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# Global socio-economic and climate change mitigation scenarios through the lens of structural change

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## Abstract

This paper analyses structural change in the economy as a key but largely unexplored aspect of global socio-economic and climate change mitigation scenarios. Structural change can actually drive energy and land use as much as economic growth and influence mitigation opportunities and barriers. Conversely, stringent climate policy is bound to induce specific structural and socio-economic transformations that are still insufficiently understood. We introduce Multi-Sectoral Integrated Assessment Models as main tools to capture the key drivers of structural change and we conduct a multi-model study to assess main structural effects – changes of the sectoral composition and intensity of trade of global and regional economies - in a baseline and 2°C policy scenario by 2050. First, the range of baseline projections across models, for which we identify the main drivers, illustrates the uncertainty on future economic pathways – in emerging economies especially – and inform on plausible alternative futures with implications for energy use and emissions. Second, in all models, climate policy in the 2°C scenario imposes only a second-order impact on the economic structure at the macro-sectoral level – agriculture, manufacturing and services - compared to changes modelled in the baseline. However, this hides more radical changes for individual industries – within the energy sector especially. The study, which adopts a top-down framing of global structural change, represents a starting point to kick-start a conversation and propose a new research agenda seeking to improve understanding of the structural change effects in socio-economic and mitigation scenarios, and better inform policy assessments.

**Keywords:** Structural change, Socio-economic pathways, Climate policy, Multi-sectoral macroeconomic modelling, Energy sector

## 1. Introduction

Meeting the ‘well below’ 2°C goal of the Paris Agreement will require profound changes of energy and land use patterns within just a few decades (IPCC, 2018; Fragkos, 2020). These changes will imply major upheavals in the global economy that need to be understood to articulate climate and other Sustainable Development Goals (SDGs). In particular, economic growth consequences of fast greenhouse gas (GHG) emissions reductions is a central concern, but the question is trapped in unresolved growth versus the environment debates (Jakob et al., 2020). Integrated Assessment Model (IAM)-based studies suggest that climate stabilisation could be compatible with dynamic growth in all world regions through fast uptake of energy-efficient technologies and decarbonisation of energy and land-use (Clarke et al., 2014; Fankhauser and Jotzo, 2018; Mercure et al., 2018b; Paroussos et al., 2019b; Rogelj and al., 2018). However, some scholars advocate a de-growth perspective (D’Alessandro et al., 2020; Kallis, 2011; Nieto et al., 2020; Keyßer and Lenzen, 2021), as long-lasting absolute decoupling of GDP growth from resource use, energy use and GHG emissions has not been observed globally (Hickel and Kallis, 2020; Semieniuk et al., 2020). Other studies propose scenarios where human development goals are met with low energy and emissions, such as the satisfaction of energy services along other SDGs (Grubler et al., 2018), broad human needs (Brand-Correa and Steinberger, 2017) or decent living and well-being for all (Millward-Hopkins et al., 2020; Rao et al., 2019). However, these studies do not explicate the required transformations of the global economy that underpin achieving these societal goals with low energy (What industrialisation and economic development trajectories for world regions? What future organisation of production and consumption? In which economic sectors will people work and get income from?). Overall, a central question remains unaddressed: what transformations of economies – as systems of production and distribution of goods and services, value creation and resource allocation - would come along the energy and material transformations required for global deep emission reductions (Krausmann et al., 2020; Pauliuk and Müller, 2014)?

In this paper we introduce the *structural change* perspective to contribute to this question and to our understanding of the socio-economic transformations in relation to climate policy and the low carbon transition. Structural change refers to “*complementary changes in various*

*aspects of the economy, such as the sector compositions of output and employment, the organization of industry, the financial system, income and wealth distribution, demography, political institutions, and even the society's value system”* (Matsuyama, 2008). We argue that structural change should be a key element of global socio-economic and climate change mitigation scenarios:

*First*, structural change at the heart of economic development is a key driver of energy use and GHG emissions, especially because different sectors and industries have heterogeneous energy and carbon intensities. A range of studies show that - beyond GDP growth and energy intensity variation of individual sectors - changes of the economic structure have been a sizable driver of energy demand and emissions in the past (Blanco et al., 2014; Marin and Mazzanti, 2019; Schäfer, 2005; Serrenho et al., 2016). In particular, changes in the industry mix have been the main driver of the observed energy intensity reduction in many countries (Voigt et al., 2014). In turn, structural change in future economic development pathways will to some degree shape emission profiles and influence climate change mitigation opportunities and barriers. For instance, fulfilling development needs may prevent shifting to low-carbon growth patterns in developing countries (Jakob et al., 2014), notably due to industrialisation processes and the need for infrastructures (Steckel et al., 2013). Existing scenarios may underestimate these barriers to lower energy use (Semieniuk et al., 2020). On the other hand, promoting low energy demand systems and dematerialisation could significantly accelerate emission reductions (Grubler et al., 2018).

*Second*, stringent climate policy is bound to induce specific structural change effects at multiple scales, from the decline of fossil fuel sectors and the rise of low carbon energy industries to broader industrial and economic restructuring (in construction and manufacturing sectors (Le Treut et al., 2021), even services). Sizable income and job displacements across sectors would occur with job losses in ‘sunset’ sectors plus their dependent industries, and the creation of direct ‘green jobs’ (Pai et al., 2021) and indirect jobs in other sectors (Barker et al., 2016; Fragkos and Paroussos, 2018; Pollitt et al., 2015). In this context, structural change reflects distributional impacts between ‘winners’ and ‘losers’ - sectors, workers and communities - and provides understanding of how mitigation could impact the social wellbeing of identified groups. Such information is usually more important for stakeholders and policy-makers than aggregate GDP impacts. In particular, structural change can inform about who is likely to be adversely affected by climate policy and in what ways, to identify needs for assistance policies

(Green and Gambhir, 2020) and ensure a “just transition” (Gambhir et al., 2018; Markkanen and Anger-Kraavi, 2019).

*Third*, structural change is associated with risks and costs of the transition process itself from current economies to a low carbon world, that need to be better understood. The speed of structural change reflects the intensity of the destabilisation of different industries with implied major economic risks such as with stranded assets in fossil fuel sectors (Mercuré et al., 2018b) or even systemic financial risks (Semieniuk et al., 2021). Structural change also implies short to medium run costs related to transition processes in labour and capital markets. These costs are linked to changes of know-how and skills between old and new technological regimes (Consoli et al., 2016), the time needed for labour reallocation driven by sectoral shifts which induces cyclical unemployment (Lilien, 1982) and to the general rigidity of labour markets (Guivarch et al., 2011). Transition costs also result from the constraints to redirect investments between countries, sectors or technologies (Paroussos et al., 2019a).

In a nutshell, the interaction between structural change and climate change mitigation is expected to have significant consequences for future development pathways of economies and societies. However, Integrated Assessment Models (IAMs), which have been extensively used to assess climate change mitigation scenarios (van Beek et al., 2020), have mostly treated structural change in the economy implicitly in baseline projections of energy demand and land use (Giarola et al., 2021; Riahi et al., 2017). In addition, the economic analysis of global mitigation scenarios continues being mostly based on aggregate cost assessment (GDP or consumption losses) (Riahi et al., 2021; Rogelj et al., 2018) with little to no explicit reference to the associated changes in the structure of the economy and the labour market. Yet, a few IAMs based on a multi-sectoral macroeconomic approach (hereafter referred to as MS-IAMs) are capable to project main structural change drivers and variables in an economy-wide perspective. However, MS-IAMs have been little used in this context, other than to address particular questions such as the employment implications of specific climate policy (Fragkos and Paroussos, 2018; Pollitt et al., 2015).

This paper aims to contribute to bridge these gaps through two objectives: i) provide the conceptual background for assessing global scenarios through the lens of structural change with MS-IAMs and ii) apply the conceptual principles to analyse structural change effects in baseline and climate change mitigation scenarios. For the latter we build on the comparative simulations of a ‘middle-of-the-road’ baseline and a corresponding 2°C scenario from three

well-established MS-IAMs (E3ME-FTT, GEM-E3-FIT and IMACLIM-R). Through this application we aim to carry out the first model inter-comparison study examining the issue of structural change in global climate change mitigation scenarios. In the remainder of the paper we first provide the background and conceptual principles in section 2. Subsequently, we develop the model inter-comparison study in section 3 and describe the study design and main results about structural change effects in global scenarios. From this first application a further research agenda is discussed in section 4 and section 5 concludes.

## **2. Background and conceptual principles**

### ***2.1. Aspects of structural change relevant for climate change mitigation analysis***

Structural change is a research domain in its own right in economics and refers to many different uses of the concept of structure. The most common one concerns the changes of the macro-sectoral composition of economies (Agriculture, Manufacturing and Services) (Herrendorf et al., 2014) and to a lesser extent the changes in the location of economic activity (urbanisation) and other concomitant aspects of industrialisation. A broad literature in development economics has explored the linkages between sectoral composition, economic growth and development across the 20<sup>th</sup> century (Syrquin, 2010). A well-known stylised fact is the transition from economies dominated by agriculture, then manufacturing and finally services activities as income grows (Chenery, 1960; Clark, 1967; Kuznets and Murphy, 1966; Syrquin, 1988).

Different aspects of structural change influence the relationships between global socio-economic transformations and energy use or GHG emissions and are thus relevant for climate change mitigation analysis (Ciarli and Savona, 2019). The *macro-sectoral composition* of economies provides a framework to identify how macroeconomic development patterns can drive energy use and emissions beyond GDP. Conversely, the macro-sectoral composition allows describing how low carbon strategies and climate policy could impact future industrialisation patterns at the macroeconomic level – especially in the most transformative societal scenarios. Beyond, *downscaling sectoral analysis* is required to assess more specific industrial restructuring in mitigation scenarios, such as the decline of fossil fuel sectors, the rise of low carbon industries and indirect impacts on upstream industries or other restructuring (e.g. from heavy to lighter industries (Barthel et al., 2014)). Closely related to sectoral composition on the production side are the *sectoral shifts of jobs* and employment which also reflect changes in the skill sets, the distribution of wages (Brynjolfsson and McAfee, 2014),

and the labour intensity of production. On the demand side, changes in the *consumption structure* are another key aspect – especially driven by human needs, consumption preferences and income. These changes refer to the structure of direct households energy consumption related to private transportation and housing but also of the consumption of other final goods and services. Eventually, changes of *international trade patterns* and fragmentation of production are other important aspects. They determine changes of the geographical organisation of production which drive emissions from freight transportation. Changes of trade patterns can also result in out-sourcing part of industrial activities between regions and off-shoring polluting activities (Paroussos et al., 2015; Savona and Ciarli, 2019). Conversely, deep mitigation is expected to disrupt international trade of energy, resources and other manufacturing goods (e.g. low carbon equipment) and thus re-organise economic power across world regions (Mercure et al., 2018b; Mercure et al 2021).

## **2.2. Measuring indicators**

The main measuring indicators of structural change refer to changes of the composition of output and employment in the economy and are divided into production and consumption measures (Herrendorf et al., 2014). The formers quantify the changes of the sectoral shares of Value-Added (VA) and employment. VA represents the production side of GDP and corresponds to output minus intermediary consumption. VA shares can be measured in nominal (current prices) or real (constant prices) terms. Employment is measured in the number of workers or number of hours worked. Consumption measures refer to expenditure shares of final consumption of goods and services. Regional production and consumption structures can diverge in practice due to intermediary consumptions (e.g. the purchase of a cotton shirt is fully allocated to manufacturing on the consumption side but also generates VA in agriculture – cotton production - and services – retail trade - sectors on the production side) and trade (the purchase of an imported cotton shirt in one region is associated to VA generated in another region). At the highest level, structural change measures the changes of the sectoral composition of the economy in terms of macro-sectors: Agriculture (agriculture, forestry and fishing), Manufacturing (mining, manufacturing, construction and utilities - electricity, water and gas) and Services (Herrendorf et al., 2014). Structural change indicators can be down-scaled to quantify more specific industrial restructuring, e.g. within the manufacturing industry (Memedovic, 2010). In addition, indexes can be used to measure the *magnitude* of structural change between two dates or the magnitude of structural differences between two

counterfactual scenarios for a given region or between two regions. For instance, the Finger-Kreinin dissimilarity index  $D$  ranges between zero (full similarity) and one (maximum dissimilarity) and measures how much a given distribution (a) differs from a chosen benchmark (b):  $D = \frac{1}{2} \sum |a_i - b_i|$ . Eventually, other indicators are used to measure international trade aspects. For instance, trade openness (ratio of total trade flows – imports plus exports – to total expenditure - consumption, investment and government spending) measures the degree of dependency of an economy or a sector to international trade and is useful to quantify the intensity of international trade and its variations (Lewis et al., 2020).

### ***2.3. Multi-Sectoral macroeconomic IAMs: frameworks to explore structural change in global climate change mitigation scenarios***

Structural change in the economy has been mostly treated implicitly in IAMs scenarios. Baseline projections are based on the Shared Socio-economic Pathways (SSPs) narratives further quantified by models to provide a description of the transformative processes in interlinked economic, energy and land-use systems (O'Neill et al., 2014; Riahi et al., 2017). In practice IAMs build on regional GDP growth (Dellink et al., 2017) and other socio-economic assumptions – e.g. population and urbanisation – to compute future energy and emission pathways. Projections are usually based on aggregated relationships between energy use and income per capita, without reference to explicit structural change assumptions (Bauer et al., 2017). Such representations thus fail to consider important mechanisms driving economic patterns that could be key determinants of future energy use and emissions. This approach can lead to overestimate energy demand (Grubb et al., 2015) or on the contrary to underestimate barriers for energy savings (Semieniuk et al., 2020) and thus incorrectly frame climate policy challenges. One reason for this practice is that many IAMs are based on a single-sector macroeconomic approach and do not represent sectoral heterogeneity, thus by definition not representing structural change. The strength of these models is to describe energy and land use systems in high details, but on the other hand they only represent aggregated relationships between technical systems and economic growth. Therefore, they are also blind to many impacts of climate policies that matter to policy-makers and stakeholders, such as impacts on sectoral employment, industrial competitiveness and the relationships between trade and growth.

A few IAMs represent the economy in more detail with a multi-sectoral macroeconomic approach based on input-output and social accounting (Robinson, 1989). These Multi-Sectoral macroeconomic IAMs (MS-IAMs) explicitly represent output, value-added (including labour and capital income) and employment for a dozen to about fifty different economic sectors on the production side. Production interacts with consumption through inter-industry intermediary demands and the structure of final consumption, demand for investment goods and net exports. Regional economies interact within the global economy through international trade of goods and services. MS-IAMs are thus capable of projecting main structural change variables related to the aspects described in section 2.1, i.e. the sectoral composition of economies on both production and consumption sides and international trade patterns.

Although differing in key aspects (e.g. Post-Keynesian demand-led models have different theoretical foundations from Computable General Equilibrium – CGE - models (Mercure et al., 2019)), MS-IAMs have in common to represent the main drivers of structural change as identified by the theoretical literature (Garcia-Santana et al., 2016; Van Neuss, 2019). These drivers refer to the “*driving forces*”, “*channels*” or “*mechanisms through which the process of structural change can take place*” (Van Neuss, 2019) and can be represented as endogenous or exogenous mechanisms in the models. The drivers of structural change in MS-IAMs can be classified in three categories: *supply-side*, *demand-side*, and *international trade* drivers. i) Supply-side drivers include relative price effects triggered by sectoral differences in factor productivity growth or energy technical progress, and changes of Input-Output linkages; ii) demand-side drivers include income effects that influence consumption structure and changes of investment or saving rates; iii) international trade drivers are linked to comparative advantages of regions (including trade costs) and the nature of the demand for imports (e.g. the demand for imported fossil fuels). In mitigation scenarios, climate policies are additional drivers of structural change that interact with other drivers to trigger deviations from baseline trends.

Finally, MS-IAMs are hybrid models (Hourcade et al., 2006) and embed modelling of energy supply (coal mining, oil and gas extraction, oil refining, electricity) and demand processes (for industry, transportation, residential and commercial buildings) in multi-sectoral macroeconomic frameworks to assess climate policy scenarios (Fujimori et al., 2017; Mercure et al., 2018a; Paroussos et al., 2019a; Sassi et al., 2010). In a nutshell, MS-IAMs bring together development economics and IAMs to explore how structural change drivers and resulting

dynamics impact energy use and emissions (Chateau et al., 2020). Conversely, MS-IAMs are capable of exploring the impacts of climate policy across the structure and geography of the global economy from changes in the energy and industrial sectors (Mercure et al., 2018b), including the development of low-carbon industries and related supply chains (Fragkos and Paroussos, 2018).

### 3. Model inter-comparison of structural change effects in baseline and mitigation scenarios

#### 3.1. Study design

To illustrate the conceptual principles, we carry-out a model-based study which aims at: i) exploring structural change dynamics of the global economy and major emitters in a ‘middle-of-the-road’ baseline scenario and ii) assessing the incremental impacts on the structure of economies induced by climate policy compared to the baseline in a corresponding 2°C scenario. With the latter we aim to provide new insights about how the global economy could be transformed under stringent climate policy in terms of sectoral composition and trade patterns. To do so, we conduct a model inter-comparison exercise using three established MS-IAMs - E3ME-FTT, GEM-E3-FIT and IMACLIM-R - capable of simulating endogenous structural change dynamics based on the drivers described in section 2.3. Table 1 provides a short description of the models and the details about how each model captures the different drivers of structural change (including if they are modelled as exogenous – exo - or endogenous – endo).

Table 1. Short description and drivers of structural change in the models

	<b>E3ME-FTT</b>	<b>GEM-E3-FIT</b>	<b>IMACLIM-R</b>
<b>Model type</b>	Demand-led macroeconomic model, hybrid with energy technology modelling	CGE model, hybrid with energy and transport modules	CGE model, hybrid with energy and sectoral modules

<b>Solution method and coverage</b>		Non-equilibrium macroeconometrics  44 sectors (5 energy sectors: coal, oil & gas, gas supply, manufactured fuels and electricity)  61 regions	Recursive dynamic  42 sectors (8 energy sectors: coal, crude oil, gas extraction, gas, petroleum fuels, ethanol, biodiesel and electricity)  46 regions	Recursive dynamic  12 sectors (5 energy sectors: coal, crude oil, natural gas, manufactured fuels and electricity)  12 regions
<b>Reference</b>		(Mercure et al., 2018a)	(Capros et al., 2013), (Paroussos et al., 2019b)	(Waisman et al., 2012) (Méjean et al., 2018)
Drivers of structural change				
<b>Supply-side</b>	<b>Relative price effects</b>  - <b>Sectoral differences in factor productivity growth</b>  - <b>Sectoral differences in energy technical progress</b>	Limited in baseline (endo related to cumulated investment)  Yes (exo + endo)	Limited (exo)  Yes (exo + endo)	Limited (exo)  Yes (exo + endo)

	<b>Changes of Input-Output linkages and input substitution</b>	Energy only (endo)	All inputs (endo)	Energy only (endo)
<b>Demand-side</b>	<b>Income effects (on consumption structure)</b>	Yes (endo)	Yes (endo)	Yes (endo)
	<b>Changes of Investment and saving rates</b>	Yes (endo)	Yes (exo)	Yes (exo)
<b>International trade</b>	<b>Comparative advantages (including trade costs)</b>	Yes (endo – ‘Armington’)	Yes (endo – ‘Armington’)	Yes (endo – ‘Armington’)
<b>Climate policies</b>	<b>Carbon prices, incentives and regulations</b>	Yes (exo)	Yes (exo)	Yes (exo)

In the first step we simulate a ‘middle-of-the-road’ baseline scenario until 2050 with the three models, based on SSP2 (Fricko et al. 2017). To do so we harmonise models on the main socio-economic and technical parameters available for SSP2 (regional population and GDP, technology and energy resources availability), whereas the drivers of structural change are based on models’ own parameterisation. As SSPs do not provide quantification of structural change, this protocol makes it possible to explore alternative structural change dynamics across the three models consistent with SSP2 socio-economic trends. However, to allow harmonisation of regional GDP across models, we limit possible sectoral differences of factor productivity growth in this exercise (i.e. sectoral productivity is not a main driver of structural change) and we calibrate adjustment factors of general productivity to reach SSP2 GDP levels. Nonetheless, all other structural change drivers remain fully active. The main goal of the

analysis is to compare global and regional structural change projections between models – to identify convergent and divergent aspects - and against historical trends. We also seek to explain key results in light of main structural change drivers across models, although a systematic analysis - e.g. as in Chateau et al. (2020) - is beyond the scope of this paper.

In the second step, based on previous baselines, we simulate a 2°C mitigation scenario to 2050 with the three models, based on a similar 2015-2050 global CO<sub>2</sub> budget of 850-950 GtCO<sub>2</sub> (energy-related CO<sub>2</sub> emissions). We use models' own climate policy assumptions, which are of broadly similar type - a mix of market-driven carbon prices and sector specific incentives and regulations to promote renewable energy, zero-emission vehicles and energy efficiency across regions. By doing so, we intend to quantify the magnitude and direction of the specific structural change induced in this type of mitigation scenario, based on standard climate policy assumptions. Beyond the global economy, we highlight structural change results for four countries and regions (India, China, Europe and the USA) which are the biggest emitters globally, at different stages of economic development, with different sectoral composition, and engaged on contrasted socio-economic development paths.

### **3.2. Results**

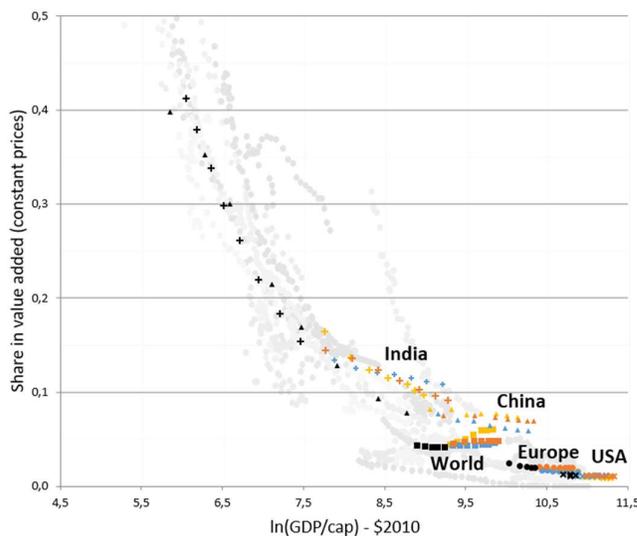
#### 3.2.1. Structural change in baseline

We assess structural change in baseline in terms of macro-sectoral composition of the economy – for value-added (VA) - but also trade openness (see section 2.2) at global and regional scales. On the former we compare models' projections with historical data for a range of countries against GDP per capita.

Results show convergent projections across models about the continuing decrease of the share of agriculture across regions (Fig. 1.a) at a faster pace in India than Europe and the USA where agriculture already represents less than 2% of total VA. Projected trends also converge about the continuing tertiarisation (increase of the VA share of services) of the economy in the USA and Europe (Fig. 1.c). These results are mainly driven by demand-side income effects at different stages of development: an increase of the budget share not allocated to food needs in India and the continuing rise of services consumption in Europe and the USA with parallel saturation of material needs. However, models have more divergent visions of future pathways for manufacturing and services sectors in large emerging economies with implications for the global economy (Fig. 1.b and 1.c). GEM-E3-FIT and IMACLIM-R project an acceleration of

global tertiarisation (a faster increase of the share of services than during past few decades) and parallel deindustrialisation. This trend is led by the fast tertiarisation of the Chinese economy as income grows towards current European level by 2050 - breaking strongly with the industrialisation trends of the 90s – 2000s - and of other emerging economies like India to a lesser extent. The parallel decline of the VA share of the manufacturing sector in China still mean increasing industrial output in absolute numbers though, given the large activity growth projected in China. On the other hand, E3ME-FTT projects a strengthening of the global manufacturing sector led by sustained industrialisation in China (diverging from the usual hump shape for the manufacturing share in the economy as income grows), despite the continuing deindustrialisation of the richest regions. Demand-side and trade drivers are at play behind these contrasted projections. IMACLIM-R and GEM-E3-FIT reflect a sharp economic bifurcation in China – already engaged in the 2010s - consistent with the ‘New normal’ (Green and Stern, 2015). Along this bifurcation, the fast decrease of average saving and investment rates towards higher private and public consumption rates mainly drives the rise of services – as investment goods contain more domestic value-added from industry and less from services than consumption goods do (Garcia-Santana et al., 2016). The income effect towards more consumption of services reinforces the sectoral shift. Differently, E3ME-FTT projects a continuation of 2000s trends due to its econometric foundations that give heavier weight to observed trends. Results are driven by a steady high investment rate of the Chinese economy and continued concentration of manufacture and trade for certain goods for which producers have a comparative advantage (heavy and tech industries).

a) Agriculture



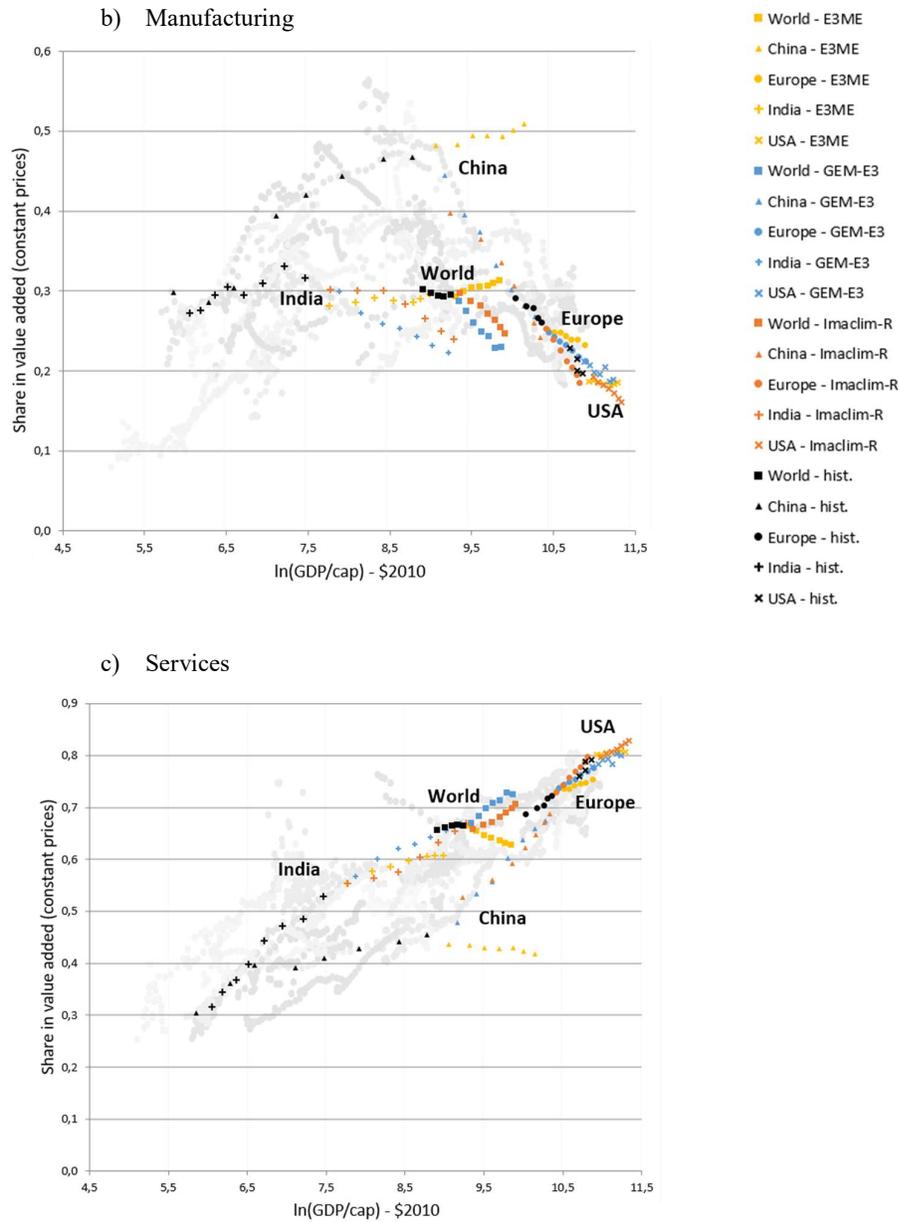


Fig. 1. Share in total real value-added (VA) (constant 2010 prices) for a) agriculture, b) manufacturing and c) services sectors against GDP per capita in India, China, Europe, the USA and at the world scale. Black dots correspond to historical data until 2015 (World Bank data) and coloured dots to models' endogenous projections from 2020 to 2050 in the baseline scenario (5 years between dots). Grey dots in the background correspond to historical data for a range of countries (World Bank data).

Models also project contrasted evolutions of the intensity of global and regional trade (Fig. 2), measured through the openness index defined in section 2.2. IMACLIM-R projects a decrease of global openness driven by a decreasing trade intensity in China and India. This projection accentuates the decreasing trend of the last ten years which broke with the very fast increase of

global trade during the precedent decades of fast globalisation (global openness doubled from 1975 to 2010). GEM-E3-FIT projects almost stable global openness by 2050 with the increase of openness in the richest regions offsetting the decrease of trade intensity in emerging economies. Finally, E3ME-FTT projects increasing global openness with an increase of openness in all four regions. Interestingly, these trade outcomes are related to sectoral projections through two main channels in the models - consistent with empirical facts and theoretical models (Lewis et al., 2020): i) first, the tertiarisation (resp. industrialisation) of the economy tends to reduce (resp. increase) overall openness as trade openness of services is roughly ten times lower than that of industrial goods in average; ii) second, reductions of trade costs strengthen comparative advantages and increase the intensity of trade of goods which tends to increase overall openness and to offset tertiarisation trends. The second mechanism explains why projected trade intensity can significantly differ for a similar vision of global and regional tertiarisation of the economy, as shown by the contrasted results between IMACLIM-R and GEM-E3-FIT. Indeed, openness is higher in the latter than the former in 2050 (in all regions) due to a more optimistic view of future trade costs.

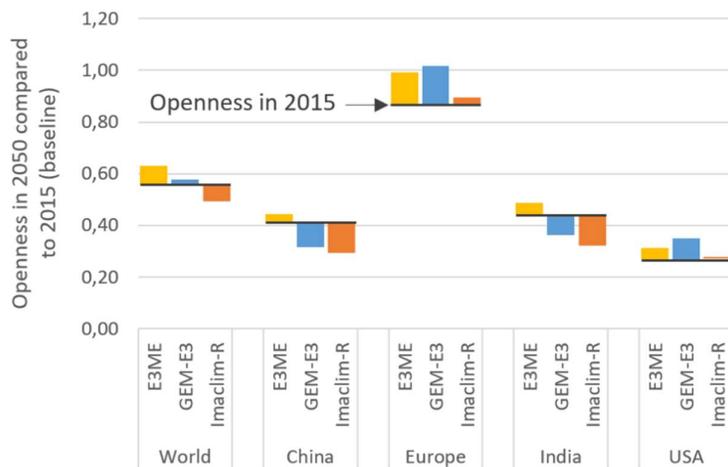


Fig. 2. Openness in 2050 compared to 2015 in the baseline scenario in China, Europe, India, the USA and at the world scale.

Overall, notwithstanding key convergent aspects, these results illustrate a degree of uncertainty about future structural change - in emerging economies especially - for IAMs capable to produce internally consistent structural change projections. A quick look at models' CO<sub>2</sub> emissions results provides a first order indication of the implications of contrasted structural change projections for emissions profiles. Models actually project an increase of CO<sub>2</sub> emissions from around 35 GtCO<sub>2</sub> in 2015 to 53 GtCO<sub>2</sub> in average in 2050 with a sizable range

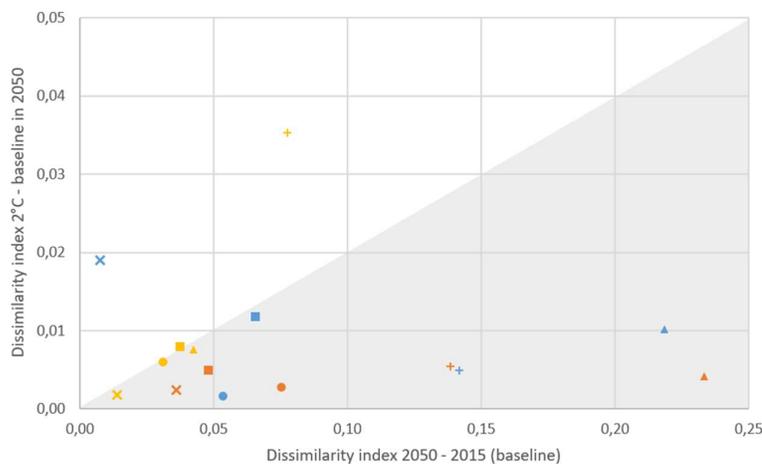
of 10-15 GtCO<sub>2</sub> across models. As models are harmonised on GDP growth and technical change – more roughly on the latter, structural change can be considered a main driver of these discrepancies. Further analysis is required to disentangle more precisely how future structural change could drive energy and emissions at global and regional scales, which we reserve for further work.

### 3.2.2. Incremental structural change in the 2°C scenario relative to the baseline

In this section we assess the *magnitude* and *direction* of the long term impacts on the economic structure induced by stringent climate policy in the 2°C scenario using the long term economic structure of the baseline as reference. These differential impacts induced by climate policy are further compared to the magnitude and direction of structural change happening in the baseline scenario between 2015 and 2050. This approach allows quantifying the deviation in terms of structural change induced by ambitious climate policy compared to baseline trends.

We use a dissimilarity index (see section 2.2) to measure the magnitude of the difference of macro-sectoral structure of economies between 2°C and baseline scenarios in 2050, that we plot against the dissimilarity of the macro-sectoral structure of economies between 2050 and 2015 (i.e. structural change) in the baseline (Fig. 3.a). The first key result is that in most cases (across models and regions including at the global level), the magnitude of the differential long term impact on the economic structure induced by climate policy is more than five times lower than the magnitude of structural change happening in baseline between 2015 and 2050. Said differently, climate change mitigation induces a second-order – although not negligible - deviation from the structural change trends of the baseline scenario *at the macro-sectoral level* at both global and regional scales. In addition, the absolute differential impacts induced by mitigation (independently from the magnitude of structural change in the baseline) are of similar magnitude across regions (less than 1% pt shift of VA) with the exception for India and the USA in particular models. Fig. 3.b and 3.c provide additional information on the direction of structural change impacts of mitigation for manufacturing and services sectors and general results differ across models. GEM-E3-FIT projects an acceleration of global and regional deindustrialisation and development of services (in China and more significantly in the USA) amplifying the baseline trends. E3ME-FTT projects an increase of the share of manufacturing in most regions (India, China and Europe) on top of already high industrialisation levels in the baseline. IMACLIM-R projects the lowest changes.

These results are primarily driven by the interaction between climate policy and supply-side drivers of structural change. In the three models climate policy and carbon prices accelerate energy technical progress across sectors and trigger substitutions of energy inputs (from fossil to clean energy) but also increase energy costs compared to the baseline. The key point is that the net impact on average relative prices of agriculture goods, manufacturing goods and services (after input substitutions and propagation of energy costs) is projected to be limited in the long run in the three models. This limited impact explains the central result and the limited macroeconomic substitutions between sectors. This central result, which could be a property of standard mitigation scenarios, is at least a common property of the three models, linked to the particular substitution possibilities and feedback mechanisms they capture. In addition, in GEM-E3-FIT, manufacturing goods and services are input substitutes to production - the amount of manufacturing goods and services used to produce one unit of a given product can change according to their relative prices, contrary to the other models which adopt a fixed input structure outside energy. Therefore, even the small relative increase of manufacturing prices compared to services (due to higher energy costs) favours the development of service-intensive activities and the service sector overall in GEM-E3-FIT. Eventually in E3ME-FTT, the relative price effects that tend to penalise the manufacturing sector are offset by the demand-side increase of the investment rate of the economy triggered by climate policy to supply for low carbon equipment in the demand-led model.



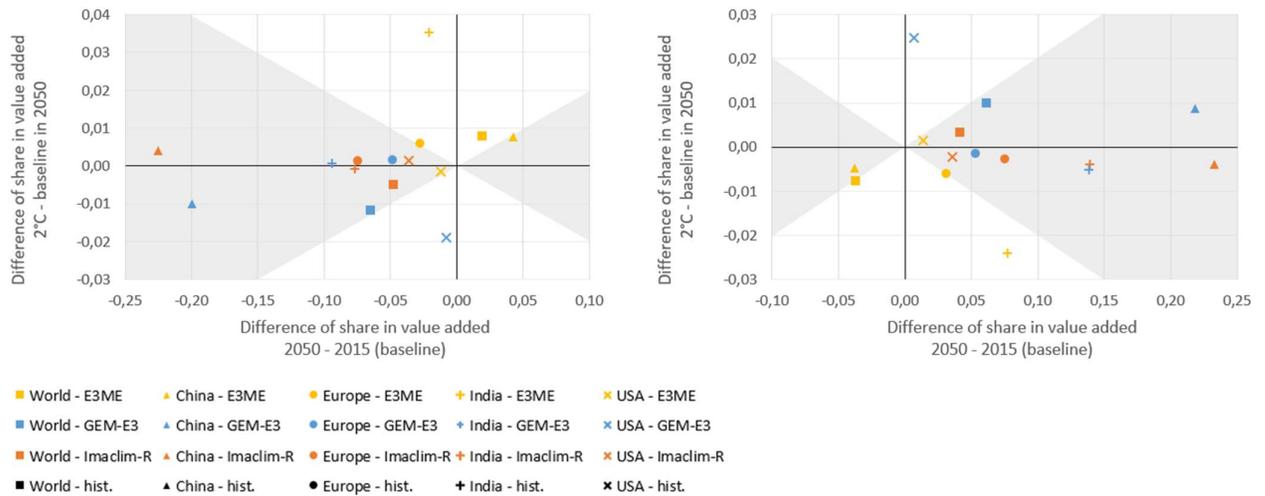


Fig. 3. a) Dissimilarity (see dissimilarity index in section 2.2) of the macro-sectoral structure (agriculture, manufacturing, services) between 2°C and baseline scenarios in 2050 against the dissimilarity of the macro-sectoral structure between 2050 and 2015 in baseline. Interpretation of a dot on the graph: in China with GEM-E3 model, the long term difference of economic structure between 2°C and baseline scenarios is only of 1% point of VA, whereas structural change happening in baseline is up to 22% point of VA; b) and c) Difference of real VA share (constant 2010 prices) of manufacturing and services sectors between 2°C and baseline scenarios in 2050 against the difference of real VA share between 2050 and 2015 in baseline. Grey surfaces correspond to areas where  $\frac{|y|}{|x|} \leq \frac{1}{5}$ : the dots inside grey areas correspond to cases where the difference between 2°C and baseline scenarios in 2050 is more than five times lower than the difference between 2050 and 2015 in baseline.

Fig. 4 further shows the differential impacts of climate policy on global and regional openness compared to baseline trends. The general result with sectoral composition applies as well: the long term impact of mitigation on openness is in most cases at least five times lower than the changes of openness in the baseline (with a few exceptions). Therefore, climate change mitigation impacts on openness can be considered as of second order compared to the baseline trend. A second result is that climate policy tends to decrease openness and trade intensity at global and regional scale (except for China and the USA where results differ across models). One reason is that climate policy tends to increase transportation costs and thus international trade costs which penalises global trade - in a future where, by assumption, international shipping is hard to decarbonise. The trade of fossil fuels is also, by design, negatively impacted by decarbonisation, thus reducing overall trade flows relative to baseline scenario, since the energy trade makes a substantial component of overall trade.

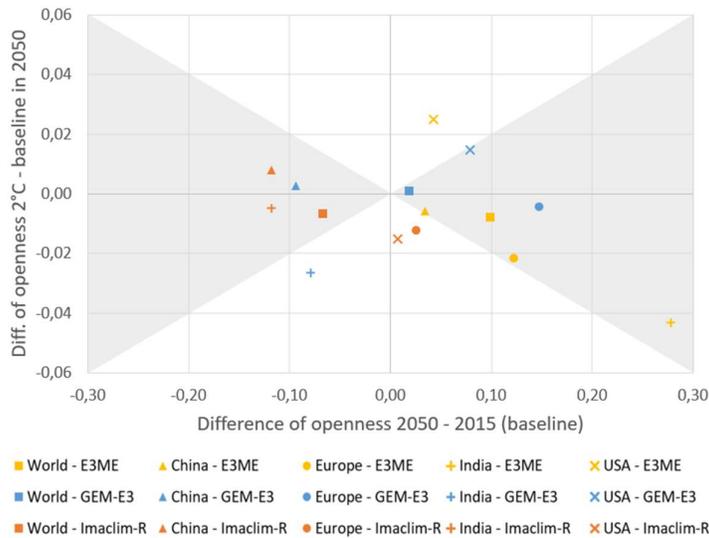
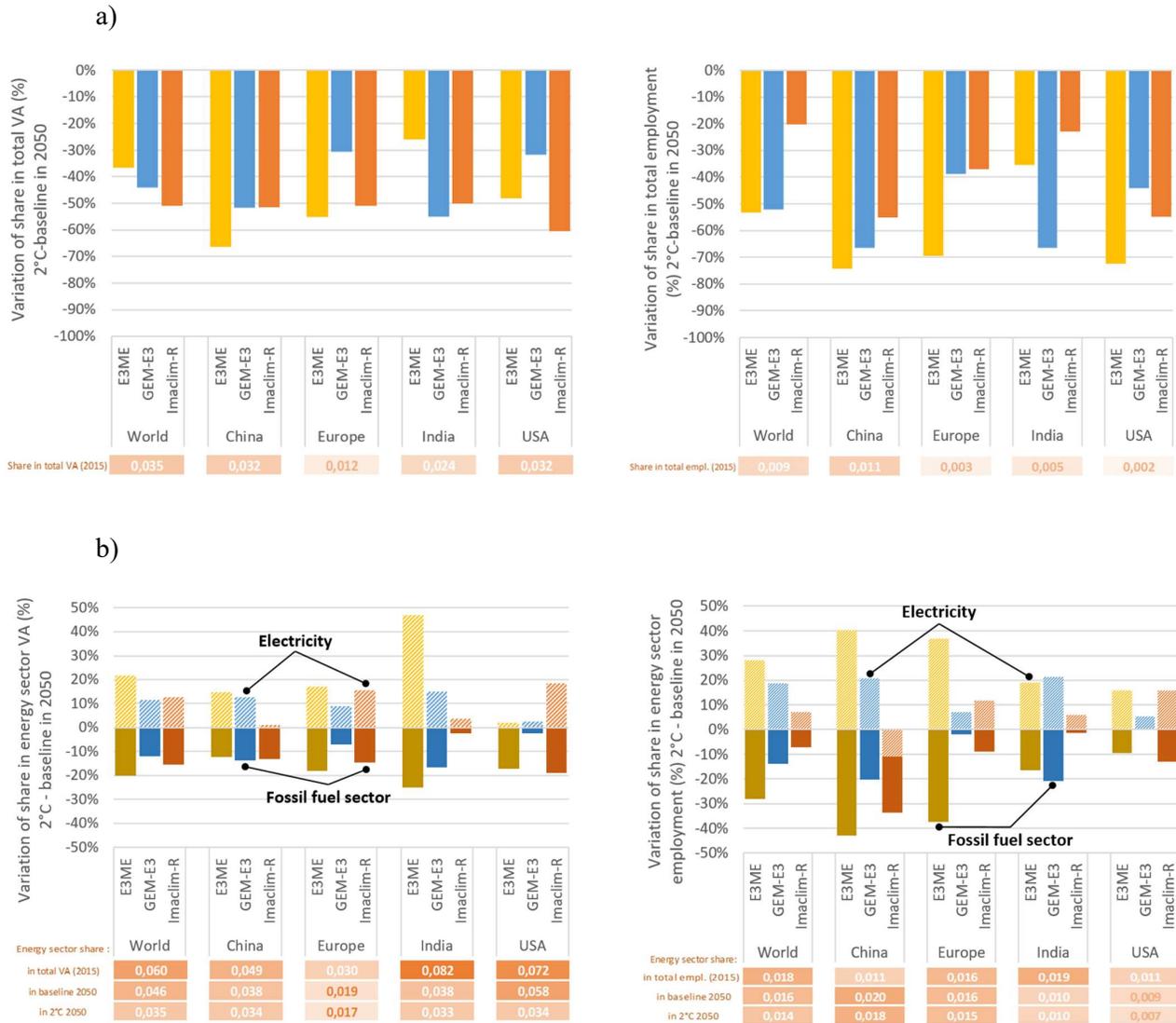


Fig. 4. Difference of openness between 2°C and baseline scenarios in 2050 against the difference of openness between 2050 and 2015 in baseline. Grey surfaces correspond to areas where  $\frac{|y|}{|x|} \leq \frac{1}{5}$ : the dots inside grey areas correspond to cases where the difference between 2°C and baseline scenarios in 2050 is more than five times lower than the difference between 2050 and 2015 in baseline.

Overall, the second order structural change effects of mitigation that we find at the macro-sectoral level in fact hide much deeper structural change effects at a more granular sectoral level with deep restructuring of energy, transport, construction and manufacturing industries. We provide an overview of the results on the restructuring of the energy sector in the following.

Fig. 5 provides an overview of the structural change effects in the energy sector induced by climate policy in the 2°C scenario. The energy sector is, as expected, heavily impacted, since reducing GHG emissions implies a drastic change in the sources of energy used, thus leading to a potential decline or rise of entire energy branches and related industries. The changes are observed here based on VA and employment indicators. As expected, the fossil fuel primary sector (coal, oil and gas production) is particularly affected and a clear decline of its VA and employment is observed in all regions for all models in the mitigation scenarios compared to the baseline (Fig.5.a). The opposite trend is projected for electricity industries (electricity and fossil fuel industries cover together the major part of the energy sector, thus the almost symmetric change between the two), with a growing share in the total energy sector VA and employment in almost all cases (Fig.5.b). This trend is explained by the increased electrification of energy and mobility end-uses (through the high uptake of electric vehicles and heat pumps) combined with the development of renewable power generation in mitigation

scenarios. VA and employment are complementary indicators that follow similar trends in the model results. Quantitative differences reflect aggregation effects and relative decoupling between VA and employment or production linked to energy markets features in the models and their effect on average margins and rents. Overall, although we reserve analysis of the impacts on regions particularly dependent on oil & gas production (e.g. Middle-East, Russia) to future work, the magnitude of the projected changes in the regions studied suggests sizable destabilisation of current systems and incumbents involved in energy supply. These changes include in particular: large shifts of jobs, skill requirements, trade flows and spatial organisation - constituting as many socio-economic issues that need to be anticipated in order to avoid them from becoming obstacles to the low-carbon transition and ensure a just transition with limited distributional impacts on most vulnerable regions and industries.



*Fig. 5. a) Variation (%) of the share in total value added (constant 2010 prices)(left) and employment (right) of the fossil fuel sector between baseline and 2°C scenarios in 2050; b) Variation (%) of the share in total energy sector value added (constant 2010 prices)(left) and employment (right) of fossil fuel and electricity sub-sectors between baseline and 2°C scenarios in 2050.*

#### **4. Discussion**

This first model inter-comparison study examining structural change in global socio-economic and climate change mitigation scenarios has several benefits. First, it demonstrates the advantages of multi-sectoral modelling to explore internally consistent structural change projections by relating structural change outcomes to key drivers. Second, it provides a first quantification of the changes in the structure of the economy in a mitigation scenario and highlights the main economic mechanisms that explain these changes in coherent modelling frameworks. Overall, it shows how IAMs could be used for analysis that goes much beyond the exploration of global energy and emissions trajectories by understanding in more detail the range of internal economic transformations that stakeholders could expect to see arise under a rapid low-carbon transition. Such analysis capacity could become invaluable to effective transition planning. The present study should thus open the way for further works for which we propose possible tracks in the following.

##### ***Expanding baseline scenarios analysis***

In this paper we have analysed three variants of structural change (one by model) consistent with SSP2 socio-economic assumptions. Beyond, the scenario base should be expanded to both cover a broader range of global socio-economic futures (e.g. across SSPs) and to perform larger uncertainty analyses on structural change drivers and outcomes with multi-sectoral models. Although the trends observed over last century for developed countries - and the key stylised facts that can be derived from them (see section 2.1) – provide a solid basis for anticipating the future, the exact development of future economic patterns remain to some degree unknowable. Therefore, the uncertainty analyses should combine stylised facts with additional assumptions and drivers to map possible futures. These analyses should take into account region specific trends such as the transition from agriculture-based to service-based economies without industrialising first in Sub-Saharan Africa (Uwitonze and Heshmati, 2016) or The ‘New normal’ in China and the fast transition towards an economy based on domestic services (Luukkanen et al., 2015). Moreover, global megatrends of the 21st century such as digitalisation, automation and artificial intelligence should be fully included as they are

expected to be major drivers of the future jobs and distribution of economic activity across sectors (Acemoglu and Restrepo, 2020, 2018). Eventually, SSPs can be a base to map structural change futures within and across global narratives. To do so, existing narratives that already describe some drivers of the economic structure, i.e. demography, consumption patterns, international trade and technology development should be revised and better defined on an industrial basis. Doing so would also strengthen the internal consistency of pathways and provide a base to derive quantitative drivers for multi-sectoral analyses.

### ***Improving impact assessment of climate policy with more granular analysis***

Based on three models, our study demonstrates that the impacts of standard climate policy on the macro-structure of economies are of second order compared to changes happening in the baseline, which is itself a new result. However, this hides radical changes at more granular sectoral and regional levels, and this is the type of evidence that is critically needed by decision-makers for climate policy design. We have shown how the structure of the energy sector would be disrupted in mitigation pathways. However additional analysis is needed on the impacts on broader fossil fuel-based industries and their supply chains, but also on the positive impacts on emerging low-carbon industries (e.g. manufacturing and installation of clean energy technologies such as solar photovoltaics, wind turbines, batteries, electric vehicles, etc.). Consequences on the distribution of jobs and economic value across regions (e.g. fossil fuel exporters vs importers, low carbon equipment producers vs importers) and economic sectors are expected to be huge with profound reconfiguration of industrial organisation at all scales. Further studies with MS-IAMs are thus needed on the impacts on global labour markets and to better understanding which countries and industries could be the most impacted by the low carbon transition and in what way, in a context of declining “sunset” industries especially. Multi-sectoral models are also in a good position to assess the opportunities offered by the low-carbon transition through the growth of new, innovative ‘sunrise’ sectors and their indirect positive effects across sectors and regions through new supply chains. Ultimately output growth in these sectors could compensate for the loss of activity in the ‘sunset’ sectors, despite the challenges posed by structural change.

### ***Improving assessment of transition constraints and risks***

Beyond structural impacts in the long run as explored in this study, it is crucial to better understand the full constraints, risks and costs associated with the transition process itself

towards low carbon economies. First, structural change in mitigation scenarios reflect the speed of changes for particular industries (e.g. coal sector) – that could be singularly high in the most ambitious scenarios. Realistic transitions should be explored with models by taking into account the full constraints weighing on the transition process. Integrating IAM analysis with socio-technical and political perspectives could provide new insights on the constraints and enablers of transitions (Cherp et al 2018). In addition, structural change will be associated to transition costs in labour and capital markets, which need to be better quantified in global scenarios. Analysing these costs especially supposes to better capture the imperfections of labour markets and the costs to retrain and displace workers from one industry to the other (Fragkiadakis et al., 2020). Eventually, the fast change of economic distribution between sectors during a rapid transition could have implications for economic and financial stability, which is mostly not addressed in existing studies (Semieniuk et al., 2021). This dimension should be more fully incorporated in climate policy assessments, as already done in some MS-IAMs (Mercure et al., 2019; Paroussos et al., 2019a).

### ***Decoupling, disruptive consumption patterns and societal transitions***

Eventually, the structural change perspective could also provide new insights on the question of the decoupling between GDP, energy and emissions. Whether it is in IAMs scenarios or studies on past data, the topic has mainly been explored through aggregated relationships between income and energy use (Haberl et al., 2020). By making explicit the composition of GDP from production and consumption sides, structural change provides an intermediary layer between GDP and energy use that could be key for better understanding the decoupling issue. In this view, MS-IAMs capture the interplay between technical and structural change in mitigation pathways and can be used to decompose their respective contributions to decoupling in future scenarios. Moreover, the multi-sectoral approach allows capturing sectoral channels of key effects such as rebound effects (Brockway et al., 2021). The present study only indirectly adds to this debate by showing that structural change at macro-sectoral level plays a limited role in the scenarios analysed. Further studies are needed to explore the role of structural change in the decoupling and the constraints or opportunities attached to it. For instance, to what extent industrialisation patterns in developing countries may be an obstacle to lower energy use in these countries (Semieniuk et al., 2020).

In addition, our study examines ‘standard’ mitigation pathways to 2°C, mainly based on technological change in energy supply and use triggered by market-based policies (e.g. carbon

price) along a middle-of-the road economic growth pathway. A few studies have explored alternative mitigation scenarios based on changes in the structure of demand (van Vuuren et al., 2018) towards low energy demand patterns (Grubler et al., 2018) and reflecting more disruptive societal transitions (Millward-Hopkins et al., 2020). These exercises have especially shown the benefits in achieving SDGs or reducing mitigation costs of a significant reconfiguration of energy demand patterns, although the underlying social, policy and economic dynamics need to be better understood (Saujot et al., 2020). The perspective of structural change and the analysis by MS-IAMs could provide valuable new insights for the assessment of such scenarios, by showing the transformation of the economy that they bring about. This type of analysis will thus provide information on the conditions for the realisation and feasibility of this type of pathway.

## **5. Conclusions**

One main challenge of the coming decades is to rapidly reduce global GHG emissions while meeting Sustainable Development Goals. The economic dimension of the global change ahead is central but economic growth and GDP form an incomplete prism to assess future scenarios. The goal of this paper is to enhance the relevance of structural change in climate change mitigation scenarios as a key complementary but underexplored perspective to provide new policy relevant insights on the economic, trade and labour market implications of mitigation policies across sectors and regions. We provide the conceptual principles and background to tackle the topic in the context of IAM-based global scenarios. In particular, structural change metrics that measure changes of different aspects of the economic structure are useful indicators complementary to GDP. They can be used as additional drivers to GDP to project future energy use and GHG emissions in baseline scenarios but also to reflect main distributional impacts of climate policy across industries, workers and regions. Ultimately, it is highly likely that evidence on the composition of structural change to be expected in a low-carbon transition matters more to stakeholders, policy-makers and citizens, than abstract notions of GDP gain or loss, as it can inform real policy to both mitigate the negative socio-economic impacts of a rapid low-carbon transition, and help promote the development of the economies of the future.

In addition, Multi-Sectoral IAMs are useful tools to explore structural change issues in global scenarios as they are capable to project main variables of the economic structure endogenously and to explicit the key underlying drivers, including technological change, income, investment

and trade effects. Applying the principles and methods to the first model inter-comparison study on the topic with three established multi-sectoral IAMs provides novel insights, as it allows the exploration of the associated uncertainty in relation to main drivers. The range of projected structure of economies across models in the baseline scenario illustrates the uncertainty about ‘what the economy of the future may look like’ – in emerging economies in particular, and calls for deepening the analysis of structural change drivers and assumptions. A better decomposition of the contributions of the drivers to structural change is especially needed. A range of complementary modelling methods - including MS-IAMs - could also be used to explore alternative baseline and low-emission transition scenarios further and how future structural change drives energy use and GHG emissions in different scenario frameworks (e.g. alternative baseline SSPs, scenarios with varying climate policy ambition or technology limitations). The second order effects of mitigation on the economic structure at macro-sectoral level that we find encourages exploring more granular sectoral and regional effects that can be supported by MS-IAMs (in particular analysing the impacts for specific fossil fuel supply sectors - coal, oil and gas - as well as separate manufacturing activities - like iron and steel, chemicals, cement, etc.). It also encourages to explore alternative mitigation pathways such as those based on disruptive consumption patterns. Eventually, the study developed in this paper provides a top-down framing for global structural change and represents a starting point to explore further the topic in a new research agenda.

## **References**

- Acemoglu, D., Restrepo, P., 2020. Robots and jobs: Evidence from US labor markets. *J. Polit. Econ.* 128, 2188–2244.
- Acemoglu, D., Restrepo, P., 2018. The race between man and machine: Implications of technology for growth, factor shares, and employment. *Am. Econ. Rev.* 108, 1488–1542.
- Barker, T., Alexandri, E., Mercure, J.-F., Ogawa, Y., Pollitt, H., 2016. GDP and employment effects of policies to close the 2020 emissions gap. *Clim. Policy* 16, 393–414.
- Barthel, C., Kharaba, I., Mioche, P. (Eds.), 2014. *Les mutations de la sidérurgie mondiale du XXe siècle à nos jours =: The transformation of the world steel industry from the XXth century to the present, L’Europe et les Europes*. P.I.E. Peter Lang, Bruxelles ; New York.

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., Eom, J., Krey, V., Kriegler, E., Mouratiadou, I., 2017. Shared socio-economic pathways of the energy sector—quantifying the narratives. *Glob. Environ. Change* 42, 316–330.

Blanco, G., Gerlagh, R., Suh, S., Barrett, J., de Coninck, H.C., Morejon, C.D., Mathur, R., Nakicenovic, N., Ahenkorah, A.O., Pan, J., 2014. Drivers, trends and mitigation.

Brand-Correa, L.I., Steinberger, J.K., 2017. A framework for decoupling human need satisfaction from energy use. *Ecol. Econ.* 141, 43–52.

Brockway, P.E., Sorrell, S., Semieniuk, G., Heun, M.K., Court, V., 2021. Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renew. Sustain. Energy Rev.* 110781.

Brynjolfsson, E., McAfee, A., 2014. *The second machine age: Work, progress, and prosperity in a time of brilliant technologies.* WW Norton & Company.

Capros, P., Van Regemorter, D., Paroussos, L., Karkatsoulis, P., Fragkiadakis, C., Tsani, S., Charalampidis, I., Revesz, T., Perry, M., Abrell, J., 2013. GEM-E3 model documentation. JRC Sci. Policy Rep. 26034.

Chateau, J., Corong, E., Lanzi, E., Carrico, C., Fouré, J., Laborde, D., 2020. Characterizing supply-side drivers of structural change in the construction of economic baseline projections. *J. Glob. Econ. Anal.* 5, 109–161.

Chenery, H.B., 1960. Patterns of industrial growth. *Am. Econ. Rev.* 50, 624–654.

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Res. Soc. Sci.* 37, 175–190.

Ciarli, T., Savona, M., 2019. Modelling the Evolution of Economic Structure and Climate Change: A Review. *Ecol. Econ.* 158, 51–64. <https://doi.org/10.1016/j.ecolecon.2018.12.008>

Clark, C., 1967. The conditions of economic progress. *Cond. Econ. Prog.*

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., others, 2014. Assessing transformation pathways.

- Consoli, D., Marin, G., Marzucchi, A., Vona, F., 2016. Do green jobs differ from non-green jobs in terms of skills and human capital? *Res. Policy* 45, 1046–1060.
- D’Alessandro, S., Cieplinski, A., Distefano, T., Dittmer, K., 2020. Feasible alternatives to green growth. *Nat. Sustain.* 3, 329–335.
- Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. *Glob. Environ. Change* 42, 200–214.
- Fankhauser, S., Jotzo, F., 2018. Economic growth and development with low-carbon energy. *Wiley Interdiscip. Rev. Clim. Change* 9, e495.
- Fragkiadakis, K., Fragkos, P., Paroussos, L., 2020. Low-Carbon R&D Can Boost EU Growth and Competitiveness. *Energies* 13, 5236.
- Fragkos, P., 2020. Global Energy System Transformations to 1.5° C: The Impact of Revised Intergovernmental Panel on Climate Change Carbon Budgets. *Energy Technol.* 8, 2000395.
- Fragkos, P., Paroussos, L., 2018. Employment creation in EU related to renewables expansion. *Appl. Energy* 230, 935–945.
- Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Glob. Environ. Change* 42, 251–267.
- Fujimori, S., Hasegawa, T., Masui, T., 2017. AIM/CGE V2. 0: basic feature of the model, in: *Post-2020 Climate Action*. Springer, pp. 305–328.
- Gambhir, A., Green, F., Pearson, P.J., 2018. Towards a just and equitable low-carbon energy transition. *Grantham Inst. Brief. Pap.* 26.
- Garcia-Santana, M., Pijoan-Mas, J., Villacorta, L., 2016. Investment demand and structural change.
- Geels, F.W., Berkhout, F., van Vuuren, D.P., 2016. Bridging analytical approaches for low-carbon transitions. *Nat. Clim. Change* 6, 576.

Giarola, S., Mittal, S., Vielle, M., Perdana, S., Campagnolo, L., Delpiazzi, E., Bui, H., Kraavi, A.A., Kolpakov, A., Sognaes, I., 2021. Challenges in the harmonisation of global integrated assessment models: A comprehensive methodology to reduce model response heterogeneity. *Sci. Total Environ.* 146861.

Green, F., Gambhir, A., 2020. Transitional assistance policies for just, equitable and smooth low-carbon transitions: who, what and how? *Clim. Policy* 20, 902–921.

Green, F., Stern, N., 2015. China's 'new normal': structural change, better growth, and peak emissions. Centre for Climate Change Economics and Policy.

Grubb, M., Sha, F., Spencer, T., Hughes, N., Zhang, Z., Agnolucci, P., 2015. A review of Chinese CO<sub>2</sub> emission projections to 2030: the role of economic structure and policy. *Clim. Policy* 15, S7–S39.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., Stercke, S., 2018. A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. *Nat. Energy* 3, 515.

Guan, D., Meng, J., Reiner, D.M., Zhang, N., Shan, Y., Mi, Z., Shao, S., Liu, Z., Zhang, Q., Davis, S.J., 2018. Structural decline in China's CO<sub>2</sub> emissions through transitions in industry and energy systems. *Nat. Geosci.* 11, 551–555.

Guivarch, C., Crassous, R., Sassi, O., Hallegatte, S., 2011. The costs of climate policies in a second-best world with labour market imperfections. *Clim. Policy* 11, 768–788.

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. *Environ. Res. Lett.* 15, 065003.

Herrendorf, B., Rogerson, R., Valentinyi, A., 2014. Growth and structural transformation, in: *Handbook of Economic Growth*. Elsevier, pp. 855–941.

Hickel, J., Kallis, G., 2020. Is green growth possible? *New Polit. Econ.* 25, 469–486.

Hourcade, J.C., Jaccard, M., Bataille, C., Gherzi, F., 2006. Hybrid modeling: New answers to old challenges. *Energy J.* 2, 1–12.

IPCC, 2018. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Jakob, M., Lamb, W.F., Steckel, J.C., Flachsland, C., Edenhofer, O., 2020. Understanding different perspectives on economic growth and climate policy. *Wiley Interdiscip. Rev. Clim. Change* 11, e677.

Jakob, M., Steckel, J.C., Klasen, S., Lay, J., Grunewald, N., Martínez-Zarzoso, I., Renner, S., Edenhofer, O., 2014. Feasible mitigation actions in developing countries. *Nat. Clim. Change* 4, 961–968.

Kallis, G., 2011. In defence of degrowth. *Ecol. Econ.* 70, 873–880.

Keyßer, L.T., Lenzen, M., 2021. 1.5 C degrowth scenarios suggest the need for new mitigation pathways. *Nat. Commun.* 12, 1–16.

Krausmann, F., Wiedenhofer, D., Haberl, H., 2020. Growing stocks of buildings, infrastructures and machinery as key challenge for compliance with climate targets. *Glob. Environ. Change* 61, 102034.

Kuznets, S., Murphy, J.T., 1966. *Modern economic growth: Rate, structure, and spread*. Yale University Press New Haven.

Le Treut, G., Lefevre, J., Lallana, F., Bravo, G., 2021. The multi-level economic impacts of deep decarbonization strategies for the energy system. *Energy Policy* 156, 112423.

Lewis, L., Monarch, R., Sposi, M., Zhang, J., 2020. Structural change and global trade.

Lilien, D.M., 1982. Sectoral shifts and cyclical unemployment. *J. Polit. Econ.* 90, 777–793.

Luukkanen, J., Panula-Ontto, J., Vehmas, J., Liyong, L., Kaivo-oja, J., Häyhä, L., Auffermann, B., 2015. Structural change in Chinese economy: Impacts on energy use and CO<sub>2</sub> emissions in the period 2013–2030. *Technol. Forecast. Soc. Change* 94, 303–317.

Marin, G., Mazzanti, M., 2019. *Structural Change and the Environment*.

Markkanen, S., Anger-Kraavi, A., 2019. Social impacts of climate change mitigation policies and their implications for inequality. *Clim. Policy* 19, 827–844.

Matsuyama, K., 2008. Structural change. *New Palgrave Dict. Econ.* 2.

Méjean, A., Guivarch, C., Lefèvre, J., Hamdi-Cherif, M., 2018. The transition in energy demand sectors to limit global warming to 1.5° C. *Energy Effic.* 1–22.

Memedovic, O., 2010. Structural change in the world economy: main features and trends.

Mercure, J.-F., Bravo, P. S., Vercoulen, P., Semieniuk, G., Lam, A., Pollitt, H., Holden, P., Vaklifard, N., Chewpreecha, U., Edwards, N., 2021. Reframing incentives for climate policy action. *Nat. Energy*. In press.

Mercure, J.-F., Knobloch, F., Pollitt, H., Paroussos, L., Scricciu, S.S., Lewney, R., 2019. Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use. *Clim. Policy* 19, 1019–1037.

Mercure, J.-F., Pollitt, H., Edwards, N.R., Holden, P.B., Chewpreecha, U., Salas, P., Lam, A., Knobloch, F., Vinuales, J.E., 2018a. Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Rev.* 20, 195–208.

Mercure, J.-F., Pollitt, H., Viñuales, J.E., Edwards, N.R., Holden, P.B., Chewpreecha, U., Salas, P., Sognaes, I., Lam, A., Knobloch, F., 2018b. Macroeconomic impact of stranded fossil fuel assets. *Nat. Clim. Change* 8, 588–593.

Millward-Hopkins, J., Steinberger, J.K., Rao, N.D., Oswald, Y., 2020. Providing decent living with minimum energy: A global scenario. *Glob. Environ. Change* 65, 102168.

Nieto, J., Carpintero, Ó., Miguel, L.J., de Blas, I., 2020. Macroeconomic modelling under energy constraints: Global low carbon transition scenarios. *Energy Policy* 137, 111090.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* 42, 169–180. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* 122, 387–400.

Pai, S., Emmerling, J., Drouet, L., Zerriffi, H., Jewell, J., 2021. Meeting well-below 2° C target would increase energy sector jobs globally. *One Earth* 4, 1026–1036.

Paroussos, L., Fragkiadakis, K., Fragkos, P., 2019a. Macro-economic analysis of green growth policies: the role of finance and technical progress in Italian green growth. *Clim. Change* 1–18.

Paroussos, L., Fragkos, P., Capros, P., Fragkiadakis, K., 2015. Assessment of carbon leakage through the industry channel: the EU perspective. *Technol. Forecast. Soc. Change* 90, 204–219.

Paroussos, L., Mandel, A., Fragkiadakis, K., Fragkos, P., Hinkel, J., Vrontisi, Z., 2019b. Climate clubs and the macro-economic benefits of international cooperation on climate policy. *Nat. Clim. Change* 9, 542–546.

Pauliuk, S., Müller, D.B., 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. *Glob. Environ. Change* 24, 132–142.

Pollitt, H., Alexandri, E., Chewpreecha, U., Klaassen, G., 2015. Macroeconomic analysis of the employment impacts of future EU climate policies. *Clim. Policy* 15, 604–625.

Rao, N.D., Min, J., Mastrucci, A., 2019. Energy requirements for decent living in India, Brazil and South Africa. *Nat. Energy* 4, 1025–1032.

Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.-M., Deppermann, A., Drouet, L., Frank, S., Fricko, O., 2021. Long-term economic benefits of stabilizing warming without overshoot—the ENGAGE model intercomparison.

Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* 42, 153–168.

Robinson, S., 1989. Multisectoral models. *Handb. Dev. Econ.* 2, 885–947.

Rogelj, J., et al., 2018. Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Sassi, O., Crassous, R., Hourcade, J.-C., Gitz, V., Waisman, H., Guivarch, C., 2010. IMACLIM-R: a modelling framework to simulate sustainable development pathways. *Int. J. Glob. Environ. Issues* 10, 5–24.

Saujot, M., Le Gallic, T., Waisman, H., 2020. Lifestyle changes in mitigation pathways: policy and scientific insights. *Environ. Res. Lett.* 16, 015005.

Savona, M., Ciarli, T., 2019. Structural changes and sustainability. A selected review of the empirical evidence. *Ecol. Econ.* 159, 244–260.

Schäfer, A., 2005. Structural change in energy use. *Energy Policy* 33, 429–437.

Semieniuk, G., Campiglio, E., Mercure, J.-F., Volz, U., Edwards, N.R., 2021. Low-carbon transition risks for finance. *Wiley Interdiscip. Rev. Clim. Change* 12, e678.

Semieniuk, G., Taylor, L., Rezai, A., Foley, D.K., 2020. Plausible energy demand patterns in a growing global economy with climate policy. *Nat. Clim. Change*.

Serrenho, A.C., Warr, B., Sousa, T., Ayres, R.U., Domingos, T., 2016. Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. *Struct. Change Econ. Dyn.* 36, 1–21.

Steckel, J.C., Brecha, R.J., Jakob, M., Strefler, J., Luderer, G., 2013. Development without energy? Assessing future scenarios of energy consumption in developing countries. *Ecol. Econ.* 90, 53–67.

Syrquin, M., 2010. Kuznets and Pasinetti on the study of structural transformation: Never the Twain shall meet? *Struct. Change Econ. Dyn.* 21, 248–257.

Syrquin, M., 1988. Patterns of structural change. *Handb. Dev. Econ.* 1, 203–273.

Uwitonze, E., Heshmati, A., 2016. Service sector development and its determinants in Rwanda.

van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D., Cassen, C., 2020. Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. *Glob. Environ. Change* 65, 102191.

Van Neuss, L., 2019. The drivers of structural change. *J. Econ. Surv.* 33, 309–349.

van Vuuren, D.P., Stehfest, E., Gernaat, D.E., Van Den Berg, M., Bijl, D.L., De Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., 2018. Alternative pathways to the 1.5 C target reduce the need for negative emission technologies. *Nat. Clim. Change* 8, 391–397.

Voigt, S., De Cian, E., Schymura, M., Verdolini, E., 2014. Energy intensity developments in 40 major economies: Structural change or technology improvement? *Energy Econ.* 41, 47–62. <https://doi.org/10.1016/j.eneco.2013.10.015>

Waisman, H., Guivarch, C., Grazi, F., Hourcade, J.C., 2012. The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Clim. Change* 114, 101–120.