (see section 4.3), has only recently started based on a 2-sector matrix that we still need to scrutinise. The current effort is on the coupling interface with the China-MAPLE bottom-up model of our Tsinghua University partner, a model of the TIMES family. The data effort on household surveys is completed but the distributional analysis stands by, depending on advancement of the multi-sectoral effort to resume.

4.1.3. India

Similar to China, prompted by the COMMONS proposal setting up, work on the Indian economy started in 2016 with the 6-month visit at CIRED of one PhD student from the Public Research Group (PRG) of the Indian Institute of Management, Ahmedabad (IIMA). **We are deeply involved in the supervision of this PhD research as one official member of its Thesis Advisory Committee.** The 6-month visit successfully produced a hybrid matrix of 2012 India. The data hybridisation work revealed interesting issues, one of which ‘captive coal mining’, i.e. the direct operation of coal mines by heavy industries. Because they do not induce commercial transactions, 12% of coal consumptions thus remain under the radar of national accounting at our calibration year. Indian government projections indicate that this share will increase in coming years. To cover it in our analyses, we transfer all captive-mining costs to the coal-mining sector (based on its cost structure) and increase the coal expenses of heavy industries accordingly. We adjust the specific margin on coal sales to such industries to reflect the fact that some share of the underlying consumption is supplied net of any operating surplus. We can control this share in our projections to reflect governmental outlooks. This is indeed a good example of the versatility of our IMACLIM approach to modelling, including its attention to agent-specific pricing (see section 1.2.3 p. 13).

Building from the hybrid matrix, work on India focused on the implementation of a 2-sector IMACLIM-IN, but the tight time constraint on the ongoing PhD completion pushes back to post-PhD activity the shaping of the produced material into a journal article. Current work is on the forcing of bottom-up scenarios of the AIM BU model of our Indian partner into the final IMACLIM-IN, for a number of sectors that we set at 22. Analysis will bear on the economic consequences of the Indian Nationally Determined Contribution (NDC) to the global mitigation effort with specific focus on the control of transportation emissions via both vehicle electrification and modal shift, under severe constraint of ‘greening’ the power system. One dimension of the analysis will be to explore the impact on the aggregate cost of transition of contrasted assumptions on the market share of domestic manufacture in renewable energy equipment. This is the line of analysis that we explored in the case of the electric vehicle in Europe (see section 2.3.1 p.45). After completion of the ongoing PhD, we plan to further this type of analysis by looking into how public support to industries could stimulate technology exports—and the attached economic trade-offs. We will also strive to nuance the too clear-cut split between imported and domestic equipment by considering a middle term in which production locates in India but proceeds from foreign capital or only foreign patents, with the consecutive capital payments outflows.⁸⁴ This line of analysis is of course relevant to many country settings other than India and we will pursue it in other IMACLIM implementations.

4.2. Reaching beyond the BRICS

Beyond BRICS countries, CIRED is already engaged in the development of two additional versions of IMACLIM.

4.2.1. Saudi Arabia

Since the beginning of 2016, we have been supervising the PhD research of Salaheddine Soummame on the consequences of domestic and global energy transition in Saudi Arabia. Dramatic sensitivity to the global energy transition is one particular feature of the Kingdom of Saudi Arabia (KSA) economy. The global transition decreases oil demand, which weighs down on the international price of oil. Saudi exports are resilient to the demand drop, because Saudi extraction costs are and will long remain far lower than they are anywhere else in the world. However, the drop of the oil price is a notorious threat on the macroeconomic balances of the Kingdom because

⁸⁴ Razmi (2013) makes the point that the capacity to innovate of developing countries is lower than that of developed countries. There is thus a chance that any carbon constraint on developing economies is going to translate into technology imports, if not in the form of actual productive equipment, then at least in the form of patents.

of its impact on the oil rent. The high contribution of this rent to GDP points at a large foreign savings deficit, one salient feature of the KSA economy (Chemingui and Lofgren, 2004). Another salient feature is the constant exchange rate or 'peg' of the Saudi currency (SAR) to the United States Dollar (USD) since 1986, which rests on the massive accumulation of foreign reserve assets. Compared to economies with floating exchange rate, the peg guarantees stability of the Saudi economy and its real effective exchange rate (REER) to fluctuations of the international oil price (Habib and Kalamova, 2007).

Proper modelling of this peg is one current development on the axis of our research agenda beyond neoclassical paradigms (see section 1 p.59). Any assumption on the REER, because it induces a constrained response of foreign savings *via* trade specifications, requires alternative closure of the model. Applied CGE models of KSA explore such options (Al Thumairi, 2012; Al Hawwas, 2010; Chemingui and Lofgren, 2004) but do not scrutinise macroeconomic statistics to support one option or the other. Statistics, though, reveal a significant, negative correlation of the REER and the trade balance contribution to GDP since the currency pegging of 1986. With the peg barring any nominal exchange rate fluctuation, it is inflation differentials that explain the revealed negative slope. Domestic Saudi prices are little sensitive to international oil prices because of stable energy costs and administered energy prices. US prices, like domestic prices of countries performing the little share of Saudi trade in currencies other than the USD, are more sensitive to international oil prices. When the oil price rises, the Saudi trade surplus rises as well, but foreign and especially US prices rise more than Saudi prices and the Saudi REER decreases.

This 30-year stable relationship between the REER and the contribution of trade to GDP is the sort of structural regularity that development economics have acknowledged via alternative closure rules (see section 1.1 above). It has the major consequence of effectively constraining the contribution of foreign savings to the Saudi economy. The further question is whether closure of the KSA model should then fall on investment or domestic savings. Macroeconomic statistics hold elements to answer this as well. They reveal that investment is a much more stable share of Saudi GDP than domestic savings. Interpretation is again enlightening: in KSA, it is standard public policy to compensate any fluctuation of the oil rent on international markets by dipping in the rent accumulated in the past. In other terms, public authorities of KSA follow a form of 'permanent income' behaviour by smoothing out income (oil rent) variations with their savings. This is how the erratic path of Saudi domestic savings rate, which is in fact strongly correlated to the movements of oil prices on international markets, explains the stable path of the Saudi investment rate. This stability, in turn, warrants that of the overall growth path, which statistics confirm that it is effectively disconnected from oil price variations. To summarise, under such public-spending behaviour, global energy transition does not affect GDP much, but mechanically reduces public surplus accumulation by cutting on the oil rent.

After building the set of hybrid accounts necessary to IMACLIM calibration, we moved on to a 2-sector IMACLIM-SA exploration of these macroeconomic stakes, under due coupling to the KEM energy model of our KAPSARC Saudi partner (see section 4.3 below). We estimate the impacts of shifting from a global NDC mitigation effort to a global 2°C-compatible effort based on IEA expertise of the induced oil price drop of -28%. At our 2032 horizon, we place the induced GDP drop in a 1.0% to 1.8% range and the trade surplus loss in a 760 to 890 billion 2011 USD range, depending on parameter variants. The trade surplus loss is thus larger than the estimated 544 billion-dollar Saudi sovereign wealth fund at the beginning of 2011.

What is more, even in higher oil price scenarios, the growth pace of oil exports lags behind that of overall GDP. This is favourable news as regards diversification of the Saudi economy, but it is a serious threat on public budgets, because it means that the close-to only source of public income will grow at a slower pace than public expenses, which statistics indicate that they roughly grow as GDP. In our numerical projections to 2032, this imbalance accumulates to 1,296 billion 2011 USD (101% of 2032 GDP) in an NDC context and to 1,890 billion 2011 USD (166% of the slightly lower 2032 GDP) in the 2°C scenario. However, the trade surplus remains positive over the entire horizon, which means that the Saudi economy as a whole is still accumulating credit over the rest of the world. The macroeconomic problem of KSA is thus a problem of income distribution between public authorities and private agents. This explains and underlines the importance of the ambitious set of reforms

planned by KSA under its *Vision 2030* initiative, which notably includes the creation of a fiscal system. We have formalised these results in a journal article that is currently under review.

The setting up of a multi-sectoral IMACLIM-SA model with full detail of secondary income distribution between domestic agents will allow us to refine this public budget analysis and investigate the impact of the proposed fiscal reforms. It will also put us in capacity to explore structural change issues, one of the core objectives of the PhD research. Ngai and Pissarides (2007) discuss two competing explanations for structural change: the technological explanation attributes it to differences in sectoral rates of total factor productivity, while the utility-based explanation relies on different income elasticities for different goods leading to structural change. We will put both lines of thought to the test of IMACLIM-SA and relate them to the structural change objectives promoted by the *Vision 2030* initiative. We plan to assess two scenarios of economic activity diversification, one shallow scenario where KSA continues playing on its current strengths and massively develops its petrochemical industry, and one deeper scenario where KSA devotes public investment efforts and possibly subsidises the development of other activities.

4.2.2. Argentina

Argentina is the latest project of IMACLIM transfer effectively started. It initiated under impulse of the French IDDRI and with the financial support of the Inter-American Development Bank (IADB). Similar to previous projects, it leans on collaboration with a local partner team, the Fundacion Bariloche, which maintains a LEAP bottom-up modelling capacity. Gaëlle Le Treut, who recently defended her PhD at CIRED (Le Treut, 2017), has already joined Fundacion Bariloche as her first postdoctoral position to set up the IMACLIM-AR model. Our personal direct involvement in the project should therefore be limited to distant guidance, but any methodological developments that it is going to produce will contribute to the emerging IMACLIM Network, which will focus much of our activity in coming years (see section 4.3 below). The research programme set up with IDDRI, IADB and Fundacion Bariloche lists several applied objectives.

The first objective is to build energy scenarios and related CO₂ emissions up to 2050 with some sectoral detail on power generation, transport, industry and buildings. One set of scenarios will cover a reference projection with existing public policies extended to 2050, including the Argentinian NDCs (one unconditional and one conditional to global action) up to 2030 and their extrapolations to 2050. Another scenario will propose a deep decarbonisation (DD) pathway compatible with a 2°C cap on global temperature increase, up to 2050. The DD pathway may involve different paths or actions than proposed by the current NDCs and require structural change not only at the national level, but also at the broader global level from 2020 on. The second objective of the Argentinian effort is to identify the additional mid-term measures needed to bifurcate from the reference towards the DD pathway and to study the economy-wide implications of these measures and the conditions enabling their implementation.

Additionally, the local expertise of Fundacion Bariloche identifies transport as one key deadlock of deep decarbonisation. The research effort will thus focus on exploring modal shift options and the penetration of clean vehicle technologies, building from our own experiments in the global and European Union frameworks (Gherssi et al., 2013; Ghersi, 2014a, 2015b). The trade-off between domestic and imported supply of clean technologies (vehicles, batteries, biofuels) will be a major factor of the economy-wide analysis. Another measure of high mitigation impact and economic potential is the substitution of heat pumps to natural-gas fuelled vented wall heaters for residential and commercial heating uses, and the combination with a natural gas export policy.

4.2.3. Moving to one Least Developed Country

Considering the historical focus of CIRED on the combination of environmental and development objectives, it is a missed opportunity to have not yet implemented IMACLIM to the analysis of any least-developed economy.

We strongly share this view with CIRED's director Franck Lecocq, who pushed us to reach to potential partners in such countries as the next step of our IMACLIM network extension. At the occasion of the International Energy Workshop 2017, we thus met with Libasse Ba, programme coordinator at ENDA Énergie, Senegal. In one later exchange, Dr. Ba confirmed ENDA's motivation to support an IMACLIM-Senegal (IMACLIM-SN) project with its LEAP bottom-up modelling capacity.⁸⁵ We are now actively engaged in looking for financial support to get this project started (see 4.3.1 below).

We are currently not in a position to discuss the specifics of Senegal's potential transition to low-carbon futures. Collaboration with Dr. Ba and conversations with senior colleagues at CIRED that carry the memory of its earlier contributions will guide our research in that regard. We can nonetheless anticipate that the 'second best' capacity developments that we aim at (section 1.2 p.63) will be of particular relevance to our analyses.

Structural change is doubtlessly one of the major challenges ahead of Senegal development and it intimately relates to factor mobility issues, particularly that of labour (see Poirson, 2001, on the connexion between labour allocation and growth in African countries). The question of labour productivity gains via education is likely to come up, although our experience with South Africa was rather inconclusive as regards the ability to calibrate this relationship and we had to fall back on ad hoc assumptions (Schers et al., 2015, p.57). Another probable question will be that of informal versus formal labour, which may require further specific methodological developments.

Investment capacity is another constraint that we must give attention to. The measure in which foreign savings will have to complement Senegalese savings will interact with the trade balance, under the currency and exchange rate constraints attached to the CFA Franc domestic currency—which we still have to properly work out. There is a possibility that a proper treatment of the underlying trade-offs will push us in the direction of endogenising international capital flows rather than assuming them the opposite of the trade balance. McKibbin and Wilcoxon (1995) or Ianchovichina and McDougal (2000) describe modelling specifications to that effect. There is also the possibility that we must take into account emigration and the attached remittances—see e.g. McDonald et al. (2006) on the remittances from Germany to Turkey and attached risk of 'Dutch disease'.

4.3. Structuring the emerging IMACLIM Network

4.3.1. Network objectives and organisation

The previous sections cover seven completed and ongoing projects of implementation of our IMACLIM capacity to developing countries, five of which under our exclusive or partial direction. There are additional prospects for two more countries, Vietnam and Senegal, where we have already identified partners carrying the capacity (including BU expertise) to engage into IMACLIM modelling, and committed to do so. We are therefore facing the prospect of a growing community of researchers involved into the maintenance and development of country versions of our IMACLIM model (Table 6, Table 7). As the most senior CIRED researcher involved, the structuring, animation and development of this community is going to mobilise a significant share of our research activity in coming years.

⁸⁵ ENDA in fact operates as a focal point of the international LEAP community in Western Africa. This opens up opportunities for later modelling projects.

Country	Partner team	Type of BU capacity	Current workforce	Start year
Brazil	COPPE-UFRJ	TIMES model	2 PhDs	2010
South Africa	ERC-UCT	TIMES model	1 PhD student	2013
India	PRG-IIMA	AIM model	1 PhD student	2016
China	EEE-Tsinghua U.	TIMES model	2 PhD students	2016
Saudi Arabia	KAPSARC	KEM model	1 PhD student	2016
Russia	CENRE-HSE Moscow	TIMES model	1 PhD student	2018
Argentina	Fundacion Bariloche	LEAP model	1 PhD	2018
Vietnam	CleanED-USTH	LEAP model	None	Not started
Senegal	ENDA	LEAP model	None	Not started

Table 6 Current extent of IMACLIM community

Country	Status			Personal involvement
	Hybrid SAM	2-sector model	Multisector model	
Brazil	Year 2005	Not explored	Running	None
South Africa	Year 2005	Not explored	Running	Co-supervisor
India	Year 2012	Running	Pending	Supervisor
China	Year 2011, pending	Pending	Not started	Supervisor
Saudi Arabia	Year 2013	Running	Pending	Supervisor
Russia	Year 2007	Not started	Not started	Supervisor
Argentina	Starting	Not started	Not started	None
Vietnam	Advanced discussions, in search of funding and student			Co-supervisor
Senegal	Advanced discussions, in search of funding			Supervisor

Table 7 Current status of IMACLIM efforts

Acknowledging this momentum, we convened a 2-day meeting of current and would-be IMACLIM users at CIRED in November 2017. All BRICS partners as well as Saudi Arabia’s KAPSARC were represented by peer researchers as well as by those students effectively developing IMACLIM models under our supervision. The first day of the meeting was the occasion for us to propose a set of guidelines to our community’s organisation into an IMACLIM Network. We suggested the following general principles to the network activities, which were unanimously agreed upon:

- The Network builds on a convergence of views regarding energy/economy modelling and its use in policy circles.

- It is a collaborative endeavour on a voluntary basis focused on scientific exchanges around the IMACLIM modelling platform initiated by CIRED.
- Network membership is entirely free-of-charge although members commit to reasonable expenses to host and participate to Network meetings.
- The Network and attached obligations and privileges are and will remain informal, resting on a gentleman's agreement between Network members as researchers rather than institutions.

We framed this set of principles to maximise the academic efficiency of the Network, while relying on our intellectual proximity to involved researchers to smooth out non-academic difficulties.⁸⁶ Indeed, the orientation of the Network towards methodology co-development and transfer as regards both data hybridisation techniques and economy/energy modelling is central. Methodological advances by any member or group of members are meant to be shared with all members, although the originating group retains priority for the purpose of scientific publications. The primary purpose of the Network is thus not a mechanical extension of the number of countries covered by IMACLIM capacity. It is rather to address additional research questions and methodological challenges raised by the specificities of each new economy, as transpires from the range of applications described in the above sections. These eventually concretise into extensions of the shared model code (see below) and allow further scenario exploration in countries previously covered. Of course, scientific co-publication of model developments and implementations is one major objective of the Network.

We intend Network activity to take the form of bilateral or multilateral working groups on model developments, with CIRED not necessarily involved. We will organise one annual meeting, which Network members agreed to host on a rotating basis. The meeting will bring Network members together to report and exchange on modelling developments and agendas. We are currently planning the 2018 meeting in Rio at COPPE-UFRJ, to happen on the last week of October or November (final decision pending).

Beyond standard publication, the reach-out potential of the Network rests on its members participating in the Energy Modeling Forum of Stanford University, the Integrated Assessment Modeling Consortium or the IPCC and UNFCCC processes. Some teams including CIRED also participate to forums at the interface between science and decision, such as the Low-Carbon Society Research Network (LCS-RNet) set up by the G8 in 2009, or the Deep Decarbonisation Pathway Project (DDPP) of the French IDDRI. The IMACLIM Network's website is under development at <http://www.centre-cired.fr/index.php/en/imaclim-network/imaclim-network-en/>. It should shortly propose as *IMACLIM Manifesto* a 2-page synthesis of the founding principles of our IMACLIM approach, currently under discussion amongst members (see Annex p.161).

Funding has so far built on various uncoordinated resources. The Brazilian endeavour benefitted from involvement of COPPE and CIRED in several EU Commission projects, as well as from the PhD funding of Julien Lefèvre by his AgroParistech public corps of engineers. More recently, it also drew resource from an ECOSUD project coordinated by the UN Economic Commission for Latin America and the Caribbean, which opened up opportunities to extend the South American coverage of the Network—these remain to be explored. The South Africa model is the product of Jules Schers' PhD thesis under funding of the *Agence Française de Développement* and the Chair Modeling For Sustainable Development.⁸⁷ Right after his PhD defence, Jules Schers will join ERC (University of Cape Town) as visiting scholar under funding of the French ministry of Foreign Affairs, to further his analyses of the South African transition. The Saudi Arabia model is the product of Salaheddine Soummane's PhD research under funding of EDF R&D.

The Indian, Chinese and Russian endeavours lean on the PhD research of students under local funding in partner institutions, although CIRED partly covered the visiting costs to France in the case of India. Additionally, we

⁸⁶ A wide and swift development of the Network may put this stance to the test. CNRS (the public institution that permanently assigns us to CIRED) offers several solutions to institutionalise the Network and explicitly settle any intellectual property issues if warranted at some point in the future.

⁸⁷ An initiative by CIRED and one allied French institution to secure 5-year funding of its modelling activities from public and private contributors.

secured a Make Our Planet Great Again funding by the French Government to cover a 4-month stay of the Russian student from September to December 2018. The starting Argentina project is under funding of the Inter-American Development Bank. At last, we recently inserted the Vietnam project into a research proposal that passed the first selection stage of a European Commission H2020 tender. The built-up proposal was submitted in early September for a final decision by the end of the year.

We will probably continue to lean on PhD funding from French or foreign public and private sources to finance further IMACLIM country versions strictly speaking, while perhaps anticipating on data hybridisation via pre-PhD internships, as we did in the case of Russia. However, we will try to secure specific funding to cover rising transversal costs. It would be an obvious asset of the Network to be able to cover some of the costs of annual meetings and attached travel expenses, particularly for the teams from poorer countries. There is also the need of one technical support staff at disposal of member teams to guide new users into the shared model code (see section 4.3.2 below) and to organise code developments from all parties. This need will grow with the number of teams involved into the project lest the underlying tasks overwhelm the agendas of involved CIREC researchers, including our own. Among potential sources, CNRS supports International Research Network initiatives (formerly known by the French acronym GDRI) that suit our purpose particularly well. We will investigate such possibilities in coming months.

4.3.2. Organisation of further transfer efforts

Experience gathered across the seven IMACLIM transfer projects started so far outlines some guidelines for further efforts.

The first step into IMACLIM modelling is the setting up of a hybrid database reconciling national accounts and energy balances via a matrix of consumption and trade prices. This is a 3- to 6-month effort at least, depending on country specifics. Some issues require particular attention:

- The energy tax system and the interaction between excise and ad valorem taxes,
- Administered prices and the system of subsidies underlying them,
- The public involvement into energy supply and distribution,
- ‘Captive’ energy resources collected by industrial operators and overlooked by national accounting,
- Commodity trade by distribution companies in deregulated markets—an economic flow without energy consumption or carbon emission counterpart.

Structuration of the Russian data effort (Henry, 2016) does not address this list comprehensively and we will have to devote some more effort to produce a complete guide to data hybridisation procedures. This can be the object of an internship proposal to École des Ponts Paristech engineering students.⁸⁸

The second step into IMACLIM shall be the thorough exploration of a 2-sector ‘KLEM’ model properly calibrated on hybrid data from the first step, as well as linked to the bottom-up capacity of the local partner. The South African model development sorely missed this step. In fact, it was one significant cause of delay of the South African PhD effort.⁸⁹ Controlling the macroeconomics of South African rapid growth in a multi-sectoral framework with methodological developments of skill-specific labour markets proved very difficult (see section 1.1 p.60). By contrast, the 2-sector exploration of Saudi Arabia produced valuable insights that we can now build

⁸⁸ École des Ponts Paristech is one of the 5 institutions who assign personnel to CIREC. It solicits CIREC every year to set up internship proposals at destination of its students.

⁸⁹ The delay was also caused by two junior researchers leaving CIREC one after the other, although they were co-supervising the IMACLIM-ZA effort. Supervision fell on CIREC director Franck Lecocq shortly after he came into office. We supervised the model development effort from April 2014 on. PhD defence is expected to happen in September 2018 only.

on to proceed with multi-sectoral analysis. It is also material fit for publication, which is now one obligation of the French PhD cursus.

Systematic operation of the compact 2-sector model will provide an introduction to ‘computable general equilibrium’ modelling, in the non-standard IMACLIM sense, but relying on the standard representation of economic flows, including the interactions of production sectors via the input-output matrix and factor markets, the budget balances of agents, international trade, etc. It will also allow settling important modelling decisions following section 1 of our research project, depending on the time horizon of planned analyses and specific country settings. These decisions encompass the choice of ‘flexprice’ versus ‘fixprice’ market specifications, of modelling barriers to labour and capital mobility and of a closure rule, with full control of its impacts on the trade balance conditional to trade elasticities. Lastly, it will introduce to model coupling at a level of aggregation that allows focusing on the conceptual differences between the bottom-up and top-down representations of energy flows and comprehending how our method bridges them. Altogether, these developments can take up to one full year, including the proper framing of macroeconomic and energy transition issues in specific national contexts via literature review.

The third and final step of IMACLIM development is the setting up and running of the multi-sectoral model, including the development of country-specific methodological improvements. The relevance of scenario exploration and possible linkages to national policymaking circles hangs on the involvement of senior researchers in partner institutions and their expertise of and contacts in the national context.

Each of the three steps of model development can provide material for communications at the annual Network meetings, with a view to share experience with the growing IMACLIM community. Another major channel of experience sharing is the online development platform where Le Treut et al. (2018) recently published the IMACLIM-Country code. All model implementations and developments will happen on this platform, which will considerably ease supervision from CIRED. Developments will proceed in ‘branches’ of the code, which we can incorporate to its ‘trunk’ when they reach stabilisation.

In this framework, our role will be one of coordination and management of the Network, with direct supervision of no more than 3 country developments at a time—which will incidentally require us to follow some training in Scilab, the programming language of the online model platform. Besides ourselves, the team focusing on the IMACLIM-country project at CIRED counts one tenure researcher, Julien Lefèvre, and three post-doctoral researchers including Gaëlle Le Treut at Fundacion Bariloche and Jules Schers (due to defend his PhD shortly) at ERC, University of Cape Town. The third post-doctoral researcher, Mériem Hamdi-Chérif, is spending part of her time on IMACLIM-R, the recursive dynamic multi-regional version of IMACLIM, which is out of our scope. There are however strong synergies with the IMACLIM-R group under supervision of Céline Guivarch, which our endeavour will benefit from.

There are also strong synergies with CIRED’s *International Summer School in Economic Modelling of Environment, Energy and Climate*. This recent initiative of Julien Lefèvre and Céline Guivarch draws students from all around the world to CIRED. Although not focused on IMACLIM modelling alone, it is an important channel of communication of CIRED’s approach to modelling. The second edition has taken place at CIRED on the week of July 4th, 2018, with a focus on “the role of demand and lifestyles in low-carbon pathways”.⁹⁰ We will doubtlessly contribute to the Summer School effort at some point in the future.

⁹⁰ See <http://www2.centre-cired.fr/Le-CIRED/International-Summer-School/>.

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Annex 1

Macroeconomic consistency issues in E3 modelling: The continued fable of the elephant and the rabbit

Macroeconomic consistency issues in E3 modelling: The continued fable of the elephant and the rabbit

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Abstract

Starting from a short presentation of the limits of using conventional production functions to hybridize energy-economy relationships, this paper presents a methodology aiming at a better integration of bottom-up policy scenarios in a top-down static general equilibrium framework. Along the lines of Ahmad's innovation possibility curve, the methodology consists in implementing top-down envelopes of production and demand functions, whose variable point elasticities of substitution provide a flexible interface for calibration on any bottom-up expertise. Numerical experiments assessing the impact of a rising carbon tax on the global 2030 economy compare the application of this methodology to that of two standard CES-based approaches. Results confirm that, in case of large departures from reference scenarios or of strong convexities in bottom-up results, the use of conventional CES production and utility functions may lead to a significant bias in cost assessment.

Introduction

This paper starts from a paradox in current efforts directed at hybridizing bottom-up (BU) and top-down (TD) analysis of energy-economy-environment (E3) linkages: while the challenge is to benefit from the technology-rich information of BU models when analyzing the macroeconomic implications of public policies, these efforts devote little attention to the consistency between technical change in the energy sector and overall technical change. Instead, they focus primarily on the gap between the engineer's and the economist's descriptions of energy technologies.

Such a practice is legitimated by the 'Elephant and Rabbit stew' metaphor of energy-economy interactions: if the stew "contains just one rabbit (the energy sector) and one elephant (the rest of the economy), won't it still taste very much like elephant stew?" (Hogan and Manne, 1977). Given the small weight of the energy sector in the economy, this metaphor justifies keeping constant the non-energy production functions of E3 models. However, if it is undoubtedly applicable when small departures from reference trends are considered, it becomes more debatable when drastic modifications of these trends are required by ambitious long-term objectives such as decarbonization.

This paper scrutinizes the terms and significance of this issue. The first section stresses the importance of adopting an endogenous technical change framework to discuss it. The second presents a methodology for defining static production and utility functions whose coefficients vary in consistency with energy systems information at a given time horizon. A third section compares the numerical results of this methodology to that of two contrasted TD modeling approaches, to demonstrate its importance in the case of large policy-induced departures from reference projections.

1. Back to the crux of the matter: production functions

One almost perfect illustration of the ‘elephant and rabbit’ metaphor, in a very aggregate form of TD analysis, is MARKAL-MACRO (Hamilton *et al.*, 1992): MARKAL minimizes the discounted sum of energy costs while MACRO maximizes the discounted sum of the utility of consumption. The link between the two models is made through MACRO’s CES production function of its unique consumption good, which trades off a composite factor KL (aggregated through a Cobb-Douglas function) and MARKAL’s 23 energy services to households and firms, while energy costs are subtracted from total output. However, the CES coefficients are constant whatever the time period and the stringency of constraints on the energy system—which amounts to assuming constancy of the macroeconomic growth engine.

Less aggregated models proceed in the same way: Böhringer (1998) demonstrates that substituting six engineering-based Leontief descriptions of electricity generation to a single CES approximation significantly impacts policy analysis, but he does so with a constant capital stock and unchanged production functions of non-energy goods. McFarland *et al.* (2004) also focus on electricity generation, stressing that constant substitution elasticities entail the risk of violating the necessary limits to the performance of a technology at a given point in time—together with, ultimately, thermodynamic laws. They develop a carefully crafted nesting structure of inputs to electricity production, but again do not change the other production or utility functions.

A first issue overlooked by these endeavors is that BU analysis provides information under a *cæteris paribus clausa*: it considers the impacts of energy price (and non-price) signals on the energy system, but not on the rest of the economy. It thus ignores impacts on (i) the prices of non-energy goods (through the input-output structure); (ii) the labor costs (through the interplay between the purchasing power of wages and the functioning of the labor markets); (iii) the capital costs (through changes of the savings rate and in the cost of equipment); (iv) the exchange rates. Eventually, a carbon tax in a BU model is only nominal, while it leads to a different signal, in real terms, after general equilibrium adjustments. What ultimately matters is that the relationships between technical choices and relative prices after general equilibrium adjustments be consistent with those described by BU analysis. The challenge is to avoid describing a Chimera economy by hybridizing BU and TD models which do not depict the same world.

A second issue is the legitimacy of the elephant and rabbit metaphor, given the possible chain of impacts of drastic changes in the energy sector on the very structure of the economy. Various examples of such interplays can be given, such as the impact of abundant domestic resources on the structure of the US steel industry if compared with Europe and Japan (Wright, 1990), or the consequences of the choice of nuclear energy, and the following electrification of industrial processes, on the French industrial structure in the seventies and eighties (Hourcade and Puisseux, 1986).

Capturing the modifications to the macroeconomic growth engine that might be induced by drastic changes in the energy sector is obviously impossible keeping constant households’ utility functions, autonomous energy efficiency indexes (AEEI)⁹¹ and the substitution between capital, labor and non-energy intermediate consumption in non-energy sectors. Understanding the underlying methodological issues demands a brief theoretical detour.

Since Berndt and Wood (1975) and Jorgenson (*e.g.* Jorgenson and Fraumeni, 1981), KLE or KLEM production functions are assumed to mimic the choices of techniques and the technical constraints impinging upon an economy. But, from the outset, an ambiguity pervades the use of this way of expanding to energy and other intermediary inputs the method employed by Solow in his growth model, *i.e.* the calibration of a hypothetical production function on observed cost shares, interpreted as an economic equilibrium. Solow himself warned (1988, p.313) that “this ‘wrinkle’ is acceptable only at an aggregate level (for specific purposes) and implies that

⁹¹ AEEI indexes account for all the indirect sources of decoupling between energy and output; these sources (R&D, energy efficiency standards, structural changes, etc.) cannot but be impacted by large-scale shifts in energy trends.

we should be cautious about the interpretation of the macroeconomic production functions as referring to a specific technical content”.

To neglect this warning leads to mix up the economic productivity of investments and the technical efficiency of equipment, a confusion that fueled the Cambridge controversy from the fifties up to the early seventies.⁹² Nonetheless, the inclination to interpret production functions as sets of actual techniques gained more ground as computational progress allowed for more disaggregated models. Whatever the level of disaggregation, though, these functions remain calibrated on cost-share data: they convert money-metric information into physical terms through Shephard’s lemma, which holds only if, at each point in time, economic data can be interpreted as the optimal response to a price vector.⁹³ Frondel and Schmidt (2002), analyzing several hundreds of econometric estimates of capital-energy substitution elasticities, emphasize the constraints due to the mathematical properties of the functional forms. They conclude that “inferences obtained from previous empirical analyses appear to be largely an artifact of cost shares and have little to do with statistical inference about technology relationships” (Frondel and Schmidt, 2002, p.72).

Even if one does not derive dramatic conclusions from such a pessimistic assessment, the point remains that translating cost shares into technical constraints is valid only at the neighborhood of an optimal equilibrium— which makes it difficult to address debates about the efficiency-gap (Jaffe and Stavins, 1994), hysteresis effects leading to multiple technological equilibria (Gritsevskiy and Nakicenovic, 2002), or any large departure from reference trends.

This discussion could be argued to be purely rhetorical, either because the distortions induced by modeling artifacts are not significant, or because there is no conceivable better alternative. The question is: if a given partial equilibrium analysis contains some piece of truth, in what way should and could it be used to inform our vision of the corresponding growth engines? Economists addressing this question are forced to accept their predictions to be conditional upon useful but often controversial engineering-based prognoses about future energy systems. Their contribution is to reveal with what plausible assumptions about the future economy these prognoses are compatible. Fulfilling this ambition implies two prerequisites.

The first is to have a description of the economy explicitly in prices and in physical quantities, which does not rely on functional forms with constant coefficients whatever the level of departure from reference trends. It is indeed unlikely that the elasticity of substitution between capital, labor and energy at a \$10/tC carbon price remains valid at a \$500/tC carbon price. This is true for any specific industry, but also in aggregate production and demand functions because structural transformations of the economy induced by energy policies at some fixed horizon also become difficult when substitution possibilities vanish on both the demand and supply side.

The second is to work under an endogenous growth framework. First, this is consistent with postulating that induced technical change in the energy field modifies the growth engine. Second, it allows for making a clear distinction between substitutions along a given production frontier at a given point in time, and the induction of new frontiers by various historical sequences of relative prices.⁹⁴ As noted by Ruttan (2002), this traces back to Hicks: “A change in the relative prices of the factors of production 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” (Hicks, 1932, p. 124).

⁹² This controversy was about the ‘re-switching’ problem in technical choices and was conducted in the most influential economic journals. Even though it started from a question about the very status of capital in growth theory, it polarized, perhaps mistakenly, around distributional issues, i.e. the remuneration of capital and labor (Cohen and Harcourt, 2003).

⁹³ Another caveat by Solow was: “[...] total-factor-productivity calculations require not only that market prices can serve as a rough-and-ready approximation of marginal products, but that aggregation does not hopelessly distort these relationships [...] over-interpretation is the endemic econometric vice.” (Solow, 1988, p.314)

⁹⁴ An improvement over the paradox of empirical work on the static production function—which, to be econometrically valid, are forced to calibrate over data covering several decades that cannot have failed to induce quite different production frontiers.

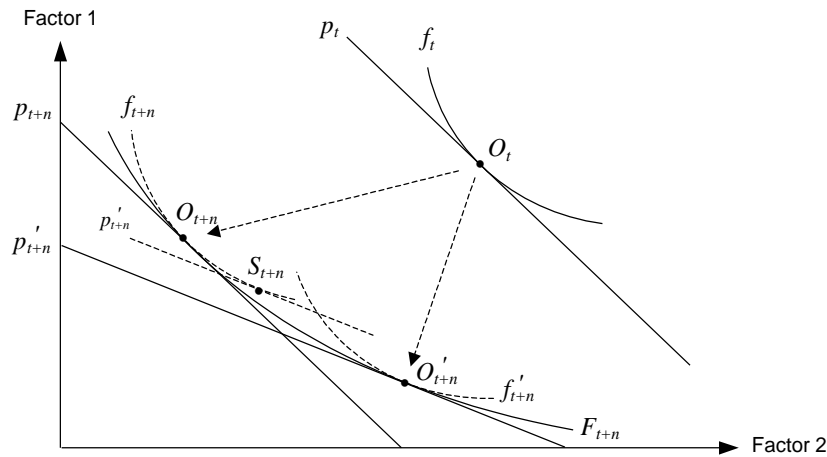


Figure 12 Induced Technical Change as a Dynamic Production Frontier

Figure 12, adapted from Ruttan (2002), illustrates this point: it pictures production techniques as combinations of two factors along unitary isoquants. The isoquant f_t describes the available set of factor combinations at time t , from which the relative prices p_t imply selecting O_t . At time $t+n$, assuming some technical change and constant relative prices $p_{t+n} = p_t$, the optimal factor combination will have shifted from O_t to O_{t+n} , on a new f_{t+n} isoquant. Now, if the historical sequence of relative prices leads to p'_{t+n} instead, the economy should generate f'_{t+n} rather than f_{t+n} , and the new optimum would be O'_{t+n} . Exploring from date t the range of possible $t+n$ relative prices reveals what Ahmad (1966) called an “innovation-possibility curve”, *i.e.* an envelope F_{t+n} of the possible production functions f_{t+n} . At $t+n$, along a given envelope the functions f mutually exclude one another: if the reference scenario leads to f_{t+n} , an instantaneous shock in relative prices will shift the choice of technique to S_{t+n} rather than O'_{t+n} , since f'_{t+n} is no longer an available option.

2. Methodology for a structured dialogue

The methodology proposed hereafter applies the notion of an innovation possibility curve to carbon pricing: over the long run, any sequence of price signals induces a specific production frontier, together with a specific households’ energy demand function through changes in end-use appliances or equipment. It builds on BU information to conduct a comparative-static analysis of two equilibria, situated at some $t+n$ horizon, on two stabilized growth pathways generated by two different sequences of carbon price signals between t and $t+n$. The underlying vision of technological dynamics is that each investment vintage embodies technical change⁹⁵ and that the static production and demand functions at a given date result from past vintages. This echoes Thomsen’s recommendation to use a short run function stripped down from a long run cost function (Thomsen, 2000).

The comparative-static analysis starts with ensuring that BU and TD no-policy projections portray the same world at the selected $t+n$ horizon. This implies constructing the value and quantity macroeconomic balances consistent with the baseline BU projection of the energy sector. Then, the revelation of the time $t+n$ envelopes of production and demand functions consistent with BU expertise is conducted for a range of carbon prices wide enough to capture the asymptotic behavior of energy systems. This revelation is made possible by interpreting the results of BU policy simulations as the partial price derivatives of the unknown static production and demand functions

⁹⁵ The ‘technical’ change in an aggregate description of production obviously incorporates changes in the composition of the output; capital turnover in part governs the pace of this transformation.

generated by the corresponding sequence of price signals. The last step is to integrate the effect of energy supply and demand capital requirements on total factor productivity.

2.1. Value and quantity balances in the no-policy projection

Any BU projection of an energy baseline is necessarily consistent with some GDP level and energy prices. It also contains other information that can be used to define some constraints impinging upon the underlying no-policy economy, but part of the necessary information is missing to develop a consistent picture of this economy.

Let us start from the price/quantity decomposition of national accounts of a global economy with two goods, energy E and the remainder of economic activity Q. In Table 8, E and Q (in rows) are used in intermediate consumption (IC) households consumption (H) and Gross Fixed Capital Formation (GFCF, nil for energy); the inputs for the production of E and Q (in columns) include, in addition to IC, labor (L) and capital (K) expenditures.⁹⁶

IC					H	GFCF	'Uses'
		Q	E	T			
Q		$p_Q \alpha_{QQ} Q$	$p_Q \alpha_{QE} E$	Σ	$p_Q Q_c$	$p_Q Q_k$	$p_Q Q$
E		$p_E \alpha_{EQ} Q$	$p_E \alpha_{EE} E$	Σ	$p_E E_c$	-	$p_E E$
T		Σ	Σ	Σ (IC)	Σ	Σ	Σ
VA	L	$w l_Q Q$	$w l_E E$	Σ			
	K	$r k_Q Q$	$r k_E E$	Σ			
	T	Σ	Σ	Σ (GDP)			
'Resources'		$p_Q Q$	$p_E E$	Σ			

Table 8 Price/Quantity decomposition of an aggregated accounting table

Subject to harmonization between the BU and macroeconomic accounting of energy and financial flows, BU analysis provides explicit information on:

- Total energy production (E),
- The energy intensity of energy production (α_{EE}),
- Households' aggregate energy consumption (E_c),
- The average price of energy p_E .⁹⁷

Adopting the composite good as *numéraire*, and setting its price to 1,⁹⁸ a vector of 12 unknowns ($w, r, \alpha_{QQ}, \alpha_{EQ}, \alpha_{QE}, l_Q, l_E, k_Q, k_E, Q, Q_c, Q_k$) remains to represent an economy compatible with the no-policy BU projection. The number of unknowns can be reduced by imposing the GDP and intermediate energy consumption $\alpha_{EQ} Q$ of the BU projection. Flow balances provide four additional constraints (one per good in both monetary and physical terms). Six unknowns thus remain, not provided by BU data.

To use Solow's "wrinkle" solves this problem by assuming that: (i) the production of *e.g.* Q is a function f_Q , valid between t and $t+n$, of real consumption of good Q, E, labor ($l_Q Q$) and capital ($k_Q Q$), and of a given autonomous technical change; (ii) these factors are substitutable, and their equilibrium demands determined by minimizing

⁹⁶ For clarity's sake, our presentation does not detail the treatment of taxes and the correlated public expenditures. Section III will describe which assumptions were made in this regard in the numerical runs.

⁹⁷ p_E is obviously differentiated among energy uses because of taxes and subsidies. We do not emphasize these differences here.

⁹⁸ This is equivalent to using the monetary values as the quantity measure of good Q, without loss of generality.

the production costs for the price vector (p_Q, p_E, w, r) . Under these assumptions, calibrating production and utility functions on the national accounts at some base year t^{99} and on the energy systems at t and $t+n$ suffices to recompose $t+n$ national accounts consistent with the BU no-policy projection.¹⁰⁰

However, this results in a stand-alone tool, which simultaneously solves the no-policy economy, and its reactions to energy policies without further reference to BU expertise. This tool thus ignores how (i) the $t+n$ partial price derivatives estimated by BU analysis vary with the sequence of price vectors between t and $t+n$, and (ii) changes in f_E , the production function of energy may impact f_Q . However, this difficulty can be turned into an advantage: it justifies revealing sequentially the BU-compatible no-policy TD projection, and the behavioral equations capturing the responses at $t+n$ to policy signals between t and $t+n$.

Returning to the six remaining unknowns above, two can be found by setting labor and capital prices to 1. Moreover, aggregate labor and capital costs of energy production can be derived from the comparison of fixed and variable costs usually incorporated in BU models. Finally, two more constraints can be econometrically set or chosen by judgment (subject to appropriate sensitivity tests): the savings rate and the share of labor expenditures in the value-added of the composite good. It now remains to define for this baseline economy some behavioral equations compatible with the BU policy simulations.

2.2. Envelope of the energy production functions

For the sake of simplicity, we consider that policies only alter the energy and capital intensities of the energy good, and we keep constant its labor and material intensities between the no-policy and policy cases.¹⁰¹ BU analyses generally provide sets of matching relative variations in factor intensities (α_{EE}, k_E) and prices (p_E, r) over a range of carbon prices—implicitly assuming all non-energy BU prices constant, including r . Relative variations of α_{EE} and p_E are directly computed, while those of k_E can be equated to those of the capital stock per physical unit of energy produced. The resulting data set is used to calibrate α_{EE} and k_E as functions of the ratio of their prices, through the least-square adjustment of an arctangent specification (selected to allow the reproduction of any asymptote to substitution possibilities).

A non-negligible difficulty regards the consistency between capital costs as they appear in national accounts, and the investment in energy production as reported by energy models. In Table 8, $r k_E E$ is a remainder of value-added (VA), once labor costs are subtracted, that encompasses not only equipment expenditures, but elements as heterogeneous as interest payments, rents (on land, water, mineral and fossil resources) and a mark-up depending on market characteristics. The credibility of a hybridizing exercise using it as an index of productive equipment is questionable, all the more so as capital costs in energy production are key in policy assessments. This difficulty can be surmounted by distinguishing, in the non-labor VA, genuine equipment expenditures,

⁹⁹ Starting from national accounts, a price-quantity decomposition supporting this calibration is conventionally made setting $p_Q = p_E = w = 1$ and deriving the price of capital and the capital contents k_Q and k_E from a measure of $p_Q K$ the value of the stock of productive capital, letting $K = k_Q Q + k_E E$.

¹⁰⁰ With the conventional production functions, the system even needs additional degrees of freedom in the form of exogenous trends of biased technical change.

¹⁰¹ The non-energy variable costs of E reported by BU expertise provide an estimate of the sum of material and labor costs. The labor content of energy production is low and its variation as a function of policy signals can be neglected at a macroeconomic level. Changes in the non-energy intermediate consumption embodied in new techniques may be more significant; should such information be delivered by BU analysis (it is not in the current state of the art), it could be easily inserted in the proposed methodology.

calibrated on total GFCF data net of investment in housing,^{102,103} and the corresponding interest payments, estimated on a limited set of exogenous assumptions: an average capital lifespan and a real interest rate.¹⁰⁴

2.3. Envelope of the composite good production functions

Contrary to the case of energy production, the labor content of composite production has a paramount influence on cost assessment. A set of functions f_Q must thus be revealed, to produce the labor content, and as a matter of fact the capital content, necessary for the calibration of the envelope of these functions. This is done based on the following assumptions:

- All policy-induced time $t+n$ economies are on a steady equilibrium path, guaranteeing to each f_Q the first-order conditions of relative marginal productivities equating relative prices (for any two production factors).
- For a given output and around a given energy price p_E , the price elasticity of energy demand is derived from BU analysis considering a marginal increase of p_E .

For a selected functional form, there is a single f_Q making these assumptions compatible with the no-policy price and factor-demand vectors. The same mathematical property can be applied successively to every pair of equilibria separated by a marginal increase of the energy price.

Let us assume, given their wide usage in the E3 modeling community,¹⁰⁵ that CES functions of capital K_Q , labor L_Q and energy E_Q approximate each real f_Q at the neighborhood of the corresponding equilibrium. A unique CES of the no-policy projection, CES_0 , can be calibrated imposing (i) the linear homogeneity condition, (ii) the first-order conditions at the no-policy equilibrium and (iii) the energy demand E_{Q1} resulting from a marginally higher energy price under constant other prices and output, as computed by BU expertise. CES_0 then provides the optimal K_{Q1} and L_{Q1} prevailing under the new price regime. The same method is applied using the newly defined (K_{Q1}, L_{Q1}, E_{Q1}) equilibrium, and the impact of a further marginal energy price increase in the BU analysis. This allows the successive identification of equilibrium (K_i, L_i) compatible with the BU information on (p_{Ei}, E_i) couples over the whole spectrum of analysis.

Figure 13 illustrates this method in a two-dimensional E-K space: CES_0 is defined by E_{Q0}, K_{Q0} , the no-policy price vector p_0 and a BU-derived (p_1, E_{Q1}) couple; it defines the optimal K_{Q1} under p_1 ; CES_1 is then in turn defined by E_{Q1}, K_{Q1}, p_1 , and a BU-derived (p_2, E_{Q2}) couple; etc.

¹⁰² Note that in the conventional price and quantity decomposition, GFCF data is disconnected from the capital intensities of production. The link exists in dynamic analysis through the equation of capital stock formation; it is lacking in many static analyses, where the capital stock K is usually kept constant through ad hoc adjustments of r .

¹⁰³ Government investment is not a problem here: in national accounts, it appears as the investment of a sector exclusively devoted to the production of one aggregate public good—the only good consumed by government. In Table 8's aggregated framework, government investment is thus part of $r k_Q Q$.

¹⁰⁴ Interest payments are a percentage of equipment expenditures, easily computed by setting an average lifespan of capital, and a constant rate of growth of equipment expenditures together with a constant real interest rate over this lifespan (the two rates are assumed equal on a stabilized growth path).

¹⁰⁵ E.g. in models as G-Cubed, MS-MRT, SGM, EPPA. See respectively Mc Kibbin and Wilcoxon (1995), Bernstein et al. (1999), Fisher-Vanden et al. (1993), Babiker et al. (2001).

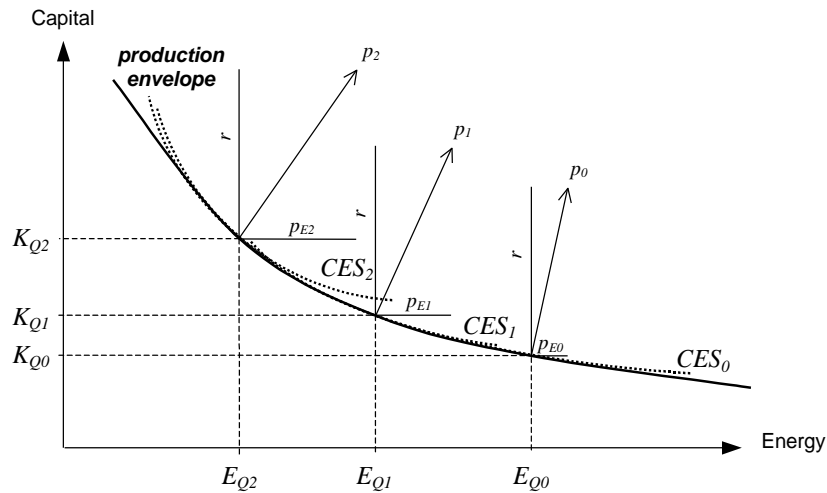


Figure 13 Production envelope of energy and capital in the composite production

The resulting set of prices (r, w, p_{Ei}) and factor demands (K_i, L_i, E_i) is used to adjust the predefined functional forms of conditional demands of the three factors. This is done at the unitary level of capital, labor and energy intensities, as the substitution elasticities revealed are assumed to hold whatever the eventual production level. Note that, even though a CES function is assumed around each equilibrium, the resulting implicit envelope has no reason to exhibit a constant elasticity of substitution, unless in the implausible case of a constant price elasticity of E_Q over the range of policies explored.

2.4. Households' savings and envelope of demand functions

The behavior of households at $t+n$ is composed of a savings decision and a trade-off between consumption of energy E_c and Q_c , subject to the income constraint. We assume a constant savings rate applied to the VA net of equipment expenditures. This means a constant ratio of households' expenditures on housing investment—while productive investment matches the equipment expenditure consistent with the production levels of E and Q.

Regarding the energy-composite trade-off, BU analyses do not systematically report on the proper arguments of utility functions, i.e. energy services (heating, lighting, passenger-kilometers, etc.), whose variations may differ from those of energy consumptions *per se* thanks to efficiency gains. Our methodology consequently focuses on the Marshallian demand functions for E_c , without revealing the underlying set of utility functions.

An envelope of the Marshallian energy demands is calibrated on BU information about households' energy consumptions. This information is first translated in terms of the share of households expenditures devoted to energy, assuming that BU analyses implicitly consider total household expenditures constant;¹⁰⁶ the envelope function is then least-square adjusted to link variations of this share to shifts of the energy and composite price ratio—again, given the constancy of non-energy prices in the BU analysis.

¹⁰⁶ Note that the assumptions of constant expenditures, constant composite consumption, and constant composite price, are incompatible with variations of the energy expenditures. Given necessarily constant non-energy prices, we prefer to consider a constant income (more compatible with the fixed GDP assumption) rather than a constant consumption of the composite good.

2.5. Feedback on Total Factor Productivity

The impact of carbon constraints on total factor productivity in the composite sector¹⁰⁷ is derived from a comparative-static analysis of an endogenous growth mechanism; it consists in modifying all factor intensities by a Hicks-neutral technical progress coefficient function of cumulated investments. The assumption that all $t+n$ projections are on a steady equilibrium path justifies the use of variations of the $t+n$ equipment expenditures as a proxy of those of cumulated investment.¹⁰⁸

Under this specification, the crowding-out effect of mobilizing more resources in the production and consumption of energy is not accounted for through the allocation of a fixed capital stock or GFCF. Instead, firms finance their investments (equipment expenditures augmented by interest payments) under the double constraint of market balances—investment goods are produced by the composite sector—and of the ability of households' purchasing power to sustain the resulting price increases. Cumulated investments and the induced productivity of the composite sector consequently align.

3. Why revealing the innovation-possibility curves matters

The following numerical experiments consist in the comparative-static assessment of a wide range of carbon taxes on a global two-sector economy in 2030.¹⁰⁹ Given the purpose of this paper, they do not envisage various recycling schemes for tax revenues, which would necessitate a discussion of issues such as the functioning of labor markets. Instead, they assume full employment and lump-sum recycling, with constant government consumption in real terms.

A first set of simulations uses energy systems information from 60 policy runs by the POLES model (Criqui, 2001), considering a price signal linearly increasing from 0 in the year 2000 to between 37 and 2,241 year-2000 euros per ton of C (hereafter €/tC) in 2030.¹¹⁰ A second set uses alternative data (ALTER) on energy efficiency, more in line than POLES' econometric treatment of energy demands with the usual outcome of a fully BU analysis: close-to-negative cost options for very low price-signals and an asymptotic saturation of policy impacts at the farther tail of the price spectrum.

POLES and ALTER data are used in general equilibrium analyses resorting to either section II's envelope methodology (the IMACLIM-S model) or a set of CES functions calibrated by minimizing the least-sum-of-squares of the differences between the BU data and their respective Marshallian demands. The experiment is enriched in the CES case by treating capital as either (i) a fixed endowment independent from macroeconomic conditions (following *e.g.* Böhringer, 1998)—hereafter the 'CES Kfix' assumption, or (ii) a variable stock of physical equipment produced by the composite sector (see 2.2 above) and endogenously affected by the constraints on the energy systems and the changes in the growth pathway—hereafter the 'CES Kvar' assumption. Table 9 synthesizes the differences between these three approaches.

¹⁰⁷ Because energy models increasingly account for the impacts of learning-by-doing and R&D efforts on the costs of energy technologies, the envelope of energy production functions is assumed to embody such effects.

¹⁰⁸ The specification is calibrated so that a doubling of cumulated investment triggers a 20% cost decrease, extrapolating 1978 to 2000 time-series for France and OECD. Further econometrics are needed to extend it to a global estimate, but sensitivity analyses demonstrate that variations of the elasticity of TFP to real investment do not qualitatively affect this paper's conclusions.

¹⁰⁹ The 2030 projection is consistent with the no-policy projection of the POLES model following section II.1 above. The annual global GDP growth rate used by POLES is a conservative 1.73% resulting from detailed projections for 140 countries by a Mankiw, Romer and Weil (1992) model (Kousnetzoff, 2001).

¹¹⁰ A linear tax sequence is a plausible policy decision that limits the risk of hysteresis effects or transitional shocks, and is consistent with the assumption of an economy on a balanced growth path.

		IMACLIM-S	CES Kvar	CES Kfix
Capital Markets	Interpretation of VA net of L costs	Sum of equipment expenditures, interest payments and mark-up (see 2.2 above)		Capital services
	K stock	Implicit, variable (fixed proportion of annual productive investment)		Explicit, fixed (endowment)
	K price	$p_{Qk} (1+\tau)$, price of composite good for GFCF corrected from interest rate variations (interest rate assumed equal to real growth)		r , market-clearing price (varying interest rate)
	Investment	Explicit, variable (fixed share of household revenues + equipment exp. of the two sectors + household abatement investment)		Implicit
Production	Capital intensity of Q, k_Q	$f(p_{Qk} (1+\tau), p_{EQ}, p_{LQ})$	CES ($p_{Qk} (1+\tau), p_{EQ}, p_{LQ}$)	CES (r, p_{EQ}, p_{LQ})
	Energy intensity of Q, α_{EQ}	$f(p_{Qk} (1+\tau), p_{EQ}, p_{LQ})$		
	Labor intensity of Q, l_Q	$f(p_{Qk} (1+\tau), p_{EQ}, p_{LQ})$		
	Capital intensity of E, k_E	$f(p_{Qk} (1+\tau), p_{EE})$	CES ($p_{Qk} (1+\tau), p_{EE}$)	CES (r, p_{EE})
	Energy intensity of E, α_{EE}	$f(p_{Qk} (1+\tau), p_{EE})$		
Consumption	Household trade-off between composite Q_c and energy E_c	$f(p_{Qc}, p_{Ec})$	CES (p_{Qc}, p_{Ec})	

Table 9 Main assumptions backing three comparative-static analyses

3.1. Ex ante differences in the calibration of production and demand functions

The ability of each specification to reproduce POLES and ALTER data is assessed by comparing, for an increasing carbon price and all other prices constant, the original data to its envelope- or CES-computed counterpart. IMACLIM-S envelopes fit unsurprisingly well (they are designed to do so), while CES functions misadjust in a proportion that varies with both the sector and the energy data considered. The question is the degree of this maladjustment, and to what extent it has a significant impact on cost assessments.

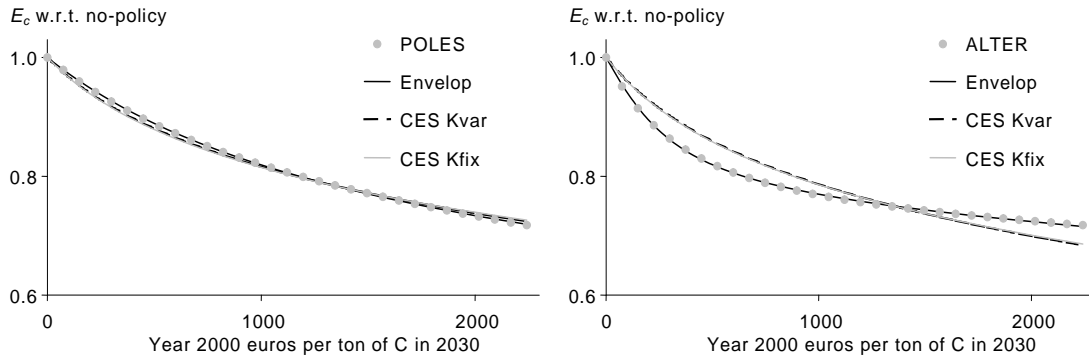


Figure 14 Households' consumption data and calibration

Starting with households' demand (Figure 14), POLES results appear 'CES-compatible', while ALTER assumptions are not: for a constant income level, the two ALTER-calibrated CES demand functions underestimate by more than 20% the decrease of households energy consumption triggered by a carbon price between 0 and 550€/tC. Conversely, for prices higher than 1000€/tC the CES allows for a continuing decrease in consumption that contradicts the saturation effects of ALTER data.

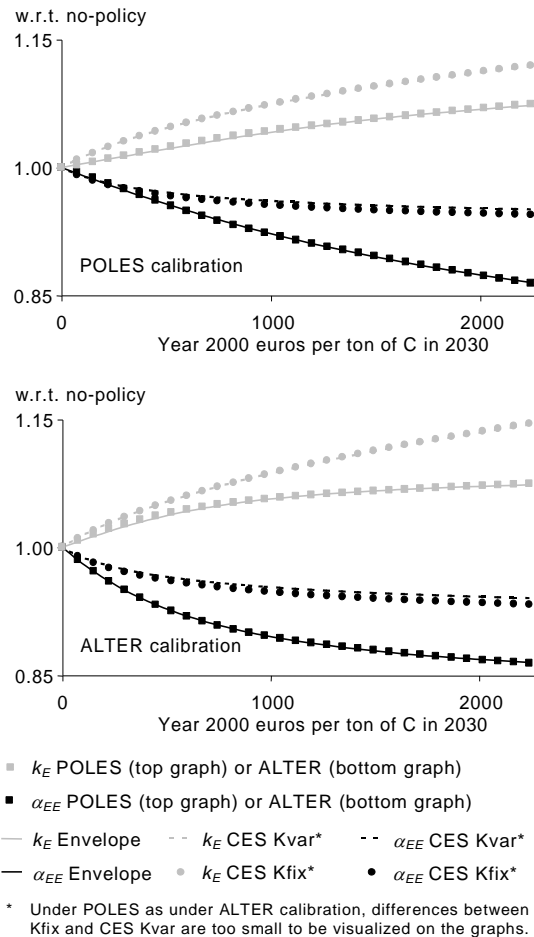


Figure 15 Energy production data and calibration

Calibrating the energy sector production proves even more difficult, as not only energy consumptions but also capital intensities are fitted on energy systems data. This causes discrepancies as significant under POLES calibration as under ALTER calibration (Figure 15): the increase of k_E is overestimated by more than 30% on the

whole price range explored, and, simultaneously the fall of α_{EE} underestimated by more than 20% beyond 370€/tC, 30% beyond 450€/tC.

Turning to composite production, all three specifications reproduce POLES' energy intensity (α_{EQ}) variations remarkably well (Figure 16), but difficulties appear again when calibrating on ALTER: the two CES underestimate α_{EQ} decreases by more than 40% up to 215€/tC, by more than 20% up to 600€/tC and cannot render saturation hypotheses for the higher price signals. Similarly to households' demand, the CES specifications thus offer an acceptable approximation of those of the energy systems data which do not exhibit strong convexities in the technical responses to carbon constraints.

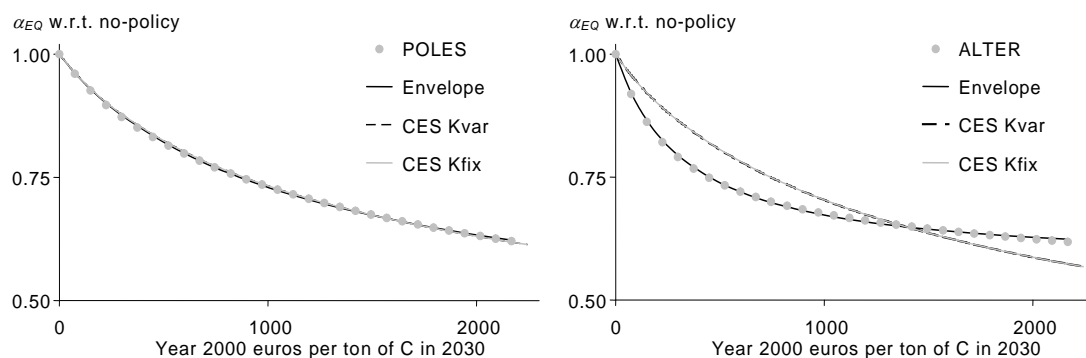


Figure 16 Energy intensity of composite production: data and calibration

Let us now compare the elasticities of the three specifications. Regarding the CES, Table 10 logically shows significantly higher substitution elasticities of production and utility functions if calibrated on ALTER. It also indicates that the assumption on capital does not impact the resulting elasticities: identical functional forms calibrated on similar data produce closely comparable results.

		Households' utility	Energy production	Composite production
Under POLES	CES Kvar	0.14	0.09	0.43
	CES Kfix	0.15	0.10	0.42
Under ALTER	CES Kvar	0.18	0.11	0.49
	CES Kfix	0.19	0.12	0.49

Table 10 Constant elasticities resulting from calibration

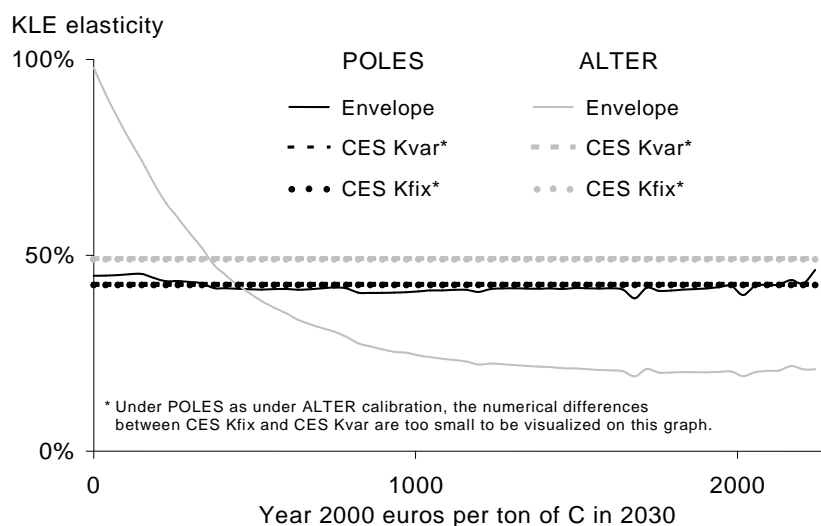


Figure 17 KLE point substitution elasticities in the composite production

Turning to the envelope, Figure 17 reports the varying point elasticities of substitution of composite production¹¹¹ across the range of carbon prices explored. While it varies closely around its constant CES counterparts with POLES data, it dramatically diverges at both ends of the carbon price range explored when calibrated on ALTER.

3.2. Ex post differences in general equilibrium cost assessment

The first metric to assess the cost of various carbon constraints is the marginal abatement cost (MAC), indicative of the burden to be passed on to the consumer. The MACs estimated with POLES data by IMACLIM-S and both CES approaches do not significantly differ for abatement targets up to a 20% emissions decrease (Figure 18). Beyond that level, the CES Kfix estimate diverges: for a 40% emissions decrease it is 13 to 14% higher than that of IMACLIM-S or CES Kvar. Since CES Kfix and Kvar share very similar elasticities, this discrepancy must originate in a contrasted evolution of the price vector, caused by a differentiated treatment of capital: in CES Kfix, the capital endowment becomes relatively abundant as economic output declines; consequently, although it faces rising capital intensities, its market-clearing price does not increase as much as the price of equipments does in IMACLIM-S or CES Kvar, where it inflates with p_Q . For a given marginal price, this leads to lower energy price increases and a lesser impact on emissions.

Calibrating on ALTER exacerbates the discrepancies between IMACLIM and the CES: up to a 34% emissions decrease, both CES estimates are 40% higher than the IMACLIM-S MAC; for higher abatement levels the gap narrows and dramatically reverses beyond 45%. This result is fully explained by the maladjustments of the CES functions for intermediate and final energy consumption (Figure 14, Figure 16) and by their inability to reproduce large low-cost abatement potentials and saturations of technical change.

¹¹¹ I.e. the substitution elasticities of the series of CES forming the envelope (see section 2.3).

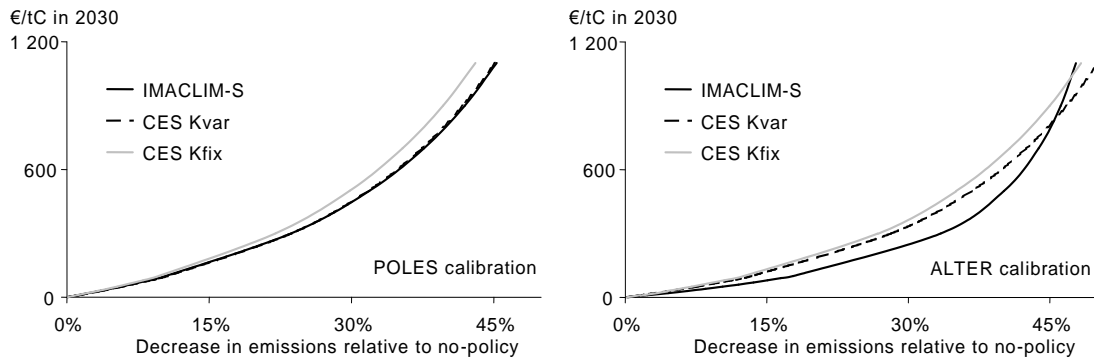


Figure 18 MAC curves under POLES and ALTER calibration

Turning to macroeconomic costs, POLES’s absence of information on energy efficiency in households’ consumption and the consecutive lack of an explicit utility function prompts the joint use of two indicators: (i) households’ composite consumption Q_c (Figure 19) as a lower bound of welfare losses, assuming stable energy services thanks to efficiency gains fully compensating the decrease in energy consumption; and (ii) real GDP (Figure 20) as an upper bound, under the opposite assumption of nil efficiency gains.

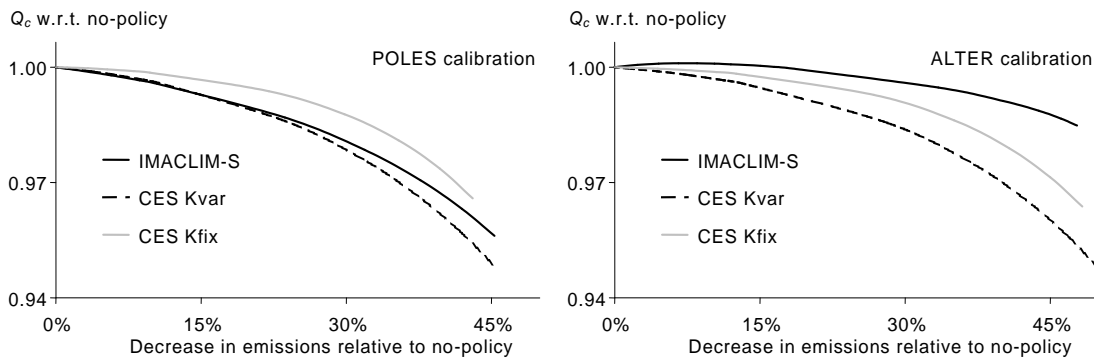


Figure 19 Households’ composite consumption under POLES and ALTER calibration

A first result is that CES Kfix is significantly more optimistic than CES Kvar, whatever the calibration data or the cost indicator considered. This is again explained by the availability, in CES Kfix, of an exogenous capital endowment causing lower price increases. The fixed capital endowment assumption, which is not fully consistent with an endogenous technical change framework, is thus proven to introduce a significant bias in cost assessments. Note that the similarity of IMACLIM-S and CES Kfix estimates for real GDP losses under ALTER assumptions is fortuitous: their households’ consumption diverge significantly because households’ revenues from capital increase far less in CES Kfix than in IMACLIM-S; but CES Kfix happens to compensate this, in terms of GDP, by higher activity in the energy sector, sustained by its overestimation of energy intensity α_{EE} .

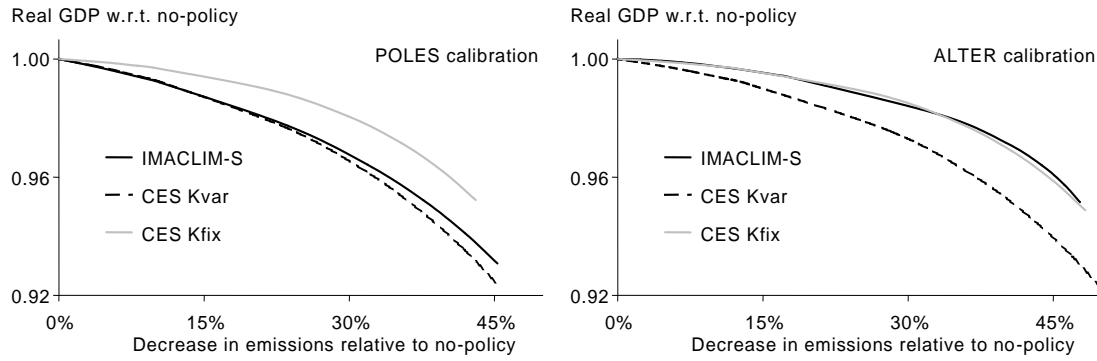


Figure 20 Real GDP variations under POLES and ALTER calibration

CES Kfix aside, this leaves CES Kvar and IMACLIM-S, with their identical treatment of capital markets, to be compared. There is a strong contrast between their resemblance under POLES calibration and their difference under ALTER calibration.

Under POLES calibration, comparable behavioral functions (see 3.1) in an identical macroeconomic framework logically result in comparable cost estimates. Still, aggregate costs are slightly more differentiated than MACs (Figure 18): CES Kvar computes Q_c losses 7% higher than IMACLIM-S for a 25% target, 10% higher for a 30% target. This increasing discrepancy comes from the biased calibration of energy production in CES Kvar: for the same carbon price, CES Kvar estimates higher energy price increases (Figure 15), with a stronger impact on households' purchasing power and general economic activity. Note that this bias remains hidden in the MACs: in terms of abatement, the overestimated reduction of economic activity is roughly compensated by the underestimation of α_{EE} decreases.

Under ALTER calibration, the divergences are markedly greater, with significantly lower costs for IMACLIM-S (at the minimum, twice as low as CES estimates). This is unsurprising for the lower targets since IMACLIM-S reproduces ALTER's extensive low-cost potentials better. These potentials help limit production price increases and maintain the purchasing power of households, which produces a negligible increase of Q_c even up to a 10% cut in emissions. For the tightest targets, the more optimistic results of IMACLIM-S are intriguing, as they apparently contradict its MAC becoming more pessimistic than CES Kvar's beyond a 45% target.

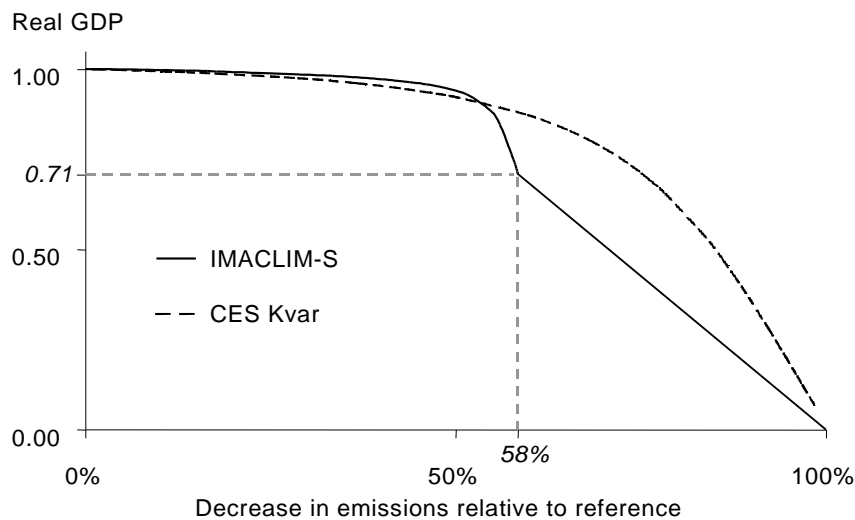


Figure 21 Limit behavior of IMACLIM-S and CES Kvar under ALTER calibration

This seeming contradiction can be understood by considering the limit behavior of IMACLIM-S and CES Kvar under ALTER calibration (Figure 21). The key driver of macroeconomic costs is ultimately, under a full

employment hypothesis, the labor intensity of output. Under the envelope approach, the marginal rate of substitution between labor and energy dramatically increases between a 45% and a 55% emissions cut, but the average labor intensity still benefits from the lower costs of the below 45% abatements. Beyond 55% this benefit is exhausted and IMACLIM-S produces higher cost assessments than CES Kvar. At a 58% target, all the ALTER technical asymptotes are saturated and it is impossible to abate more through higher carbon taxes; these have only a nominal impact (scalar multiplication of the price vector) without consequences for the demand and supply levels. The only way of further decreasing emissions is to abandon the full employment assumption and cut back economic activity, thereby reducing them in a linear proportion. Under a CES specification, the average labor intensity grows more slowly and triggers lower real GDP losses. The constant factor substitutability allows carbon emissions to continue decreasing through additional increases in labor intensity—or decreases in labor productivity. Under full employment of a constant labor endowment, this progressively drives real GDP to 0, but more slowly than with the envelope.

Conclusion

The numerical experiments conducted in this paper argue in favor of revisiting the ‘Elephant and Rabbit stew’ metaphor. We demonstrate that the answer to Hogan and Manne’s ‘taste-of-the-stew’ question is conditional upon (i) the information conveyed by BU analysis of the energy sector, and (ii) as they had duly remarked, the magnitude of the departure from reference scenarios required by the policy objectives explored.

A TD framework combining behavioral functions with constant elasticities of substitution and exogenous technical change will satisfactorily approximate any BU analysis not revealing large convexities or singularities in the energy supply and demand—the bias introduced will be negligible for low to moderate departures from the baseline scenarios, and remain tolerable for larger ones. However, the same TD framework based on constant elasticities and exogenous technical change will introduce a significant bias in cost assessment, at both ends of the range of policy objectives explored, when calibrated on a BU analysis revealing large flexibilities for low policy targets and saturation effects for higher ones.

That the non-energy supply and demand functions prevailing at some static horizon should evolve along with the energy sector is fully demonstrated by analyzing energy-economy interactions in case of asymptotes to the adaptation potentials. The potentially large substitution possibilities prevailing in a no-policy economy progressively vanish when approaching absolute asymptotes, ultimately consistent with Leontief functions only.

Developing hybridizing methodologies that admit non-constant macro-economic supply and demand functions is all the more important as the analysis goes beyond the aggregate description of the non-energy economy retained in this paper. If indeed saturation effects occur on a single coefficient of a more disaggregated input-output matrix (such as transportation requirements, see e.g. Crassous *et al.*, 2006), this coefficient will operate as a multiplier of policy costs even though, in the reference scenario, the corresponding value share is small.

We do not pretend that the methodology developed in this paper is the only possible one. At the very least it should probably be adapted to fit the specifics of each existing model. Still, we venture to say that its fundamental principles as laid down in section 1 should be respected.

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Annex 2

Carbon tax and equity The importance of policy design

Carbon tax and equity

The importance of policy design

Published as

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Abstract

This research aims at clearing up misunderstandings about the distributive impacts of carbon taxes, which proved to be a decisive obstacle to their further consideration in public debates. It highlights the gap between partial equilibrium analyses, which are close to the agents' perception of the costs of taxation, and general equilibrium analyses, which better capture its ultimate consequences. It shows that the real impact on households' income distribution is not mechanically determined by the initial energy budgets and their flexibilities but also depends upon the way tax revenues are recycled, and upon the general equilibrium consequences of the reform thus defined. The comparison of three tax-recycling schemes, modelled in a general equilibrium framework applied to 2004 France, demonstrates the existence of trade-offs between aggregate impacts on GDP and employment, the consumption of the low-income classes, and a neutralisation of distributive impacts. Two more recycling schemes allow outlining a space for a compromise between the equity and efficiency criteria.

Keywords

Carbon tax, income distribution, equity-efficiency dilemma.

JEL classification codes

H23, Q52.

Introduction

Consistently prescribed as an efficient tool to mitigate climate change (since at least Pearce, 1991), the idea of a carbon tax periodically shows up on public agendas in industrialised countries, to be adopted in some instances (Finland, 1990; Sweden, 1991; Italy and Germany, 1999; Switzerland, 2008),¹¹² but to be rejected more often than not: failures of the French *Mission Interministérielle sur l'Effet de Serre* (1990), of the carbon-energy tax of the European Union (1992), of the BTU tax of the Clinton Administration (1993), of the 'ecotax' of the Jospin government in France again (1998), of the projects in Australia and New Zealand (Baranzini et al., 2000: 396), etc.

¹¹² The UK Road Fuel Duty Escalator (1993-1999) could be added to this list.

These failed attempts doubtlessly have specific historical reasons of their own. Still, they all seem to have faced a similar ‘refusal front’, based on two major arguments: that of competitiveness distortion, and that of a negative impact on the poorer households (Ekins, 1999). However well-grounded these fears, it is surprising to observe that they were systematically used to reject the carbon tax, rather than treated as surmountable obstacles that merely required careful consideration in its implementation.

In the wake of the *Grenelle de l’Environnement*, a nationwide consultation held over the last quarter of 2007, the carbon tax came back on the French political agenda. However, the volatility of oil prices and the ongoing economic crisis currently strengthen the threat it seems to pose to the poorer households, which hinders its political acceptability. This article is consequently devoted to the equity argument, with as main objective to avoid that the actual stakes of a carbon tax reform be blurred by the misconception that the agent paying the tax is necessarily the one bearing its ultimate cost. The gap between the direct and the ultimate cost can indeed be substantial, as will be proven in the case of France.

1. Perceived vs. real impacts: reasons for the gap

The immediate impact of a carbon tax on the welfare of households¹¹³ is obviously linked to the share of their budgets devoted to energy consumption. It is thus intuitively regressive (Parry et al., 2005): the richer households admittedly consume more energy and are bound to pay more carbon tax in absolute terms, but the share of energy is larger in the budget of the lower-income households, at least in most OECD countries.¹¹⁴ The welfare of the lower-income households is thus a priori more impacted by both an income effect (lower purchasing power of the disposable income), and the ‘necessity good’ quality of the carbon-intensive energy consumptions (stronger utility loss).

This basic reasoning already appears in early works by Poterba (1991) or Pearson and Smith (1991)—who also stress that the ‘partial equilibrium’ framework implicit behind it has substantial shortcomings: it assumes that energy producers or distributors pass the entire tax burden through to the consumers; it considers a fixed level and structure of energy supply and demand, thereby precluding adaptive behaviour; at last, it ignores the propagation of the carbon tax to other goods and services prices through their intermediate energy consumptions, and thus the ultimate effects on the economy and household income. This chain of effects resorts to fiscal incidence, which deals with possible discrepancies between the directly perceived distributive impacts and those ultimately resulting from ‘general equilibrium’ effects.

Partial equilibrium analyses were admittedly extended by allowing for consumption trade-offs through the introduction of price-elasticities differentiated by class. It turned out that such adaptive behaviour attenuates the immediate direct impact of a tax, but hardly ever reverses its sign (Cornwell and Creedy, 1996; West and Williams, 2004). On the contrary, the use of input-output tables for evaluating the propagation of the tax effect to all prices tends to reinforce the regressive effect (Hamilton and Cameron, 1994; Hassett et al., 2007; Wier et al., 2005). But such computation, however close to the immediate perception of consumers and facilitated by quite simple arithmetic or linear algebra, ultimately reasons in a fictitious world: it assumes constant nominal income, and ignores the use made of the tax revenue, which disappears in some unexplainable potlatch.

Although less intuitive and consequently more contrasted, general equilibrium analyses are also more realistic in that they forbid any form of potlatch and guarantee a sort of ‘mass conservation principle’, through their

¹¹³ The following analysis is restrained to the distribution of the economic cost of a carbon tax, i.e. does not extend to the distribution of the induced environmental benefits.

¹¹⁴ Although Bosquet (2000) points to exceptions, and Hassett et al. (2007) show that conclusions differ whether current consumption or current income are used as richness indicator. Pearson and Smith (1991) analyse 6 European countries to find that Ireland only shows a strong correlation between income and energy expenses. Scarcer research on developing countries reveals a loose correlation, if not an inverse relationship (Yusuf and Resosudarmo, 2007).

representation of a balanced accounting framework. This indeed allows to demonstrate the crucial role of the recycling mode in determining the ultimate effect of a carbon tax. Historically, general equilibrium analyses of the carbon tax were focused on the ‘double dividend’ debate, i.e. the question whether the environmental benefit induced by a carbon tax could be combined to gains in economic growth and employment. While the abundant literature dedicated to this question is still open to further research,¹¹⁵ it has nevertheless reached a rather consensual set of conclusions:

- Recycling carbon tax revenues in a decrease of a pre-existing distortive tax produces a ‘weak’ double-dividend, i.e. achieves some environmental target at a lower welfare cost than a tax whose proceeds are lump-sum recycled—or than other economic instruments as norms, for that matter.¹¹⁶ The more distortive the pre-existing tax, the better. In Europe a consensus tends to view decreasing labour taxes (payroll taxes) superior to decreasing other taxes, subsidies, public deficit or debt reduction, etc. (see IPCC, 1995, Chapter 8).
- Obtaining a ‘strong’ double dividend, that is recycling the carbon tax proceeds in such a way that the total economic cost of the reform is negative, is far from being automatic. Intuitively, substituting a carbon tax to payroll taxes should indeed favour employment, and hence growth. But taxing carbon means taxing consumption, and taxing consumption is equivalent to taxing the income that pays for it. A payroll-tax substituting carbon tax thus ultimately weighs on labour as a source of income, same as the levy it is replacing (Bovenberg and De Mooij, 1994a, 1994b; Goulder, 1995).¹¹⁷
- The ‘strong’ double dividend potential is less elusive when accounting for the fact, as empirical models do, that the carbon tax burden is not entirely borne by labour or the national productive capital. Indeed it also weighs on non-wage household income (financial and property rents, transfer revenues), as well as on the oil and gas rent of exporting countries (Goulder, 1995; Ligthart, 1998). In total, the levy on national labour is indeed decreased and net gains can occur, all the more so as the labour market is rigid (Carraro and Soubeyran, 1996).

In this perspective, accounting for general equilibrium effects becomes crucial to assess the fate of low-income classes: a carbon tax that reduces income inequality can also reduce the latter classes’ welfare if it has a positive total cost; conversely, a carbon tax causing a strong double dividend, i.e. inducing negative total costs, can increase income inequality while improving the welfare of the low-income class.

Notwithstanding, general equilibrium literature on the distributive effects of a carbon tax is much less abundant than that on the aggregate double dividend, and still less extensive than the partial equilibrium one on the same subject.¹¹⁸ As a matter of fact, the past decade has seen less research on the carbon tax because of the prejudice of a political impairment, despite the acknowledged theoretical potential,¹¹⁹ and because of the attention gained by the tradable emission permit option, in the wake of the Kyoto Protocol.¹²⁰ The resulting weakness in the state-of-the-art requires the economist to be modest on the numerical results, but should not prevent him from

¹¹⁵ Bovenberg (1999) provides a synthesis of the theoretical underpinnings. A survey of empirical studies can be found in sections of the second and third Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC, 1995; IPCC, 2001; IPCC, 2007).

¹¹⁶ Norms create rents benefitting the polluting industries beyond what is legitimated by the cost of their technological restructuring. Besides, the marginal cost of a norm is at least partially passed through to intermediate and final consumers, whereas that of a carbon tax can be compensated by a recycling in the decrease of other production taxes.

¹¹⁷ Besides, a carbon tax distorts the consumption goods market, thus degrading the utility households derive from their income. In stylized models like that of Bovenberg and De Mooij (op. cit.), where unemployment is voluntary, this discourages labour supply and depresses activity.

¹¹⁸ Let us still quote Proost and Van Regemorter (1995) on Belgium, and Yusuf and Resosudarmo (2007) on Indonesia.

¹¹⁹ See the recent Harvard Project on International Climate Change Agreement (Aldy and Stavins, 2008). The body of the report stresses the advantages of coordinated national taxes; but these are barred from the summary because their adoption is seen as “politically unlikely”.

¹²⁰ This rests on a wrong interpretation of the Protocol, which indeed creates a permit market between States, but leaves to each State the choice of which domestic instruments to implement. A State could couple a fiscal reform with programs on buildings and transport, to become a permit seller on international markets without having created a domestic permit market.

delivering insights on the robust mechanisms determining the ultimate consequences of alternative carbon tax reforms.

The following two sections thus shed light on how the perceived impact of a carbon tax changes with the level of analysis. They envisage the implementation of a tax up to €200 per tonne of CO₂ (hereafter /tCO₂)¹²¹ in 2004 France, whose household agent is divided into 20 income classes on the basis of an INSEE *Budget des Familles* survey covering the years 2000-2001.¹²² The welfare index used to measure class impacts is the change in real consumption, i.e. the sum of a class’s consumption expenses deflated by its specific Fisher price index.¹²³ For the sake of clarity, results are reported aggregated into 5 household classes, of the 5% ‘poorest’, the 30% ‘modest’, the 30% ‘median’, the 30% ‘rich’ and the 5% ‘richest’ households.

2. Lessons from partial equilibrium analysis

2.1. Direct impacts with constant energy consumptions

Let us first consider the impact of a carbon tax as spontaneously perceived at the time of its implementation, that is notwithstanding changes in the energy consumptions and their carbon intensities, in the relative prices net of the new tax, in nominal incomes or indeed in the consumption-savings trade-off. Facing such constraints households can adjust their non-energy consumptions only. This provides a first order approximation of the tax effects.¹²⁴

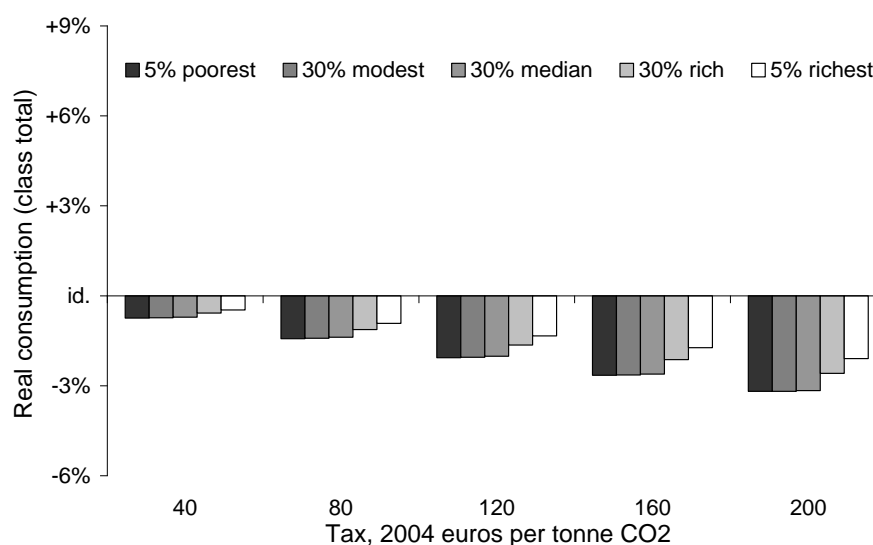


Figure 1 Distributive effects, partial equilibrium with constant energy consumptions

¹²¹ Which ex ante increases the average price of gasoline by 54%, and that of residential energy by 38%. Although the fossil fuels of residential use are much less taxed than gasoline the heavy share of electricity in residential consumption accounts for the lower strength of the signal.

¹²² Following INSEE “income” is defined as total household income over household number of consumption units (CU), with CU measured following a modified OECD scale: 1 CU for the first adult, 0.5 CU for any other person above 14 and 0.3 CU per children below 14.

¹²³ Consumption is preferred to total income to ease the comparison between partial and total equilibrium. In general equilibrium the class-specific propensities to consume have limited variations that are correlated enough to guarantee that comparing the classes’ variations of real consumption is very similar to comparing their total income variations.

¹²⁴ The first order monetary measurement of the welfare variation (compensating variation) is the cost increase of the initial good and services consumed. This approximation is only valid for marginal price variations (Bourguignon and Spadaro 2006).

Unsurprisingly, from such an angle the carbon tax appears regressive whatever its level (Figure 1). Indeed, poorest, modest and median households alike consistently lose a share of their real consumption roughly one and a half times that lost by the richest households, for the simple reason that their energy budget share is respectively 38%, 36% and 33% higher—the higher rate of motorisation of the median and modest classes explains why their loss is closely comparable to that of the poorest class, despite lower budget shares.

2.2. Impacts after adaptation to the new relative prices

Turning to the ability of households to adapt to the new set of relative prices implies facing three difficulties related to estimating energy price elasticities:

- The questions raised by time series econometrics in energy matters: (i) the difference between short- and long-term elasticities, and the irreversibility or asymmetry effects of a price increase vs. a price decrease (Gately, 1992; Peltzman, 2000); (ii) the erratic nature of energy prices since the first oil shock in 1973, that make them ill-suited to provide estimates for stable policy-related price-signals; (iii) the questionable use of a general consumer price index to deflate current energy prices, considering the dominant role of a certain set of prices (*e.g.* that of house rental services) in the shaping of mobility demand.
- The lack of panel data over both a period long enough and sufficiently disaggregated households to grasp the long-term heterogeneity of households' behaviour—acknowledging that the ability of households to adapt depends on, beyond their income level, parameters as diverse as the degree of urban sprawl, the share of rurality, or the equipment in infrastructures.
- The impossibility to reason with constant elasticities over the large spectrum of taxes tested in this paper, be it only because of the existence of basic needs and technical asymptotes to energy efficiency at any given temporal horizon.

For lack of a better solution, we derived own-price, cross-price and income elasticities that are, for each household class:

- Based on an Almost Ideal Demand System (Deaton and Muellbauer, 1980) estimated on long-term time series (INSEE, 2007),¹²⁵
- Decreasing with the tax level, in order to have consumption tend towards an asymptotic value meant as an incompressible basic need.¹²⁶ Energy asymptotic values are assumed identical for all classes and set at 80% of the lowest consumption *per capita*.

Taking account of these elasticities and asymptotes produces impact estimates that can be interpreted as those of a carbon tax having had sufficient time before 2004 to deploy its adaptation effects. These estimates seem very close to those obtained without adaptive behaviour (compare Figure 2 to Figure 1): for all household classes consumption flexibility only slightly alleviates the tax burden, and the regressive effect is hardly changed.¹²⁷

¹²⁵ Elasticities for automotive fuel (-50% on average, standard deviation across classes of 7%) and for residential energy (-11% on average, standard deviation of 12% across classes) are comparable to values found in the existing literature (Graham and Glaister, 2002).

¹²⁶ The reasons for this modelling choice are discussed in a special issue of *The Energy Journal* dedicated to hybrid modelling (Hourcade et al., 2006 ; Gherzi and Hourcade, 2006).

¹²⁷ Part of this lack of sensitivity is explained by the use of real consumption as indicator. Real consumption cannot capture 'basket composition' effects that would certainly show if some utility function could have been properly calibrated. Indeed, detailed modelling results reveal consumption decreases of up to 21% for automotive fuel, 5% for residential energy (for a €200/tCO₂ tax).

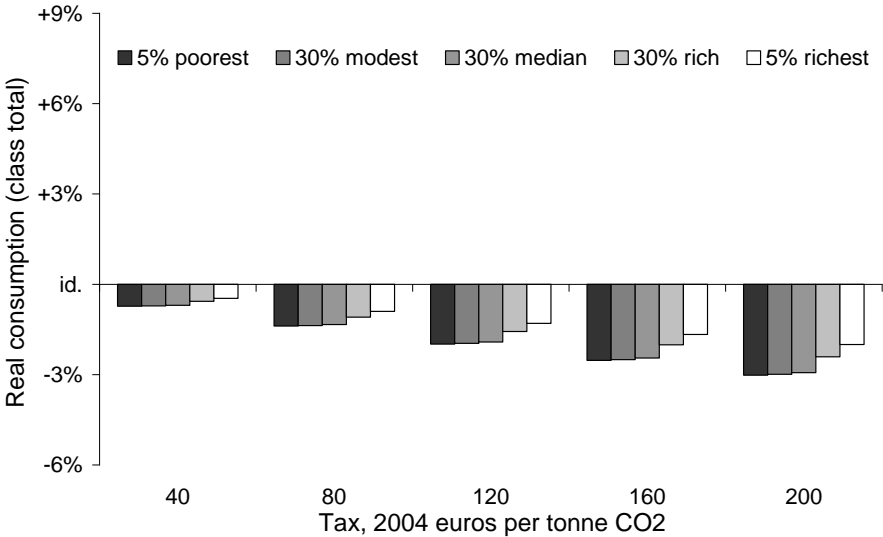


Figure 2 Distributive effects, partial equilibrium with adaptive energy consumptions

2.3. Introducing a ‘mass conservation’ principle

Before turning to the more complex general equilibrium effects, the partial equilibrium analysis can be further refined by the introduction of a simple ‘mass conservation’ principle, with the aim of correcting the ‘potlatch’ disappearance of carbon tax revenues. Let us assume that this revenue is redistributed to households as a fixed amount per consumption unit (CU, see footnote 122). This recycling rule, through which a substantial share of carbon tax payments of the higher classes is redistributed to the poorer, results in a dramatically different distribution impact: whatever the tax level the reform turns out progressive (Figure 3).

That an obviously highly egalitarian recycling rule should lead to a progressive impact might appear tautological. This step is simply meant as a demonstration that, beyond the direct regressive effect of the carbon tax, the recycling mode of its fiscal product induces another distributive effect that is potentially strongly progressive.

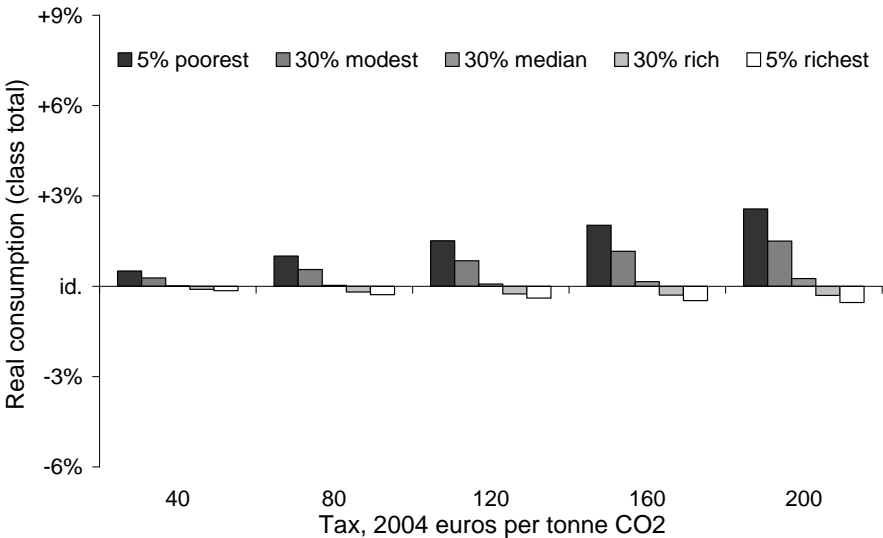


Figure 3 Distributive effects, partial equilibrium with adaptive energy consumptions and fixed per-CU recycling

In this context it is commonly recognised a good practice to analyse the ‘pure’ effect of taxation by simulating lump-sum recycling, i.e. that each agent or aggregate thereof gets its carbon tax payments refunded. Lump-sum recycling provides indeed a useful framework in which to compare the efficiency of diverse recycling options. But this does not mean that it is the only legitimate assumption to be made when assessing a double dividend potential, as is sometimes argued under the pretense that any other recycling option could be organised as an independent set of transfers between agents. It indeed remains that, if a carbon tax were levied, it would be desirable to explore the best possible recycling option. That best possible recycling option is as much part of the carbon tax reform as the tax itself.

Introducing a ‘mass conservation principle’ thus forces to jointly analyse the tax and its recycling, which is proven to loosen the mechanical link between the carbon tax and the regressive effect. Then general equilibrium modelling is required to grasp the simultaneous adaptation of agents to the diverse forms such general reorganisations of the fiscal structure can take.

3. Ultimate distributive impacts: general equilibrium analyses

The analysis below is based on comparative static modelling conducted with the IMACLIM-S computable general equilibrium model. The version used is an open-economy one distinguishing 4 productions: 3 energy goods and a composite remainder; it is enhanced from previous versions by the disaggregation of 20 income classes, endowed with the same adaptation capabilities as those used in partial equilibrium, and by a detailed description of the distribution of the national income among the 20 classes, firms, public administrations and the rest of the world. The resulting financial positions are balanced by agent-specific interest rates on a financial market, and debt services duly represented.¹²⁸

Our purpose being to demonstrate the importance of the tax-recycling option, we choose to base our simulations on a given set of macro-economic behavioural assumptions: identical decreasing relation between propensity to consume and income; fixed investment-disposable income ratio; identical technical asymptotes and basic needs; fixed international prices; *etc.* Two sets of assumptions are crucial enough to deserve more exposition.

A first set regards public administrations. On the one hand, we assume a strict ‘euro for a euro’ budget neutrality of the carbon tax: whatever its use the amount recycled is strictly identical to the amount levied, to the euro.¹²⁹ On the other hand we consider constant real public expenses (public consumption, public investment, per capita transfers) and a fixed ratio of public debt to GDP as well. Eliminating the latter two adjustment variables facilitates the comparison of different options. It also triggers either a vicious or a virtuous circle, as it implies the need to raise or lower other taxes¹³⁰, depending on whether the variations of the fiscal bases compensate the direct losses of the interior tax on petroleum products (hereafter TIPP according to the French acronym) caused by the drop in automotive fuel consumption.¹³¹

A second set of assumptions relates to the labour market and its degree of imperfection. First, to represent structural situations of unemployment and limited wage flexibility, we adopt a wage curve (Blanchflower and Oswald, 2005) that correlates the average wage relative to foreign prices to the unemployment rate. The choice

¹²⁸ Gherzi (2009) presents a ‘core’ version of the model limited to one global region and 2 productions. Gherzi et al. (2009) propose a detailed description of the 2.3 version, only marginally different from version 2.1 applied to this research. Gherzi and Hourcade (2006) develop the particular stance regarding the producers’ behaviour.

¹²⁹ In the quite detailed framework of IMACLIM-S, there are many possible interpretations of the budget neutrality hypothesis (constant fiscal pressure, constant absolute deficit, constant ratio of deficit to GDP, etc.), all of which have specific macro-economic impacts. We opt for a definition that is arguably the most tangible, and also echoes the ‘mass conservation principle’ explored in partial equilibrium (see above).

¹³⁰ The required shift is modelled as an identical scalar applied to all tax rates and excise taxes represented (including the payroll taxes in the case when they benefit from the euro for a euro recycling).

¹³¹ The VAT on automotive fuel does not constitute such losses as the VAT is similarly levied on any consumption that is substituted to them (even if in some instances at a reduced rate).

of correlating the wage relative to foreign prices rather than the real wage (i.e. the wage relative to some domestic consumer price index) is made to reflect competitiveness constraints specific to the French-European Union context. It forces a wage moderation that sets limits on the energy price propagation effects and amplifies a trade-off in favour of labour, but simultaneously allows for higher real wage losses. Second, aggregate employment impacts are assumed to affect classes proportionally to their initial number of unemployed—which makes classes all the more sensitive to employment variations as they are poor. This simplifying assumption is adopted for lack of information and should be revised in future research.

The resulting modelling framework is calibrated on 2004 France and applied to simulate five reforms (Table 1):

- The R1 reform consists in taxing carbon emissions from the households, then refunding them the entire tax product as a fixed amount per CU—a reform identical to the one assessed with the introduction of a ‘mass conservation’ principle above.
- The R2 reform enlarges the carbon tax base of R1 to carbon emissions from the firms.
- The R3 reform covers emissions as R2 but recycles the tax proceeds in a decrease of payroll taxes.
- R3_{ND} and R4 reforms are two variants that impose a neutralisation of the distributive impacts.

Reform	Carbon tax on	Revenue recycled	Distributive impacts neutralised
R1	Household emissions	To households, fixed per CU amount	No
R2	All emissions	To households, fixed per CU amount	No
R3	All emissions	In a decrease of payroll taxes	No
R3 _{ND}	All emissions	In a decrease of payroll taxes	Through a zero-sum transfer among income classes
R4	All emissions	To households, their aggregate tax payment; In a decrease of payroll taxes, the remainder.	Through an adjustment of the amount refunded to each class

Table 1 Five alternative reforms for a carbon tax

3.1. Recycling modes and activity levels: towards an equity-efficiency dilemma?

By nature, shifting to a general equilibrium framework multiplies the criteria for comparing different policies. Focusing on the reforms R1 to R3 to begin with, we will start by delineating their aggregate economic impact, and then examine how this aggregate impact is distributed among household classes.

R1 has a decreasing effect on GDP (Table 2), fundamentally consistent with the theoretical analysis stressing that taxing one good is less efficient than putting the same burden on total income—because of the Slutsky substitution effect. In our simulation this effect is not compensated by the mild growth stemming from a redistribution in favour of the poorer classes and their higher propensity to consume, notably because our budget neutrality constraint implies increases of the pre-existing taxes. The net effect on employment is nonetheless mildly positive (+0.15% for a tax level of €200/tCO₂), thanks to a shift in demand towards labour-intensive rather than energy-intensive goods.

Carbon Tax, € per tCO ₂		40	80	120	160	200
Real	R1	-0.1%	-0.1%	-0.2%	-0.2%	-0.3%

GDP	R2	-0.2%	-0.4%	-0.6%	-0.7%	-0.9%
	R3	+0.5%	+0.8%	+1.1%	+1.3%	+1.5%
	R3 _{ND}	+0.5%	+0.9%	+1.2%	+1.4%	+1.6%
	R4	+0.2%	+0.4%	+0.5%	+0.6%	+0.7%
Real	R1	-0.0%	-0.1%	-0.1%	-0.2%	-0.2%
Household	R2	+0.2%	+0.3%	+0.4%	+0.4%	+0.4%
Consumption	R3	+0.6%	+0.9%	+1.2%	+1.5%	+1.7%
	R3 _{ND}	+0.6%	+1.1%	+1.4%	+1.7%	+1.9%
	R4	+0.4%	+0.7%	+1.0%	+1.1%	+1.3%
Employment	R1	+0.04%	+0.08%	+0.11%	+0.12%	+0.15%
	R2	+0.02%	-0.01%	-0.06%	-0.11%	-0.16%
	R3	+0.78%	+1.40%	+1.93%	+2.38%	+2.79%
	R3 _{ND}	+0.81%	+1.44%	+1.98%	+2.45%	+2.87%
	R4	+0.50%	+0.88%	+1.21%	+1.49%	+1.73%
Total	R1	-4.2%	-8.0%	-11.5%	-14.9%	-18.1%
CO ₂ Emissions	R2	-8.7%	-15.0%	-20.2%	-24.6%	-28.5%
	R3	-8.2%	-14.2%	-19.1%	-23.3%	-27.1%
	R3 _{ND}	-8.1%	-14.1%	-19.0%	-23.2%	-27.0%
	R4	-8.4%	-14.5%	-19.5%	-23.7%	-27.6%

N.B.: The variations prevail at the end of a post-reform adjustment process. If 20 years are required for energy mutations and macro-economic adjustments, then the 2.4% GDP gap between R2 and R3 is equivalent to a 0.12% variation of the average annual growth rate over the period.

Table 2 General equilibrium aggregate impacts

R2, by extending the tax base to emissions from firms, increases the GDP losses. This is again consistent with theoretical results (Bovenberg and Goulder 1996): the tax on intermediate inputs propagates to other goods and services, which leads to a reinforcement of the deadweight loss caused by the Slutsky substitution effect. In addition, the resulting general price increase hurts competitiveness, which contracts economic activity, which in turn forces public administrations to increase other tax rates—and starts a vicious circle.

In the light of such GDP losses, the consumption gains of R2 might seem paradoxical. They are permitted by a significant redistribution of national income in favour of households due to (i) the indexation of social transfers on prices; (ii) the payment to households of all carbon tax proceeds including those whose burden is ultimately borne by other agents.

The comparative results of R3 are themselves in line with the literature on second best economies:¹³² using the carbon tax proceeds to lower payroll taxes increases the activity level. At €200/tCO₂ GDP increases by 1.5%, employment by 2.8%, and carbon emissions drop by 27%. On the latter environmental achievement, it is interesting to note the hardly perceivable influence of the recycling mode; this indicates dominance of the direct impact of the tax on relative prices over any indirect effect, including the variations in activity.¹³³

¹³² See the surveys provided by the relevant sections of the successive IPCC (1995, 2001, 2007). The results are also in line with previous modelling analyses by IMACLIM-S (Hourcade and Gherzi, 2000; Gherzi et al., 2001).

¹³³ For the obvious reason of a smaller tax base, R1 induces abatement that is up to half as high.

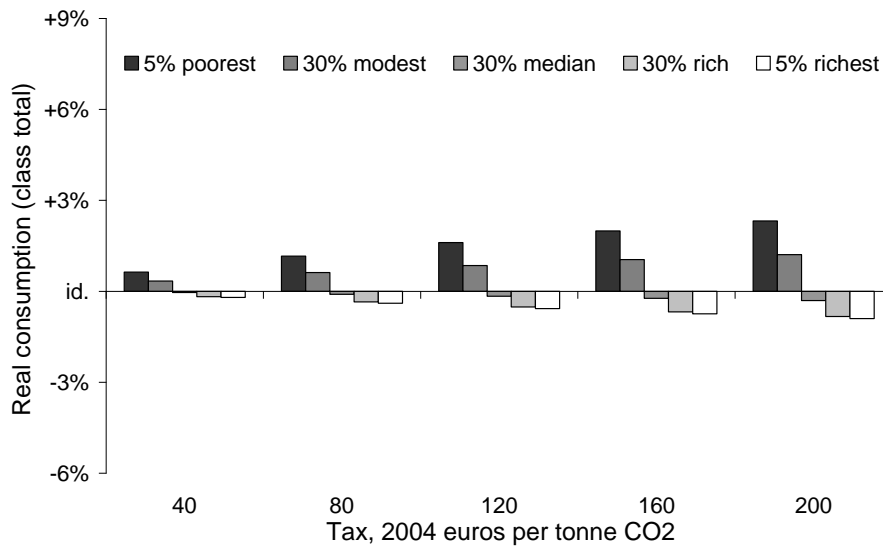


Figure 4 General equilibrium distributive impact, reform R1

Let us now analyse how these impacts affect the different classes. Unsurprisingly R1, which strictly reproduces the ‘constant mass’ partial equilibrium variant (see section 2.3), shows a comparable distributive impact (compare Figures 3 and 4). However, general equilibrium mechanisms systematically decrease the welfare of the three richest classes, whereas they increase that of the poorest classes up to €120/tCO₂. The reason for this difference in sensitivity lies in heterogeneous income structures and labour market situations. The poorest and modest classes indeed have high proportions of their income (resp. 51% and 46%) guaranteed in real terms in the form of price-indexed social transfers. Besides, thanks to high unemployment rates (resp. 42% and 22%) they benefit relatively more from a mild labour creation effect (+0.15% for €120/tCO₂). For the lower tax levels, these two benefits compensate the erosion of purchasing power caused by the increased fiscal pressure necessary to maintain public expenses and debt in a context of lower growth, which adds up to the direct energy price increase. By contrast the higher income classes face an income loss strongly correlated to the GDP decrease; this loss cannot be compensated by gains on the labour market that are limited by much lower unemployment levels.¹³⁴

¹³⁴ This holds even though the gap between unemployment benefits and the average wage, i.e. the gain from employment creation, is strongly increasing with income.

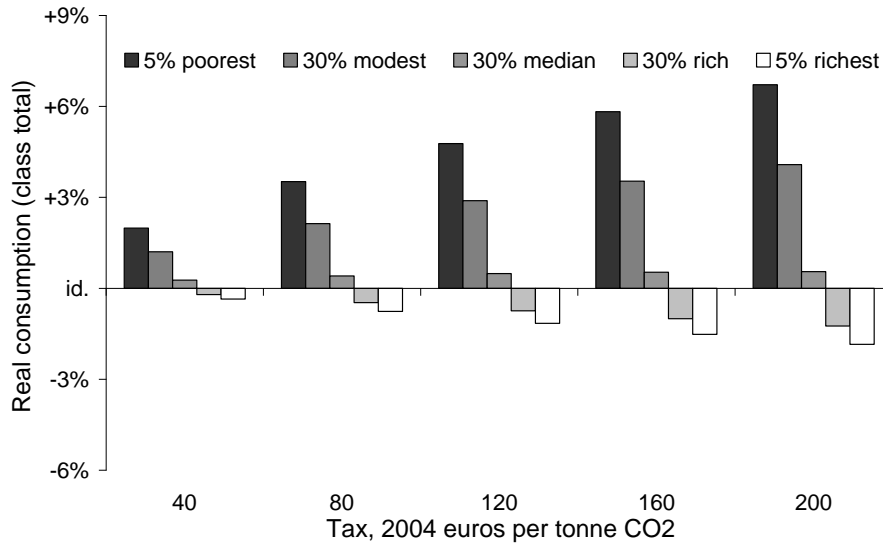


Figure 5 General equilibrium distributive impact, reform R2

The distributive impact of R2 (Figure 5) is profiled as that of R1, but much more contrasted. This directly results from the multiplication by 2.5 of the tax proceeds, and their highly progressive recycling rule. The poorest households are strongly advantaged: at €200/tCO₂ their yearly tax payments amount to €500, but the generalised *per-CU* recycling rule hands them back €2 131; the €1 631 balance amounts to 8% of their consumption expenditures. The higher the income class, the smaller this balance compared to the revenue losses caused by macro-economic adjustments. It is still high enough to allow the median class to turn its R1 loss into a gain, but not so for the higher classes: at €200/tCO₂ the highest class benefits from a €916 balance that amounts to a modest 1.3% of its consumption expenditures, and cannot compensate a marked decline in activity income (wages and rents).

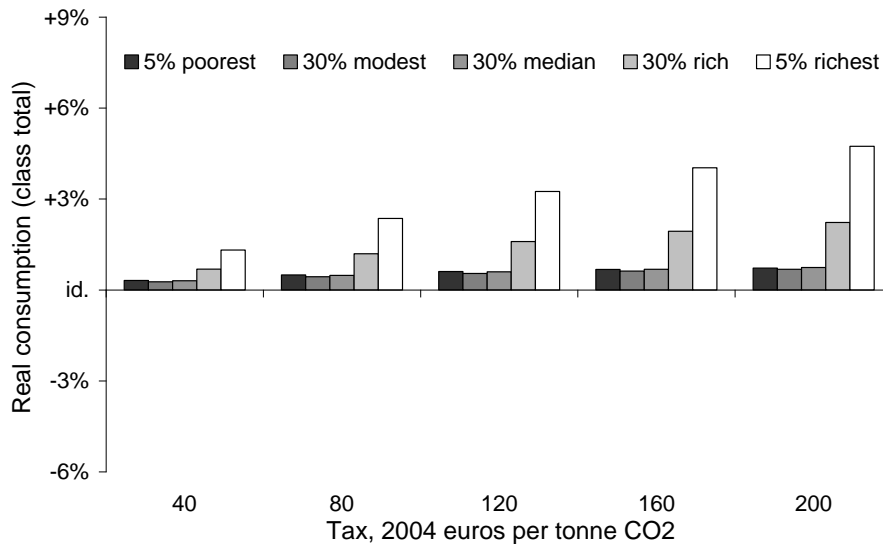


Figure 6 General equilibrium distributive impact, reform R3

R3 results are quite different from those of R1 and R2: although R3 increases both the aggregate income and total household consumption (Table 2), it widens the gap between income classes. At €200/tCO₂ the real consumption increase of the richest class is *ca.* six times larger than that of the poorest (Figure 6). The lower income households are indeed compensated from the carbon tax burden through employment creation only, and lose the benefit of the direct redistribution scheme. Besides, the social transfers that guarantee them against

GDP losses also limit their ability to benefit from GDP gains. By contrast the richer classes, less sensitive to higher energy prices, capture a greater share of the increased growth thanks to income sources that are more correlated to general activity.

In total, the comparison between R1, R2 and R3 ultimately leads to an equity-efficiency dilemma. R1 and R2, through the choice of a direct redistribution of the carbon tax proceeds to households, overturn the distributive impacts of the tax, but do so at the cost of GDP and either aggregate consumption or employment losses. Conversely, R3 simultaneously improves GDP, employment and aggregate consumption, but does so by renouncing to a direct action on income distribution, and consequently leads to an inequitable distribution of the fruits of the growth it triggers.

3.2. Options for a compromise

The relative performance of R3 arguably encourages deriving variants of this reform that, while conserving its aggregate efficiency, might fare better in terms of equity. The spectrum of possible variants is quite large, and it is obviously beyond the scope of this paper to try to cover it. R3_{ND} and R4 are merely selected to illustrate how the ultimate consequences of a carbon tax hang on the political compromises expressed in its recycling rule.

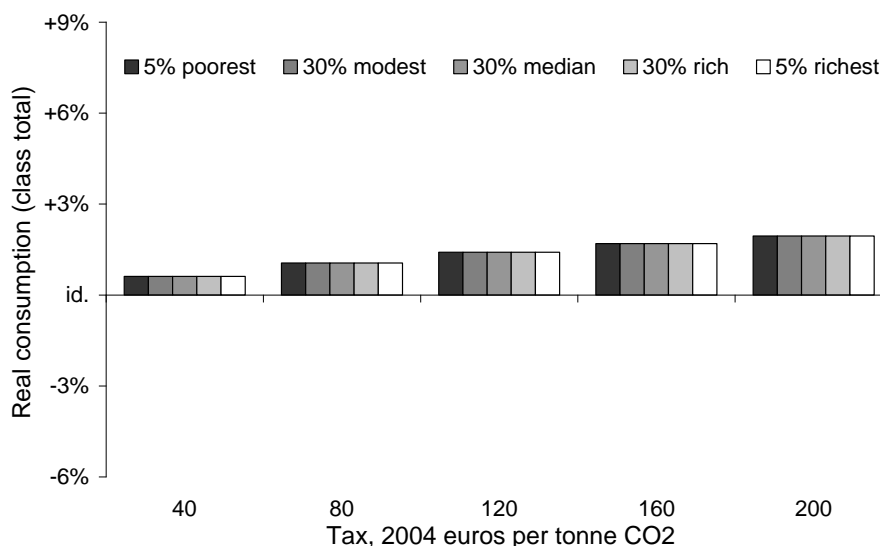


Figure 7 General equilibrium distributive impact, reform R3_{ND}

The R3_{ND} variant combines R3 assumptions with a zero-sum transfer among household classes that aims at equalising their real consumption variations (Figure 7)¹³⁵. Its aggregate impacts are very close to those of R3 in both environmental and macro-economic terms (Table 2).¹³⁶ Such a quasi separability of efficiency and equity indicates that the behaviour of income classes is not heterogeneous enough to substantially modify the carbon tax impact on the productive system, aggregate consumption and emissions. However, any optimistic inference on a possible conciliation of both criteria must be qualified by a caveat concerning political acceptability: R3_{ND} submits the richer classes to a double levy (levy to compensate the poorer households on top of the carbon tax) that could only be justified under a general political compromise to decrease inequalities.

¹³⁵ This indicator, obviously not the most appropriate equity criterion, is merely retained for its legibility in the format used to present distributive results. Any more appropriate criterion could be targeted to shape the distributive compensations of R3_{ND} and R4 without substantially changing aggregate results—as hinted by the very similar macroeconomic outcomes of R3 and R3_{ND}.

¹³⁶ The mild macro-economic advantage of R3_{ND} over R3 is caused by the higher propensity to consume of lower income classes, who benefit from the transfers at the expense of the richer classes.

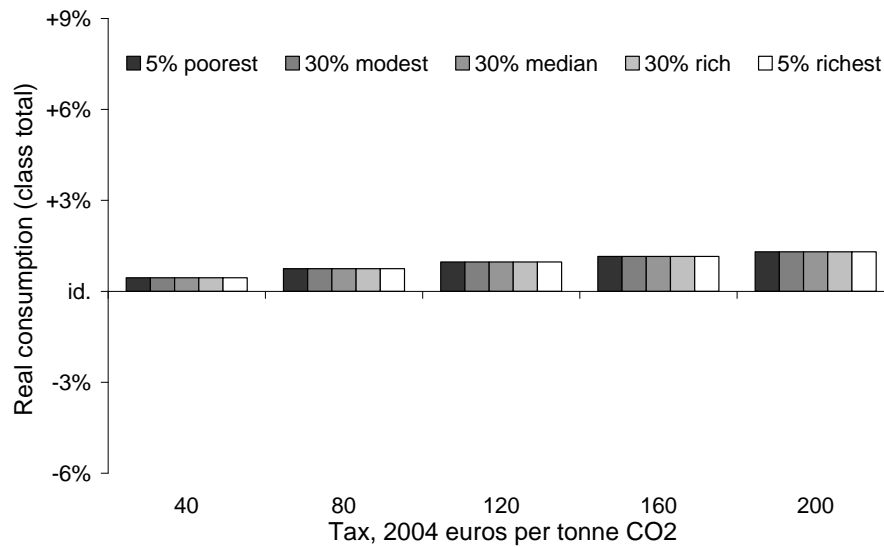


Figure 8 General equilibrium distributive impact, reform R4

The R4 variant, at last, anticipates any argument about the burden sharing between households and firms by opting for a scheme that redistributes their own tax payments to the former, and uses the tax payments of the latter to decrease payroll taxes.¹³⁷ The share of the proceeds redistributed to households then allows controlling the distributive effect in a manner similar to that of R3_{ND} (Figure 8). The macroeconomic and distributive impacts of R4 turn out to fall between those of R2 on one side, and R3 on the other side. By contrast to R2 GDP increases, as production costs benefit from the recycling of the tax proceeds levied on intermediate consumption; this generates consumption gains that, by contrast to R3, are distributed in a controlled manner.

Conclusion

The contrasted impacts of a carbon tax on different household classes ultimately result from the interaction of three effects: (i) the sheer weight of the tax payments, strongly determined by the budget share of energy expenses and hence rather regressive; (ii) the distribution of the macroeconomic consequences of the tax (themselves strongly sensitive to the recycling of its proceeds), which hangs both on the specific position of each class on the labour market (rate of unemployment, wedge between wage and unemployment benefits) and on its income structure (share of revenue only remotely connected to variations in general activity—transfer payments); (iii) potential direct redistribution schemes of part or of all the tax proceeds to households, which offer a powerful leverage to overturn the first two effects.

Contrary to a misconception inherited from partial equilibrium analyses, there is thus no mechanical link between a carbon tax and its ultimate distributive effects. The implementation of a carbon tax invites indeed to a political trade-off through the choice of a recycling rule. A direct redistribution of the tax proceeds to households can be used to favour the poorest household classes, but at a macroeconomic cost in terms of both GDP and either aggregate consumption or employment. Conversely, a recycling of all tax proceeds in lower payroll taxes results in higher GDP, consumption and employment, but at the cost of a widening of the gap between the lower and the higher revenue classes—although it manages to increase the consumption of all classes. A mix recycling scheme, which devotes the tax levied on firms to payroll tax rebates, and that levied on

¹³⁷ This dual recycling has been prevailing in Switzerland since January 2008: tax proceeds levied on intermediate consumption are redistributed to firms on the basis of their labour costs; those levied on final consumption are redistributed to households through a rebate on their public health insurance cost.

household to the financing of redistributive transfers, is proven to provide a compromise between the two polar options: it allows to achieve both an improvement of all macroeconomic indicators, and a control of the distributive impacts of the reform.

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Annex 3

Low-carbon policy making vs. low-carbon policy modelling: State-of-the-art and challenges

Low-carbon policy making vs. low-carbon policy modelling: State-of-the-art and challenges

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Abstract

This paper surveys the use made of modelling expertise in the recent literature focused on the policymaking of low-carbon societies in Europe, both peer-reviewed and 'grey'. The first section focuses on the prominent policy instrument of carbon pricing. It starts by analysing the somewhat confusing use made of carbon pricing modelling in policy reports emanating from the French and British governments, then reviews some modelling results on carbon pricing in a 'second best' world. The second section lists the impressive collection of more focused policy instruments that are advocated in both governmental and non-governmental literature. It insists on the contrast between the high degree of precision of some of these policy proposals, and the limited modelling of their impacts, either from an environmental or an economic point of view. The third section concludes on recommendations to the policy modelling community inspired by this survey. Purposely avoiding the current controversies surrounding cost-benefit analysis, it advocates further applied research on the cost-efficiency of carbon pricing trajectories (when flexibility); on the *terra incognita* beyond first best uniform pricing (where flexibility); on the elicitation of policy overlaps; and on the modelling of extended policy portfolios in comprehensive, consistent modelling frameworks.

Keywords

Carbon valuation. Low-carbon policy portfolios. Low-carbon policy modelling.

Introduction

The dramatic shifts in lifestyles and development patterns implied by the transition to low-carbon¹³⁸ societies call for an ambitious policy action in both its strength and coverage. Crafting the details of such action requires particular care, considering the stakes: the orders of magnitude of long term studies hint that the cost of deviating from the least-cost option—whatever this option—could be in the order of some GDP points in 2050 for the most ambitious targets, a level that translates into hundreds of billions of Euros in Europe. From the literature on the topic a set of generic principles emerges that, for some of them, theoretically guarantee cost minimisation and for some others, should at least hedge against massive excess costs.

First and foremost, a requisite to efficient action is some coordination in the policy process. 'Where flexibility' is to be guaranteed to abatement measures: since their climate impact is independent from their geographical origin, emissions should be cut down where it is the cheapest to do so. The rationale is certainly relevant at the

¹³⁸ We will continually refer to 'carbon' when discussing policy options as carbon pricing, a carbon tax, carbon abatement, etc. All greenhouse gases (GHG) are implied on carbon-equivalent terms.

European level, and duly taken up by recent governmental reports [78, 16-18, 9]. It also holds at global level, although the semi-failures of the Copenhagen and Doha summits, and the monitoring difficulties inherent to Clean Development Mechanism (CDM) actions, postpone to some unknown future the equalisation of marginal abatement costs across the globe.

The same series of governmental reports, building on a profuse literature, stresses the importance of timing—‘when flexibility’: despite the persisting economic crisis, delayed action closes, one after another, windows of opportunity to reach the lower concentration levels, while it increases the costs of the still attainable objectives. Policy action is required at least to set Europe on such tracks that its laxer 2050 emission target of an 80% cut from 1990 levels is still reachable—it is feared that the 2020 objective of a 20% cut could be too-conservative a milestone on the way to this ambitious 2050 target. Considering the political process that led to these targets, it is hard to rule out that another emission pathway might induce the same environmental benefits at a lower cost.

Another generic recommendation of policymaking reports is that the distributive consequences of ambitious climate policies should be assessed and controlled, as far as can be: on households, to shield the poorer from strong impacts on their living standards; on firms, to prevent unilateral action to overly degrade their competitiveness on international markets; on governments,¹³⁹ to guarantee that climate policies neither deteriorate (through subsidies and tax cuts) nor improve (through tax and auction proceeds) public budget balances.

At last, many studies underline that the climate policy portfolio will have to be straightforward enough to be accepted by public opinions, considering the constraints envisaged. This, adding to its theoretical properties, points to some form of generalised carbon pricing as the core of policy action—our first section addresses this central instrument, contrasting its treatment by policymaking reports and the scientific literature. However, some more targeted policy measures could be required to circumvent a number of market failures hampering mitigation actions of moderate cost. Our second section details the wide range of such instruments promoted in the policy-oriented literature, but also stresses the weakness of supporting modelling experiments. Our third section concludes on the rich policy modelling agenda emerging from this obvious gap between policy literature and applied studies, even in the restricted framework of cost-efficiency analysis.

1. Carbon pricing: lessons and limits

Many if not all low-carbon studies rely partially at least on uniform carbon pricing to trigger the dramatic abatement levels they envision. The economic rationale sustaining such quasi unanimity is well known: by equating marginal abatement costs across agents and localisations, uniform carbon pricing holds the theoretical virtue of minimising the aggregate cost of reaching any abatement target. This rationale governs by and large carbon policymaking, as our first subsection below testifies. We however clarify its practical implications in a second subsection, while we address its limits in a third one.

1.1. A normative value of carbon as a pillar to policy action

Uniform, economy-wide carbon prices are consistently used in academic and political circles as a support to discussion. On top of their theoretical virtues, they are perceived as concise measures of the ‘effort’ required to achieve the target envisioned,¹⁴⁰ and therefore as a basis of comparison between *e.g.* the conclusions of different

¹³⁹ National accounting distinguishes households, firms and public administrations for the secondary distribution of income. In that sense the public budget impact of policy actions is a matter of income distribution.

¹⁴⁰ Two *caveats* apply here: first, carbon prices deliver information on the marginal cost, not the total cost, of climate action. Secondly, it is only in the theoretical framework of a benevolent planner maximising utility under perfect foresight, and in a closed economy, that the

modelling endeavours, or the stringency of different regional targets.¹⁴¹ The static framework of marginal cost equating across agents and regions at some given date, fit for the short-term and modest objectives of the Kyoto protocol, had however to be expanded to dynamic pricing trajectories to match the longer-term, ambitious goals of low-carbon societies.

Following this shift of focus of the climate policy agenda, most energy-economy models applied to climate policy assessment produced one or several analyses of long-term abatement targets. The 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC) surveys such studies up to 2007 [53, section 3.3]. Since then, the 22nd round of the Energy Modelling Forum of Stanford University [25 and articles of the same journal issue], the European project ADAM [35 and again articles of the same journal issue], or the RECIPE project [34] added to the available expertise.¹⁴²

The policy implications of these estimates require clarification. While Kyoto marginal costs could be interpreted as prices on a quota market, price trajectories to the middle if not the end of the century do not easily translate into policy action, for contrasted reasons: when estimated globally, because ‘first best’ agreements at that scale appear too optimistic, at least in the short to mid-term, as testified by the current state of international negotiations; when estimated at the level of the European Union, because of an emerging policy framework incompatible with them—namely, the disconnected provisions of an EU-wide Emissions Trading System (EU-ETS) covering large emitting sites, and of 27 national targets for the remainder of emissions up to 2020.¹⁴³ Uniform pricing trajectories should thus rather be taken as normative assessments of the theoretical least-cost option. Such assessments are nonetheless of high policy significance. Indeed, three reports of the French and British governments [29, 18, 28] are specifically devoted to establishing normative carbon value trajectories, which they consistently present as pillars to climate policy action. We now turn to an in-depth presentation of these reports, to stress the shortcomings of their use of applied modelling studies.

The reports by the French *Conseil d’Analyse Stratégique* (CAS) [18] and by the British Department of Energy and Climate Change (DECC) [28]¹⁴⁴ employ similar methods to pinpoint these trajectories: from heteroclitte modelling experiments on exogenous emission trajectories they derive carbon values for pivotal years, then interpolate or extrapolate.

To be more specific, CAS identifies a pivotal value of €100 (2008 Euros here and hereafter) in 2030 by averaging the 2030 carbon values computed by three models for a “Europe alone” scenario—2050 European emissions 60% below their 1990 level without any international offsets. Based on an adaptation of Hotelling’s rule the report then advocates extrapolating the 2030 value to 2050 and reprojecting it to 2008 using the 4% discount rate applying to public policy appraisal in France. However, its final recommendation differs: in 2008 it rather connects to a trajectory established back in 2001 [23]; in 2050 it rounds up the €219 resulting from 20 years of 4% annual growth to €200, which it complements with a €150 to €350 range—the path between 2030 and this revised value remaining unspecified (Figure 22).

carbon price strictly matches the marginal social cost of the constraint [36, 48, 10]. The carbon prices computed in other modelling frameworks should not be interpreted beyond the price signals that trigger the desired abatement. The mismatch between the private and social abatement costs has important policy implications that are further addressed below.

¹⁴¹ By mentioning “targets” (in whichever form these come) we implicitly focus on cost-efficiency analysis, thereby acknowledging its dominance over cost-benefit analysis in both European policy making and European climate policy research. Our third section below further motivates this important angle to our survey.

¹⁴² The ongoing AMPERE and LIMITS European projects should shortly deliver further contributions.

¹⁴³ Independent studies confirm the analysis of the European commission itself [15] that the limited amount of emission trading provisioned among the 27 quotas does not allow for marginal cost equating. Our following subsection further addresses this issue.

¹⁴⁴ The report by DECC [28] is explicitly stated as a revision of the one by DEFRA [29], which we therefore do not present at length. DEFRA based its trajectory on the Stern report estimate of the social cost of carbon for 2000, which it updated to ca €37 in 2007, and then assumed a 2% annual increase to reach €48 in 2020, €58 in 2030 and €86 in 2050 (all of these 2008 Euros to allow comparison with Figure 22 below). Our third section below further comments on the corresponding shift from cost-benefit to cost-efficiency analysis.

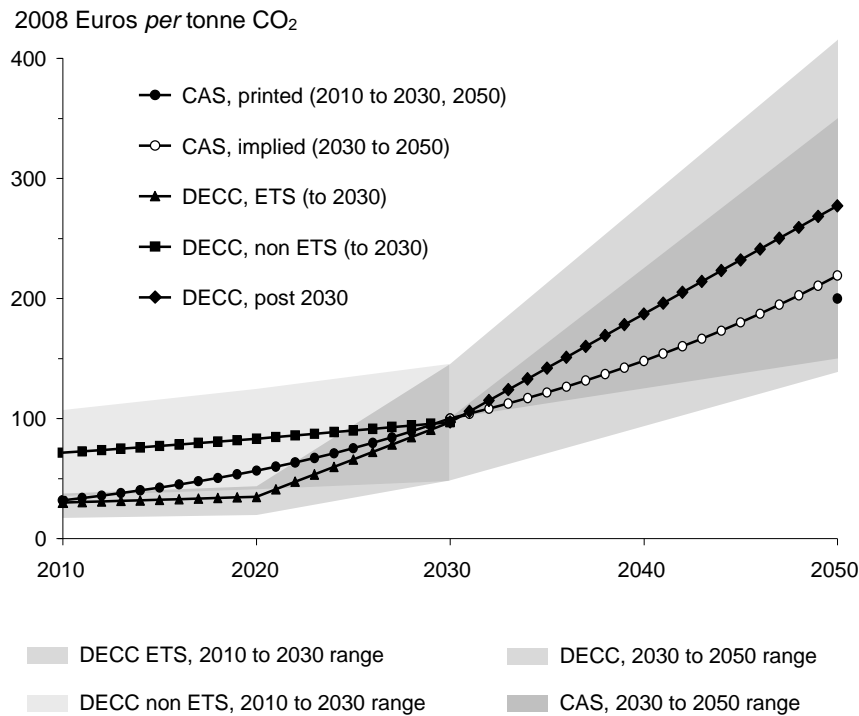


Figure 22 Normative carbon value trajectories from the CAS and DECC reports¹⁴⁵

Contrary to CAS, DECC acknowledges the European Climate and Energy Package by defining two trajectories up to 2020:¹⁴⁶ one, applying to emissions covered by the EU ETS, derives a 2014 value from modelling experiments, then extends it to 2008 and 2020 using a constant 1.5% annual rate of increase on a cost-of-carry rationale. The resulting path is complemented by a range defined by the modelling of lower and higher assumptions on fossil fuel prices (Figure 22). Another trajectory applying to non-ETS emissions rests on a 2020 pivotal value, which derives from a set of 2020 bottom-up marginal abatement cost curves (MACCs) drawn from the British Committee on Climate Change (CCC) [20]. This value is retroprojected to 2008 considering a 1.5% rate of annual increase again, then complemented by a -50% to +50% range inspired by sensitivity analysis on the availability of technical potentials (Figure 22). Beyond 2020, the two trajectories linearly converge to a pivotal 2030 value. This, together with a 2050 value, is drawn from another DECC model’s results, adjusted in some unspecified manner to account for other modelling exercises. The latter exercises—including indeed those of the CAS—also sustain a -50% to +50% uncertainty range on the entire horizon. Both the 2030 and 2050 values are based on the assumption of unrestricted global emissions trading.

For the sake of concision we will not comment on the somewhat misleadingly comparable resulting trajectories—let us simply emphasise that the apparent 2030 consensus partly derives from cross-reference (DECC explicitly quoting CAS), while being backed by strongly contrasted modelling scenarios (full global cooperation vs. “Europe alone” assumption). We rather focus on both reports’ ambiguous use of modelling expertise.

On the one hand, modelling results from various models provide the raw material from which the trajectories derive. On the other hand, these results are systematically stripped down to values for some pivotal years, which are systematically rounded up to some central estimate,¹⁴⁷ while their spreads provide the loose basis to some

¹⁴⁵ 2009 British Pounds were converted to 2005 Euros using the 0.778 ratio retained by DECC (31.1/40). 2005 Euros were converted to 2008 Euros using a 0.928 ratio based on inflation data from the Central European Bank.

¹⁴⁶ On the European Energy Package see http://ec.europa.eu/environment/climat/climate_action.htm.

¹⁴⁷ Both reports round up many of the price estimates averaged on different runs. CAS eventually rounds up its own 2050 estimate. DECC argues this avoids giving a misleading sense of precision—a questionable position, as the trajectories will regularly have to be corrected for inflation, and will also be converted to other currencies or deflated, for comparison purposes (see e.g. Figure 22).

accompanying range.¹⁴⁸ Then, the dynamics of the signal between the pivotal years and beyond are postulated exogenously, on the basis of Hotelling’s rule for CAS, and on a simple linear basis for DECC. But the consistency of such assumptions with the trajectories outlined by the initial modelling exercises is not discussed—indeed the latter trajectories are not detailed in either of the two reports. In the case of CAS at least it is obvious that the abstract model that supports adopting Hotelling’s rule is incompatible with the dynamics of the POLES, IMACLIM-R or GEMINI-E3 models from which the 2030 pivotal value derives, as it appears from the 4 point estimates reported for these models (Figure 23). The challenge of reconciling such contrasted trajectories should have been highlighted rather than masked.

More fundamentally, both reports lack a minimal discussion of the exogenous emission trajectories imposed to the models to compute carbon value estimates beyond 2020. They do discuss targets in terms of both CO₂-equivalent concentrations and cap on temperature increase. However, the crucial question of how these targets are translated in emission trajectories accommodating 2020 and 2050 point commitments is unclear. CAS graphically presents its constrained emission trajectories and laconically indicates deriving them from the 4th IPCC report [53]. DECC does not print its own and only reports their source, the SimCap model. Regrettably, the optimality of these trajectories is unaddressed.

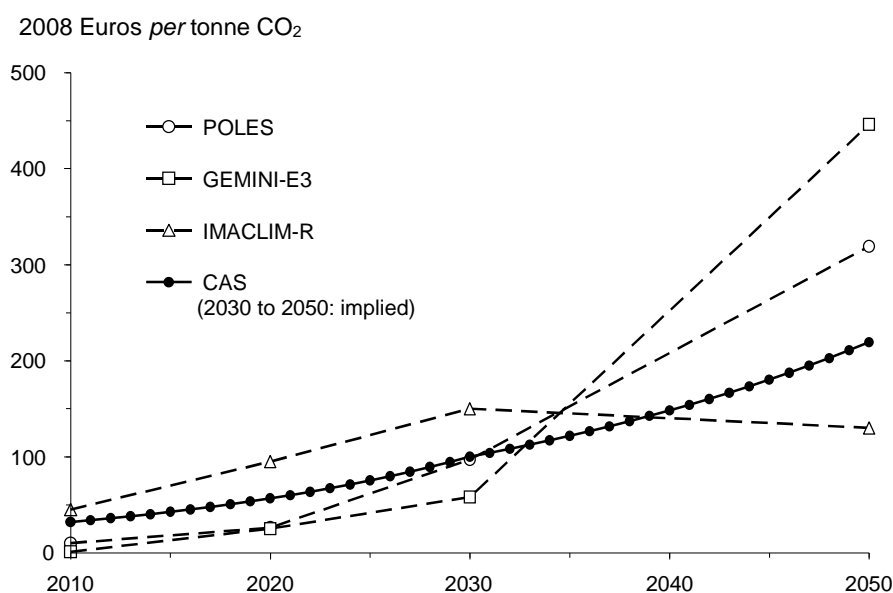


Figure 23 Normative value of carbon from the CAS report and supporting modelling estimates

This is indeed a shortcoming shared by a central piece of low-carbon policymaking in Europe, the European commission’s *Roadmap for moving to a competitive low-carbon economy in 2050* [21]: this Roadmap claims that the emission trajectory it sketches (emissions 40% and 60% below their 1990 level in 2030 and 2040) is a cost-effective pathway to the pre-existing 2050 -80% target; but this is not demonstrated by the accompanying technical document [22], and could indeed hardly be substantiated by any of the 3 models mobilised by the Roadmap, none of them being a macro-economic optimisation model. If anything, the linear quality of the trajectory casts doubts on its optimality.¹⁴⁹

¹⁴⁸ This with the exception of DECC’s price estimate for the ETS sector to 2020, whose lower and higher ranges are set by further modelling through sensitivity analysis.

¹⁴⁹ The “cost-efficient” pathways developed by the *Conseil d’Analyse Stratégique* [19] are similarly questionable; the material complementing the report in its French version clearly establishes they derive from pre-determined carbon price dynamics (see http://www.strategie.gouv.fr/system/files/01_complements_rapp_trajecoire_final.pdf, p. 112, and footnote 167).

1.2. Carbon prices in a ‘second best’ world

The policy instruments that jump to mind to embody a normative value of carbon are either a universal carbon tax, or the market price of some comprehensive ETS. The choice between the two options is already partially made in the European Union: the EU-ETS has been extended to 2020 and complemented by national 2020 targets with highly restricted emissions trading.¹⁵⁰ But this segmented treatment comes at the risk of transgressing the uniform pricing rule. The Commission’s expertise itself evaluates that the 2020 ETS market price could be up to 33% higher than the average 2020 non-ETS marginal cost, while not reporting on the country-specific marginal costs that make up this average [15]. Kretschmer et al. [62] estimate a comparable wedge between slightly higher prices, while Bernard and Vielle [8] and especially Böhringer et al. [10]¹⁵¹ assess a larger and reversed gap: an average marginal cost of non-ETS abatement up to 7 times higher than the ETS market price in 2020 ([10], “ets+rps” scenario). The two former papers also assess even larger discrepancies in the country-specific non-ETS marginal costs, particularly between western and eastern European countries.

The key question is then that of the excess compliance costs theoretically induced by such forecasted discrepancies. Böhringer et al. [10] compute indeed that the existence of two carbon prices only, one for the ETS and one for the non-ETS emissions (assuming unrestricted trading), increases compliance costs by ca 50%. The two other papers estimate up to a 40% supplementary increase from the country specificity of non-ETS commitments. However, Böhringer et al. [10] also develop a set of sensitivity analyses of critical importance: in two out of four cases defined by alternative baseline growth, uniform pricing turns out to induce higher compliance costs than the segmented efforts. The authors identify, as reasons for these heterodox results, that the private and social marginal abatement costs do not match in their modelling framework, on the simple ground that it accounts for the distortions embedded in pre-existing tax systems and international trade. Deviating from uniform pricing can thus be welfare-improving, if the increase in private abatement costs caused by differential pricing is more than offset by terms-of-trade gains, or the alleviation of initial tax distortions.

The consequences for policymaking are to some extent daunting: in a ‘second best’ world, even one as close to a first best optimum as the computable general equilibrium model of [10], optimal abatement policies cannot be explored by moving the cursor of a uniform carbon price along its monetary axis, at least under the standard assumption of a lump-sum rebate to households.¹⁵² In fact, Lipsey and Lancaster [66] establish that the smallest departure from ‘first best’ conditions forbids any preconception on the optimal pricing policy—*e.g.* that sectors with identical ex-ante tax burdens should have their emissions priced identically.

This does not disqualify the establishment of a normative pricing trajectory: beyond remaining valid as a yardstick to concrete public abatement endeavours, it also constitutes the benchmark value from which deviations have to be considered, to an extent that depends on the magnitude of the pre-existing distortions and inertias. The further policy design challenge is to identify these distortions and adapt the pricing policy to them, but also to carefully make the most of the pricing proceeds in second best economic conditions.

Incidentally, this gap between private and social abatement costs echoes the vast literature devoted to the ‘double dividend’ issue:¹⁵³ the gains from alleviating pre-existing distortions may be such that they supersede the direct technical costs, making up for negative abatement costs.¹⁵⁴

¹⁵⁰ By the ‘EU climate and energy package’, see footnote 146.

¹⁵¹ Böhringer et al. [11] sum up the findings of the three papers. Their research is part of [25].

¹⁵² In less applied settings, another strand of literature demonstrates that the specific inertias of the many abatement options also warrant differentiated prices, particularly under the assumption of imperfect foresight [63, 54, 87, 88].

¹⁵³ For a survey see [52], section 8.2.2.1; [53], section 2.4.2.2 sums up the case for a double dividend and provides three further references.

¹⁵⁴ A recent complementary French report [19] innovatively devotes long developments to this issue. By implementing the macroeconomic MESANGE model of the French *direction du Trésor* it indeed identifies double dividend potentials when carbon tax proceeds are recycled in lower labour taxes.

1.3. Beyond carbon pricing

The recent literature devoted to low-carbon scenarios describes many instances of failure of pricing policies to induce the most ambitious objectives [85, 79, 25, 35]. Clarke *et al.* [25] question these inabilities, identifying (beside more straightforward international participation issues, solving limitations and the availability of technological options)¹⁵⁵ “decline or expansion constraints” in key aspects of the decarbonisation process: in most models, the penetration rate of techniques is bounded by asymptotes that are either explicit or induced by constant depreciation rates of the capital stock.¹⁵⁶

It is hard to draw robust policy conclusions from such evidence: there is no theoretical reason why extreme prices should not end up impacting on penetration rates, *e.g.* by gradually inducing the early retirement of the existing capital stock—although the practical question of calibrating such fundamental shifts is certainly on the frontier of current climate policy modelling. In that sense the unreachable nature of some targets could be attributed to modelling limitations rather than to a shortcoming of the pricing instrument. This is implicit in the use by some modelling teams of exogenous scenario assumptions on alternate development patterns.¹⁵⁷ On a similar note, the widespread use of carbon pricing in models is to some extent ambiguous: some studies explicitly state that carbon pricing is only meant as a proxy to unspecified policy portfolios better apt to trigger abatement, especially for the most ambitious emission cuts, which require carbon prices reaching heights that raise serious implementation issues.

In a different corpus of literature, stemming from Jaffe and Stavins [56], a number of energy market failures have been identified as warranting policy instruments beyond the market-based ones (see *e.g.* [7]):

- A series of market imperfections drive a wedge between the socially optimal and the effective innovation effort on low-carbon technologies. Among these, knowledge spillovers prevent innovators from capturing the full return on their investment; insufficient or lacking infrastructure hinders the penetration of some technologies; fragmented technological markets provide little economic leverage to engage in R&D programmes characterised by high initial costs, while historical energy market operators have little incentive to innovate.¹⁵⁸
- Another series of market failures hamper the adoption of low-carbon end-use technologies or behaviours. First, information is fragmented if not sparse on the particulars of the available technology options. Secondly, capital constraints prevent the more modest households and firms from investing into end-use equipment profitable over the long-term only. A third market failure is caused by misaligned incentives, whereby the beneficiaries of abatement actions are not entitled to them, *e.g.* the landlord/tenant problem or the split incentives between professional drivers and their companies. At last, intangible costs linked to real or perceived non-monetary characteristics of technology options, limit the adoption of seemingly cost-effective technologies.

It is again possible that the abatement actions impeded by these market failures could be triggered by sufficiently high carbon prices. It is reasonable to think, though, that more targeted, not necessarily market-based policies could tap this abatement potential at a lower social cost; these should thus complement carbon pricing if the cost-efficient option is to be struck. But this conclusion is at the most glimpsed at in peer-reviewed literature,

¹⁵⁵ This latter point is also stressed by Edenhofer *et al.* [35]: some of the models of the ADAM European project they report on had to be extended with Carbon Capture and Storage (CCS) and combined biomass and CCS options to reach the most ambitious targets envisaged.

¹⁵⁶ Clarke *et al.* [25] insist on the methodological difficulties of pinpointing the causes of modelling failures. This calls for a thorough examination of some mathematical and parametrical particulars that are out of reach of anyone but the modellers themselves. This is another example that drawing conclusions from any simulation requires a deep understanding of the underlying modelling tool.

¹⁵⁷ See *e.g.* [27], [40].

¹⁵⁸ Jaffe *et al.* [55] insist on the concomitancy of the environmental and technological market failures to advocate complementary carbon pricing and R&D subsidies to climate friendly technologies; this has stimulated some modelling exploration *e.g.* [12], [41].

where comprehensive assessments of policy portfolios are sorely missing,¹⁵⁹ either because the issue is shunned and the uniform pricing rationale still prevails, or because of modelling limitations. ‘Grey’ literature, on the contrary, offers studies and reports that insist on the necessity to combine a wide range of policy instruments to achieve high rates of decarbonisation, and propose such combinations.

2. Targeted policies and measures: a survey

The set of recent studies and reports matching extended policy portfolios with high rates of decarbonisation in the middle of the century is conveniently split between works commissioned or carried out by public bodies, and works produced by non-governmental organisations (NGOs).

In the first of these categories, France, Germany and the United Kingdom (UK) each produced studies focusing on the way to comply with their national 2050 commitments, a factor 4 emission cut for France, and a factor 5 cut for Germany and the UK.¹⁶⁰ The French report [16] was commissioned by the French government to an advisory body, the *Centre d’Analyse Stratégique* (CAS). The German report [9] was commissioned by the German federal environment ministry (BMU) to a consortium of 4 research centres. The British report [20] emanates from the Committee on Climate Change, an independent advisory body. Prior to the CAS 2006 report, France had also issued a shorter note on the Factor 4 objective [78]; besides, in 2008 the CAS reported on French energy perspectives to 2020 and 2050 [17], and the document contains many climate policy recommendations. Some policy measures beyond carbon pricing can also be gleaned from the previously quoted Quinet report on the shadow price of carbon [18], or from a more recent effort focused on identifying abatement pathways to 2050 [19].

In the second category, Greenpeace issued a report in 2005 focusing on EU-25 that envisages a 70% emission cut in 2050 from 2000 levels [43]. In 2008 the same NGO published a much expanded report at global scale, which describes a 78% emission cut in 2050 from 1990 levels for OECD Europe [44]. In 2010 the European Climate Fund (ECF) developed another extensive prospective study for the European Union [32, 33]. The INFORSE network proposes less extended scenarios, which include an EU-27 scenario that envisages a phase-out of fossil energy by 2050 [50]. INFORSE is itself a network of NGOs, among which a militant Zero Carbon Britain, which produced two detailed reports specific to Britain describing a provocative total phase-out of carbon emissions in the course of 20 years only: [91] updated and expanded to [92]. In 2006 the Negawatt association published a more synthetic report for France [69].¹⁶¹

In echo to our first section, let us note that most if not all the surveyed studies advocate carbon pricing as a core mitigation measure. Carbon prices are however rarely pinned down, and at exogenous levels when so—e.g. by [9] or [44]—with the only exceptions of [20] and [19]. We will come back to this in a further subsection on the modelling support of the studies.

¹⁵⁹ Many energy and carbon policy instruments beyond the carbon tax and ETS (green and white certificates, performance standards, border tax adjustments, etc.) have been explored in a body of specific literature, mostly sustained by analytical modelling. What is missing is the comparative assessment of the aggregate social cost of complex policy portfolios (see our third section below).

¹⁶⁰ The German and British targets are with reference to 1990 levels, echoing the Kyoto commitments. The French target is more loosely established; CAS [16] assumes it is also with reference to 1990, but it could also be measured against 2003, 2004 or 2005 levels, the years in which the target made its way into the French political agenda.

¹⁶¹ In a 2011 report, Negawatt updates this scenario but not its policy recommendations.

2.1. Advocated policies and measures

The advocated policies and measures range from the field of energy supply to that of energy demand, as well as to actions beyond the energy markets.¹⁶²

The stress on **energy supply** is mainly put on accelerating the penetration of renewables. A first policy move should be to restore a ‘level playing field’ to energy supply competition [9, 43] by definitively suppressing any subsidy to conventional electricity production. Some studies also insist on the necessity to even competition between the renewable options themselves: the existing incentives should be thoroughly reviewed, and brought into consistency [9]. Indeed, the reviews by CAS [18] and DECC [28] of the existing instruments in France and the UK reveal large discrepancies in the underlying carbon valuation.

Beyond this prerequisite, most studies recommend complementary measures as feed-in tariffs [43-44, 91-92, 9], legally binding renewable targets [43, 20, 33], together with a simplification of the administrative procedures surrounding electricity production and access to the grid [43, 9, 20, 33], whose cost should be borne by a central grid authority rather than billed to the renewable energy projects themselves. Some studies insist on the necessity, for the renewable targets and the feed-in tariffs alike, to preserve a technological diversity crucial to the most ambitious targets [43]. This obviously constitutes a real challenge for tariffs, as it implies a thorough prospective on the future relative costs of the renewable technologies.

The targeted increase in renewable energy supply calls for improvements in the electric grid, in the three dimensions of storage, transport and distribution. An upgrade to ‘smart grids’ should allow balancing power production by decentralised and intermittent units ([17], specifically targeting electric heating; [91], promoting a ‘vehicle-to-grid’ system—although [92] minimises the contribution of such a system; [33]), if not managing the level and timing of demand against financial incentives ([17]; [43]; [91] and [92], which advocate heterogeneous pricing based on interruptibility of supply).

It is worth mentioning that none of the surveyed studies place a strong emphasis on biofuels. The general stance is one of cautious support, considering both the uncertainties regarding the life-cycle assessment of such energy forms [17], especially when imported from outside the EU [9], and the potential undesired side-effects on food prices [9].

To conclude on energy supply, beyond renewables BMU [9] underlines the necessity to tap the huge potential energy-return gains of combined heat and power (CHP) systems. It supports the German CHP Act, although questioning the level of subsidies to heat providers based on two studies.

Turning to **energy demand**, mandatory energy efficiency improvements are advocated by ECF [33], and by Greenpeace [43] at the annual level of at least 2.5% for the private sector and 3% for the public sector. In the case of France, CAS [17] advocates putting an end to regulated energy prices to attain such ambitious objectives. More specific measures focus on the main potential contributors to energy savings: buildings, transportation, appliances and end-use equipment—while industry is consistently viewed as sensitive enough to market signals to not require complementary measures.

Many studies identify action on buildings as necessary to ambitious targets [91-92, 17, 78, 33], while emphasising their slow dynamics. CAS [17] stresses the highly decentralised nature of decision making in the building sector, and the financial constraints weighing on many of its actors—ZCB [91] insists on the latter as well, and advocates that some of the proceeds of the quota auction it promotes be used to finance investment by the poorer households.¹⁶³ Beyond this, general recommendations include a strengthened and anticipated development of building regulations for new construction, which should already reach up to 2030 [19]. INFORSE [50] more

¹⁶² Section 2.4.2 of [24] provides an extended version of this section.

¹⁶³ Although it is specifically pregnant in the building sector where investment costs are high, limited investment capacity also impacts end-use equipment.

specifically proposes to raise mandatory building-codes to current low-energy housing levels as early as 2010, and to require that all major renovations include a major energy renovation. It also advocates that passive houses should benefit from a massive R&D programme to become the basis of updated energy standards. ECF [33] sets a 2020 deadline to this objective. CAS [17] proposes that any new building should be equipped with either heat pumps, renewable heating, or solar thermal hot water. Greenpeace [44] recommends a similar mandatory share of renewable sources to heating and cooling, while CCC [20] calls for some appropriate framework to support the wide-scale deployment of renewable heat. A couple of studies insist on the necessity to monitor these constraints and liabilities [91, 17], based on surveys revealing the ‘implementation gap’ between regulations and actual performances.

The existing stock should also be subjected to an ambitious refurbishment programme [9, 0, 33], to hasten convergence between its efficiency and that of new constructions [78, 19]. To implement this convergence ZCB [91] proposes “mandatory energy efficiency improvement at exchange of contract on sale, and when letting”. Less targeted measures include tax rebates in exchange for efficiency measures, and a VAT exemption on refurbishment expenses. ZCB also expresses support to the British Warm Front programme (grant programme directed to the poorer households) and the Decent Homes programme (refurbishment of social homes). CAS [17, 19], CCC [20] and ECF [33] support the certificates mandated by the EU directive on the energy performance of buildings, as these concretise the constraint on real estate markets. Among other provisions based on energy performance certificates (EPCs) CAS [17] proposes that

- firms be required to publish an indicator of the energy performance of the buildings they own or occupy,
- landowners be forbidden to increase the rents of the properties that belong to the lower EPC categories,
- an accelerated amortisement of the acquisition or refurbishment costs be allowed to buildings belonging to the higher EPC categories.

CAS also advocates measures more specific to France.¹⁶⁴ Alternatively, ZCB [91, 92] supports a transition to energy services companies that charge for the provision of energy services (lighting, warmth, hot water, *etc.*) rather than energy volumes, with the advantage of trusting to such specialised companies the complex optimisation of energy systems. The shift to such market organisation is tentatively started by the Supplier Obligation in the UK, which CCC [20] strongly supports.

Another most targeted energy demand sector is transportation, because of its continued growth and reliance on fossil fuels [17]. General recommendations regard a ‘systemic approach’ to the transportation problem: the concerted reform of a broad range of public policies related to urban planning, land settlement, supply chains organisation, *etc.*, is necessary to contain the challenging growth of transportation services, and reorient them to carbon sober modes [78, 65, 17—although subordinating such changes to public acceptance, 33, 19]. Radanne [78] particularly urges for early action, considering the dynamics at work. ZCB [91] advocates infrastructure changes as improved cycle lanes (also supported by Greenpeace [43]) and pedestrian facilities. Negawatt [69] or CAS [17] recommend fostering telecommuting and car-sharing, although they do not pinpoint specific instruments. CAS still urges to lift the legal obstacles hampering car-sharing (insurance, expenses eligibility, *etc.*).

More targeted measures primarily regard passenger cars. Greenpeace [44] advocates strict technical standards and measures to guarantee vehicle size decrease. CAS [19] recommends emission standards anticipated to 2030; CAS [17] pinpoints an objective of 120g/km in 2012 for new personal cars—10g/km stricter than the EU objective, and CCC [20] one of 100 g/km in 2020. Both studies agree that standards are necessary on all other classes of motor vehicles as well. CAS [17] also suggests mandating existing efficiency improving equipment (instant fuel consumption display, tire pressure gauge, cruise control, *etc.*). To downsize vehicles Radanne [78] supports a

¹⁶⁴ Extension to landlords of the tax credits earned by energy saving investments; effective implementation of the obligation of individual accounting for collective heating systems; increase of the VAT rate on cooling systems installation.

bonus/malus scheme akin to the one introduced in France in 2008,¹⁶⁵ highlighting it as a good use of the fiscal instrument as a lever on consumer behaviour rather than a source of public money. CCC [20] supports a similar incentive. Radanne also suggests an EU-wide mandatory tie-down of engines, stating this could reduce fuel consumption by 20%—but without addressing the problem of heterogeneity of speed limits in Member States. CAS [17] does by advocating a harmonised upper limit of 130 km/h, not so much for its direct impact on fuel consumption, as for its indirect impact on the power of cars, allowing for reduced consumption in all driving cycles alike. CAS also stresses the role that training drivers to ‘eco-driving’ and information campaigns could play; advocates the development of urban tolls and time-dependent toll pricing (to reduce fuel waste through congestion); and suggests that a *vignette* should be reintroduced on a CO₂ emission basis considering a €100 carbon value and an average 14,000 km per year. CCC [20] also mentions the potential of a CO₂-based *vignette*, without pinpointing levels.

Targeted measures on other transportation modes are few. On road freight, CAS [17] recommends a kilometre-fee enforced through GPS data. Negawatt [69] advocates a specific taxation of low-cost air transport, without more precision. ZCB [91] goes as far as suggesting that the nationalisation of coach and railways could be required to meet its ambitious objective of a fourfold development of these modes. It also urges to complete the electrification of the British rail network.

Another series of measures concerning energy demand regard appliances and end-use equipment. Recommendations include:

- Extending of environmental labelling to more product information [44, 17, 91, 20]. ZCB [91] specifies that energy ratings should be permanent and clearly visible, to play on reputation effects, and should extend to standby power consumption.
- Strict technical standards [78, 44, 17, 33]. Radanne [78] underlines this should reduce the costs of efficient appliances by guaranteeing them larger markets. CAS [17] specifically mentions the case of light bulbs.

At last, most studies promote **complementary measures beyond energy markets**. First, the need for a strong, coordinated and immediate R&D effort is consistently stressed, to foster technical change in energy supply technologies and end-use equipment alike. Some studies identify particular fields of research, which can be split in two:

- Specific end-uses and end-use equipment: cooling [44]; personal cars [78]; positive energy buildings [17].
- Ancillary technologies: heat storage [44], electricity storage, transport and distribution [91, 17]; carbon sequestration [78, 17, 20]—although some studies exclude it as a non-sustainable option [91, 9].

Although most if not all studies advocate support to renewable technology development, CAS [17] is the only one identifying a priority, namely second generation biomass, stressing that support cannot be generalised considering the current state of public budgets.¹⁶⁶ On the contrary, ZCB [91] or CAS [19] stress that R&D programmes should strive to balance their support to competing technologies and let the market elect the most cost-efficient ones.

A second policy recommendation beyond energy markets regards public awareness campaigns, which many reports advocate, either on loose terms (“energy efficiency”), or on more specific issues. These include driving behaviour, heating and cooling practices, and standby power consumption. In a similar line of thought

¹⁶⁵ The buyer of a new car is subject to a range of taxes or subsidies depending on the car’s average CO₂ emissions *per* kilometre.

¹⁶⁶ CAS also advocates strong public support to 4th generation nuclear and nuclear waste treatment. We have deliberately left out the nuclear phase-out question, which is clear-cut in most NGO reports, and strictly echoing national agendas for the British, French and German public reports.

demonstration projects are advocated on the particular questions of building efficiency by Greenpeace [44], and on the CCS technology by CCC [20].

A third and last field of policy intervention outside energy markets regards the implementation of the ambitious training programmes required to face the escalating demand induced by low-carbon policies on many job markets. Primarily concerned is the construction market broadly understood, from building conception to consultancy on energy performance to refurbishment and construction proper [17, 19, 44, 91]. Again, some stress is put on the timing issue of organising and developing the appropriate training courses [17, 19]. CAS [19] identifies the carbon pricing proceeds as a potential source of funding, while ZCB [92] calls on the proceeds of a border-tax adjustment system—it is indeed the only report opting for such a compensation of competitiveness effects.

2.2. Modelling support

The above list of policy options is thus extended in both its coverage and level of detail, especially in some end-use sectors as transportation or buildings. It is however only partially backed by modelling support. To begin with, 8 of the 13 surveyed studies follow a ‘storytelling’ approach to scenario building [16, 19,¹⁶⁷ 43, 50, 69, 78—as far as can be told from the scant methodological information, 91, 92]¹⁶⁸: they combine detailed exogenous assumptions on the qualitative and quantitative evolution of energy supply and demand, mostly leaning on more or less precisely documented external expertise—which can in turn derive from modelling experiments, or not. Such constructions come at the expense of consistency: there is no guarantee that the underlying expertises share compatible assumptions on such major drivers as economic growth, fossil fuel prices, the costs of technical options or even demography. Beyond this consistency problem, in some policy instances the lack of support is total. Indeed, ZCB [91] develops a minute multigas cap-and-trade system strictly enforcing the 20-year emission phasing-out it promotes, with 40% of the yearly quota freely allocated to households on a *per capita* basis, to correct distributional impacts, while the remaining 60% is auctioned to firms and public institutions, and the auction revenue “ring-fenced for use in easing the transition to a zero-carbon economy”. Although on carbon pricing rather than on targeted measures, this offers the most striking example of the imperious necessity of economic assessment: while ZCB cautiously avoids providing estimates, it is quite likely that auction prices for such drastic carbon constraints would reach unsustainable heights, inducing such shifts in the relative prices (including *vis-à-vis* international prices) as to cause entire sectors of the British economy to collapse—or more likely the policy action to be abandoned under public pressure.¹⁶⁹

Four additional studies derive their prospective outlooks of energy systems from models of the ‘bottom-up’ family [9, 44, 17, 20], thus improving on the consistency of their analyses—only partially so for Greenpeace [44], which articulates the modelling of 4 different institutes without reporting on any harmonisation process. However, bottom-up models picture little economic behaviour if any. Energy demand is explicitly described as a parameter of scenario building: the impacts of the collection of policy measures envisioned are—mostly undocumented—exogenous estimates. In short, the advocated policy portfolios generally lack support from (i) microeconomic expertise, which could assert that the wide array of advocated measures match the often dramatic impacts attributed to them, and (ii) a macroeconomic integrating framework, in which these measures

¹⁶⁷ CAS [19] uses the POLES model to derive emission pathways that are “cost-effective” in a quite restrictive sense only (minimisation of technical abatement costs of fossil CO₂; policy constrained to uniform carbon pricing with constant growth rates). It tests the price trajectories produced by POLES in a set of macroeconomic models to check for sectoral activity and employment impacts, but omits controlling for consistency. Ultimately, neither the advocated sectoral emission pathways nor the recommended policies and measures derive from modelling.

¹⁶⁸ ZCB [91] evokes a transport model p. 137 et seq., but this appears to have both exogenous demand and modal shift, see the table p. 138.

¹⁶⁹ Combet et al. [26] assess substantial GDP and employment losses induced by terms of trade effects for schemes close to ZCB’s proposal, in the case of France, and for a €100 to €400 *per* tonne CO₂ carbon tax. It is doubtless that the prices induced by ZCB’s proposal would rapidly exceed €400 *per* tonne CO₂.

could interact to form a consistent economic and energy system picture, accounting for the feedbacks from equipment goods, capital or labour markets. The latter shortcoming indeed constricts aggregate impact assessment to technical costs and forbids reporting on GDP or welfare costs.¹⁷⁰

Lastly, the ECF study [32, 33] distinguishes itself by founding its scenarios on a combination of bottom-up and top-down modelling approaches. Although the report lacks a thorough methodological exposition, it appears from its appendixes that bottom-up expertise (if not modelling: a “Mc Kinsey [power] generation model” is mentioned, but not referenced), extending to energy demands and energy efficiencies, together with the investment costs of electric vehicles, heat pumps and biofuels penetration, are fed into a computable general equilibrium model to assess the macro-economic impacts of low-carbon scenarios. The extension of the modelling scope to macro-economic variables is an obvious improvement over the other approaches. However, energy demands, at the heart of the modelling architecture, remain exogenous. The links between the advocated policies and measures and the targeted energy and carbon efficiency improvements are again a series of hardly connected educated guesses.

3. A blueprint for further policy modelling research

Addressed from the viewpoint of the modeller, the above panorama calls for extensive further policy analysis. Both our sections on carbon pricing and targeted measures lay some lineaments that we can now develop and weave into a research agenda. We purposely limit it to cost-efficiency analysis, thereby both acknowledging current EU policymaking and shunning from the current debate surrounding cost-benefit analysis (Box 4). In this latter choice we follow Dietz [30] or Yohe and Hope [90], who react to the persisting if not increasing failure of damage assessment to reach any form of consensus.^{171,172} As Kopp and Mignone [60] establish (without formally endorsing it), this shift is a transcription to climate affairs of Baumol’s prescription to degrade the Pigouvian policy principles when faced with too-elusive externality costs [6].

We also avoid opening our renewed agenda to the transversal issue of uncertainty: the development of stochastic programming and the increasing use of Monte-Carlo simulations appear appropriate improvements on the way to facing this important challenge, although they should be more systematically applied beyond climate sensitivity and damage uncertainties.¹⁷³

¹⁷⁰ It must be noted that this scope limitation is voluntary for CCC [20], considering the uncertainty surrounding impacts beyond the energy markets. Hourcade and Gheris [48] propose a disambiguation of climate policy ‘costs’.

¹⁷¹ Dietz observes that the gap of about one order-of-magnitude between the plausible ranges of the social cost of carbon and the corresponding marginal abatement costs that he estimated in 2010 [31] has likely been amplified by more recent publications.

¹⁷² Ackerman and Stanton [2] also advocate focus on cost-efficiency analysis, not only because the social cost of carbon is highly uncertain, but also because they reassess the corresponding uncertainty range to values confidently greater or equal to the estimated range of the marginal costs of the total global abatement potential up to 2050.

¹⁷³ Many of the references of Box 4, beginning with [0], address uncertainty through Monte Carlo techniques. Haurie *et al.* [47] and articles of the same journal issue report on recent applied research on the uncertainty about socio-economic factors including behavioural parameters, the availability of technological options, the outcome of international negotiations, etc. The series of papers in Filar and Haurie [37], particularly the first chapter by the two editors, conceptualises the issue and introduces the methods.

The 2007 Stern review [82] and the 2010 United States Interagency Group on the Social Cost of Carbon [51] successively fueled an escalating controversy on cost-benefit analysis,¹⁷⁴ including three recent special journal issues [61, 67 and parts of 45]. The most debated points are:¹⁷⁵

- Climate sensitivity, *i.e.* the long-term impact of CO₂ concentration on temperatures, and particularly the consequence of considering a ‘fat’ rather than a ‘thin’ tail to its probability distribution [89, 76, 77, 83, 72].
- The damage function linking temperature change to economic impacts. The quadratic form introduced by Nordhaus [70] is suspected not convex enough, and alternatives explored [89, 76, 83, 3, 30, 59].¹⁷⁶ Besides, the available damage estimates are criticised as incompletely covering the many impact channels [30, 60, 67, 83]. Kopp and Mignone [60] also stress how inappropriate a social cost of carbon is if measured off a baseline already beyond some ‘tipping point’ of the climate system (*i.e.* when the damage function is only piecewise convex).
- The discount rate, which in the standard Ramsey framework dissociates in the rate of pure time preference and the constant relative risk aversion. Prescriptive vs. descriptive approaches to discounting lead to markedly higher vs. lower assessments of the social cost of carbon *i.e.* the optimal mitigation requirements [71, 60, 4, 83]

Uncertainty on these three dimensions dramatically increases the range of plausible social costs of carbon. Fearing that this uncertainty is in part irreducible, some recent papers more or less openly question the ultimate contribution of cost-benefit analysis [30, 89, 90, 83].

Box 4 Current controversies on cost-benefit analysis

On this contained agenda, the first field of policy research emerging from our survey regards the establishment of cost-efficient carbon pricing trajectories to point-in-time mitigation commitments.¹⁷⁷ When assessing such commitments, most available studies indeed constraint their pricing trajectories to either some transposition of Hotelling’s rule, or *ex-ante* full-blown emission trajectories encompassing the targets—see our section 1.1 on prominent policy reports and Box 5 for a generic formulation of modelling approaches. The rationale for Hotelling is explained at length in [18].¹⁷⁸ However this same report makes it very clear that Hotelling applies only if the policy objective is specified as a CO₂ concentration ceiling, and as long as this ceiling is not reached. Although it is not their primary purpose, Vogt-Schilb and Hallegatte [87] demonstrate that the optimal time profile of emissions varies substantially if policy objectives are rather expressed in terms of constraints at pivotal years.¹⁷⁹ They derive this insight from a model in which they depict the inertia of abatement potentials: the multiple specific stock dynamics of end-use equipment, energy production, the building stock and ultimately urban and transportation infrastructures, shape the dynamics of abatement options. Three other determinants of the development of the mitigation potential are:

- Demographics, which impact on the available manpower, on public budgets in many European countries where pension systems are public, and also on the average savings rate: they strongly influence growth and emissions, but also the resource available to finance abatement actions.

¹⁷⁴ Some earlier caveats on a sound use of integrated assessment modelling are provided by Schneider [81], who stresses the contribution of Ravetz [80].

¹⁷⁵ Another increasingly researched question is the consequences of damages impacting the capital stock [59] [0], the growth rate [75], utility [59], technical progress [68] [0] or its rate of change [68] [0], rather than (standardly) economic output.

¹⁷⁶ Similarly, [1] questions the optimism of several elements of the disaggregated treatment of damages by the FUND model.

¹⁷⁷ The policy conclusions of the ADAM project [58] touch on this unresolved challenge of dynamic efficiency.

¹⁷⁸ Theoretically amended to account for the rate of carbon uptake by natural reservoirs.

¹⁷⁹ They also compute a 62% excess cost from the loss of ‘when flexibility’ implied by forcing point-in-time targets rather than some aggregate carbon budget at a 2050 horizon—constraint (7b) rather than (7a) in our Box 5.

- Fossil fuel prices, the sum of extraction costs and rents. Their specific dynamics, conventional and unconventional resources alike, constitute another price signal that will all the more impact mitigation measures as stocks deplete—conversely, ambitious mitigation cannot but reduce the pressure on fossil fuel markets, thereby inducing a ‘rebound’ of consumption.
- Technical progress, which defines how input substitution flexibilities evolve with each capital vintage. It is driven by both research and development activities, and learning-by-doing. The former activity and the latter phenomenon must be accounted for to determine, even if only tentatively, the ‘carbon intensity’ embodied in successive capital vintages.

The four interacting dynamics should be integrated in some intertemporal optimisation framework, that in the European case could target a 2050 emission objective, with at least carbon pricing and public R&D trajectories as variables. The task is not out of reach of some models currently in use, and indeed some of the dynamic interactions at play have already been touched upon—particularly as regards trajectories of R&D investment, see e.g. [12], [41]. Of course the resulting pricing pathways, as any modelling outcome, would be dependent on a particular set of assumptions (including those determining the discount rate, which attracted great attention in the wake of the Stern review), but at least these could be explicitly discussed, and the policymaker allowed more informed decisions.

The second field of investigation emerging from our survey is the *Terra Incognita* beyond first best static policy design. Section 1.2 echoes the firmly established fact that the uniform pricing rationale is a challenge to enforce in real world ‘second best’ economies, where market distortions can be large enough to significantly increase costs if these are distributed in a standard way (taxes or auction proceeds rebated lump-sum to households, grandfathered permits). Böhringer et al. [10] identify two such distortions:

- Pre-existing taxes and subsidies. These impact public budgets, and the shift in their fiscal bases or beneficiary activities induced by carbon pricing must be accounted for: some carefully differentiated pricing could lower the social cost of the carbon constraint by minimising its impact on the pre-existing public financing structure.¹⁸⁰
- Terms-of-trade effects. The degree of exposure to international competition is highly variable across sectors, from poorly differentiated raw materials to local services. It is hard to rule out that some moderate increase of the carbon price laid on unexposed activities to compensate for carbon price cuts granted to exposed sectors could lower the social cost of some mitigation objective.

These two types of distortion are easily modelled as they rest upon the interplay of readily observable relative prices. More controversial distortions regard some ‘imperfect’ features of e.g. labour markets in many European countries, where numerous regulations and transaction costs prevent full clearing through prices.

¹⁸⁰ This is further complicated by the varying possible assumptions about public budget constraints. A standard assumption is that of the ‘budget neutrality’ of the reform, mostly defined as a maintained budget balance under the constraint of constant real public expenditures. This implies selecting some adjustable tax rate that allows balancing the induced variations. It is obvious that the cost of any abatement target will depend on the selected adjustable rate and the induced shift in any pre-existing distortions.

A generic, discrete carbon/economy model can be defined as:¹⁸¹

$$U_t = u_t((1-s_t)Y_t, \alpha D_t) \quad (1)$$

$$Y_t = f_t(K_t, \beta D_t, \tau_t) \quad (2)$$

$$K_{t+1} = k_t(K_t, s_t Y_t) \quad (3)$$

$$e_t = \varepsilon_t(\tau_0, \dots, \tau_t) \quad (4)$$

$$D_t = d\left(\sum_{i=0}^t e_i Y_i\right) \quad (5)$$

where at each time period t (we drop t subscripts for readability):

- Social welfare U is a function u of output Y minus savings sY ($\partial u/\partial Y > 0$, $\partial u/\partial s < 0$) and of an α share of impacts $D \geq 0$, which turn to harmful damages beyond some threshold \bar{D} ($0 \leq \alpha \leq 1$, $\forall D > \bar{D}$ $\partial u/\partial D < 0$).¹⁸²
- Output net of damages Y is a function f of the capital stock K ($\partial f/\partial K \geq 0$), of a β share of D ($\beta \geq 0$, $\beta + \alpha \leq 1$, $\forall D > \bar{D}$ $\partial f/\partial D < 0$) and of a marginal technical abatement cost $\tau \geq 0$, which turns harmful beyond some threshold $\bar{\tau}$ ($\forall \tau > \bar{\tau}$ $\partial f/\partial \tau < 0$).¹⁸³
- Capital stock K accumulates through time according to a function k considering savings sY ($\partial k/\partial K > 0$, $\partial k/\partial s Y > 0$).¹⁸⁴
- Emission intensity of output e is a decreasing function ε of the trajectory of τ ($\partial \varepsilon/\partial \tau < 0$).
- Impacts D are an increasing function of cumulative emissions ΣeY ($\partial d/\partial \Sigma eY > 0$)—eq. (5) aggregates climate sensitivity and the damage function of Box 4.

In this framework, provided damages are accounted for ($\alpha + \beta = 1$) and considering a pure rate of time preference ρ , standard cost-benefit analysis is

$$\text{Max}_{s, \tau} \sum_{t=0}^{+\infty} e^{-\rho t} U_t \quad (6)$$

Alternatively, cost-efficiency analysis abstracts from impacts ($\alpha = \beta = 0$) to consider the same objective function (6), subject to either some carbon budget up to T ¹⁸⁵

$$\sum_{t=0}^T e_t Y_t = A \quad (7a)$$

or more pragmatically some emission target at date T :

$$e_T Y_T = A_T \quad (7b)$$

However, many published low-carbon modelling studies enforce a stronger

$$\{e_1 Y_1, \dots, e_{T-1} Y_{T-1}\} = \{A_1, \dots, A_{T-1}\} \quad (8)$$

[e.g. 57, 10, 62], while another set of studies alternatively add

$$\forall t > 0 \quad \tau_t = (1+r)^t \tau_0, \quad (9)$$

with some exogenous r related to the discount or interest rate [85, 46, 13, 14] (see also footnote 149) or the consumer price index [5]. In some studies relying on it condition (8) is the pathway of a separate analysis [57], while in some others it is explicitly a simple interpolation [10, 62]. Similarly, condition (9) aims at optimality by applying Hotelling's rule (see section 1.1).¹⁸⁶ No study however offers proof that (8) or (9) do not constrain τ (and s if warranted) to a suboptimal pathway in their own modelling framework.¹⁸⁷

Box 5 A generic formulation of low-carbon modelling

The consequences of such second best features on policymaking do not receive the attention they deserve, considering the stakes of significantly reduced if not inverted abatement costs illustrated by the formerly quoted IPCC survey [51]. They should be explored in a pragmatic way, notwithstanding the unsettled academic dispute whether the benefits from alleviating distortions should be attributed to the climate policy *per se* or not—a point arguably irrelevant to the policymaker. Case studies firmly anchored in some dominating traits of the real world economies can contribute to elicit them. To be thorough these should give greater attention to the rebating option that closes the loop of any price-based policy, as CAS [19] indeed does. In that regard attempts at pinpointing ‘the’ optimal recycling scheme through modelling are probably vain, as they are likely to point at some corner solution blatantly ignoring the political constraints that weigh on public decision making. Still, it should be made clearer to the policymaker how contrasted recycling options lead to contrasted welfare and distributional impacts.

A third field of further research regards the microeconomic elicitation of incentive overlaps. Section 2 demonstrates that the available literature on low-carbon policy portfolios is more a catalogue of policy measures than anything else, with too little attempts at rationalising the corresponding wide array of incentives. These incentives thus partly overlap, see *e.g.* the manifold measures simultaneously targeting the speed, power, carbon efficiency, equipment, road access, *etc.*, of personal cars. On a strict efficiency ground this comes at the risk of exaggerating the incentives to some forms of abatement, thereby incurring unnecessary costs—it is a fact established since Tinbergen [84] that public policy instruments should be sufficiently focused to address one market failure and one only,¹⁸⁸ although this conclusion has been qualified in different ways by recent research, *e.g.* by Benneer and Stavins in a general second best setting [7], or by Lecuyer and Quirion as hedging against the risk of pricing policy failure [65]. It is also a threat to policy implementation, as it manifestly contradicts the ‘pedagogy’ principle that an ambitious carbon policy should be stripped down to the most simple possible expression if it is to gather public acceptance.

A body of literature exists that compares the merits of different policies aimed at the same carbon abatement options, mostly in an analytical microeconomic framework—Fischer and Preonas [39] provide a survey extending beyond their focus on renewable energy promotion. It should be systematically extended to more of the policy options identified in the grey literature on low-carbon societies, under the Tinbergen requirement that each of these options could be pointed at a particular market failure, which should be analytically qualified as well. The tentative framework developed by Oikonomou and Jepma [74] for analysing the interactions of policy instruments could provide the basis for a more systematic approach. It should also be complemented, as its authors indeed call for, by numerical analyses simulating the particular conditions of the current economies, and indeed exploring some of the anticipated trends of the relevant set of parameters, along the lines of Goulder et al. [42] or Fischer and Newell [38]—Lecuyer and Bibas [64] offer more references of that effect.

Last but not least, the three outlined research strands should eventually be brought together into an integrated framework of analysis that could be applied to policy assessment: it is necessary that the carbon pricing trajectories resulting from the first and second lines of research, and the policies and measures emerging from the third one, should be assessed simultaneously, lest some significant interactions and feedbacks be disregarded, at the cost of economic efficiency.

This last task is probably the most daunting: even if their numbers are cut down by the elicitation of a rational combination of incentives, most of the recommendable policies and measures play at a scale, and are justified by market imperfections, which comprehensive modelling structures will be hard put to model. The hybridising methods explored to bridge the gap between bottom-up and top-down energy modelling (see [49] and articles of the same journal issue) offer the beginning of an answer to these challenges, but the beginning only. Their further development is essential, if the current fragmented economic expertise is to be built up into a comprehensive vision of future low-carbon policy portfolios.

¹⁸⁸ This point has been repeatedly made by the OECD in recent years [73].

Conclusion

In this paper we have surveyed central pieces of the scientific and policy-oriented literature on low-carbon futures. We first stressed the somewhat confusing use of modelling expertise by French and British governmental endeavours to pinpoint a normative value of carbon, the admitted backbone of climate policies. We then highlighted the striking gap between the wide array of policy instruments envisioned in the policymaking literature and the scarce modelling expertise on policies and measures beyond carbon pricing. These shortcomings inspire us an updated, pragmatic low-carbon policy modelling agenda insisting on (i) the assessment of cost-efficient trajectories to point-in-time targets freed from any preconceived emission or pricing pathway; (ii) the exploration of the *terra incognita* beyond uniform pricing, accounting for pre-existing distortions or inertias of abatement options; (iii) a systematic elicitation of incentive overlaps and possible justifications of them; (iv) an integration of these key features in some consistent modelling framework.

A transversal conclusion to our research is that low-carbon modelling studies appear too isolated from, on one side, a scientific literature that has long started to come to grasp with some of the real-life complexities disqualifying the disincarnate ‘first best’ policy options; on the other side, a policymaking corpus whose diversity echoes the same real-life complexities, in a probably more comprehensive but doubtlessly less articulate manner. Beyond the scientific challenges we outline, it is only by opening to both influences, leaning on the former one to rationalise the latter, that applied modelling studies can significantly enhance their policy relevance, thereby hopefully increasing their necessary influence on the policymaking process.

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Annex 4

The IMACLIM Network Manifesto

The IMACLIM Network Manifesto

The community of researchers engaged in the development of IMACLIM models share two core methodological principles:

1. Designing policy-relevant outlooks requires combining the economist's and the engineer's approaches to describing human systems¹⁸⁹

- 1.1. Interrelations between consumption patterns, production & end-use techniques and geographical localisations shape the economic, social and environmental characteristics of development pathways and thus their sustainability. They constrain the development path of energy systems as well as that of other key technical systems such as agriculture, urban geography, transportation and industrial systems.
- 1.2. A prerequisite to modelling such interrelations, i.e. to connecting expertise that remains fragmented so far, is to construct 'hybrid' datasets that reconcile national accounting—the integrative framework of economic analysis at economy-wide level—and underlying physical balances *via* relevant sets of prices.
- 1.3. Among physical balances, the energy balance stands out¹⁹⁰ but other dimensions deserve close scrutiny: the physical composition of investment flows (tons of steel, cement, glass, *etc.*);¹⁹¹ physical measures of transportation activities (passenger- and ton-kilometres) or of space occupation (use of natural land, extension of artificial surfaces, housing surfaces); the physical water system; *etc.*
- 1.4. The microeconomic toolbox of utility and production functions is ill-equipped to represent the inertias and discontinuities of technical systems dynamics that constrain behavioural changes.¹⁹² 'Bottom-up' analysis is more adapted to a consistent description of technologies, equipment stocks and consumption flows, particularly at shorter time horizons.
- 1.5. Outlining alternative development pathways therefore requires addressing the major scientific challenge of linking 'bottom-up' analysis to economy-wide or 'top-down' analysis, to warrant that technical systems are projected in consistency with macroeconomic conditions regarding relative prices, investment availability, private and public budget constraints, *etc.*¹⁹³

¹⁸⁹ [Hourcade et al. \(2006\)](#) provide a general introduction to "hybrid modelling".

¹⁹⁰ [Combet et al. \(2014\)](#) describe the IMACLIM methodology of energy and economic data hybridisation.

¹⁹¹ [Le Treut \(2018\)](#) produces analysis based on extended hybridisation for France.

¹⁹² [Gherzi and Hourcade \(2006\)](#) demonstrate this point in the case of energy.

¹⁹³ [Gherzi \(2015\)](#) surveys the 'linking experiments' conducted with IMACLIM for the energy systems.

2. Exploring the initiation and conduct of transformation pathways, in contrasted contexts and under multiple uncertainties, calls for mobilising a wide array of modelling paradigms

- 2.1. Analysing the transition processes that lead to long-term socio-economic futures, and the conditions to their triggering and deployment, is as important as analysing long-term socio-economic futures in themselves.
- 2.2. Addressing both close and distant time horizons requires combining model specifications that acknowledge short-term inertias and long-term flexibilities of the technical, social and institutional systems, at all scales of analysis including at the most aggregate macroeconomic level.
- 2.3. The gap between potential and effective economic growth deserves scrutiny at all time horizons: ‘second best’ dimensions of real economies should be at the core of the modelling agenda.¹⁹⁴ They encompass the inertia of physical capital, the constrained mobility of labour, the imperfect foresight of economic agents or the constrained access to capital.
- 2.4. The distributive impacts of transformation pathways and their retroactions on aggregate consumption, savings, investment and capital flows, as well as their consequences on the magnitude and role of informal economic activity, should not be overlooked.
- 2.5. The multiple uncertainties characterising the technical, social and economic dimensions of the produced outlooks call for the exploration of scenarios combining potentially contrasted viewpoints on all three dimensions.
- 2.6. On the economic dimension, providing microfoundations to the producer’s and the consumer’s behaviour is not an absolute necessity. Alternative scenario-based approaches, or ‘structuralist’ analyses considering stylised economic facts, can allow embarking information from other fields of social sciences about individual and collective behavioural changes, particularly at closer time horizons.
- 2.7. Analyses at national scale should always be conducted under explicit assumptions regarding the future of globalisation, i.e. in light of specific conjectures regarding international trade of goods and services, financial flows, industrial geography and human migrations.

¹⁹⁴ [Gherzi \(2014\)](#) develops this point in the case of low-carbon policy modelling.