

Structural change and socio-economic disparities in a net zero transition

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Abstract

A sustainability transition is likely to generate substantial and irreversible economic transformation. Old high-carbon industries and related occupations will disappear, while new low-carbon industries and occupations will be created. Whilst in the aggregate, the impact of the transition on global GDP and employment is commonly projected to be relatively moderate, such estimates hide drastic distributional issues that are sectorally and regionally concentrated, with profound implications for households, employees, companies, and nations. Here, we use three sectorally detailed and regionally disaggregated global macroeconomic models to explore the likely levels and impacts of structural change in the global and national economies in a net zero transition. We observe a drastic transformation that affects production and employment in sunset carbon-intensive industries and their dependent value chains, alongside value and job creation in the sunrise industries of a relatively similar magnitude. The impacts of post-industrial decline resulting from decarbonisation are regionally and sectorally concentrated and transmitted across the global economy through channels of demand and international trade. The risks entailed with structural change involve worsening economic disparity and societal division that could exacerbate existing socio-economic and political polarisation. We call for the further development of tools with suitable sectoral and regional disaggregation to investigate structural change and distributional impacts, especially in industries severely affected (positively or negatively) by the low-carbon transition.

Keywords

Structural change, Post-industrial decline, Multi-sectoral macroeconomic modelling, Climate policy

1. Introduction

The low-carbon transition necessary to achieve the objectives of the Paris Agreement for mitigating climate change is, by design, transformative for the global economy (Mercure et al., 2021a). The energy supply sector, together with industry, transport, and households must evolve to use new methods and low-carbon technologies, while old systems, carbon-intensive manufacturing and fossil-based production processes, durable goods and their value chains must be phased out (Geels et al., 2017).

For the economy and the well-being of workers and citizens, the transition could have impacts more pervasive than could be foreseen by simple aggregate economic models, such as Integrated Assessment Models (IAMs). Indeed, while the impacts of the transition on aggregate variables such as global GDP and employment are projected to be relatively moderate (ILO, 2018; IEA, 2021; IPCC, 2022), there is the potential for the creation of significant disparities between and within countries

and sectors as a result of the simultaneous birth and death of numerous industries, occupations and ways of making a living (Carley & Konisky, 2020; Fragkos et al., 2021). As the economy transforms at a pace dictated by the climate and emissions reduction objectives, notably the net zero emission targets in Europe, China, and the United States (Rogelj et al., 2021), rapid investment is required for low- and zero-carbon technologies at the same time as fossil fuel assets should be rapidly decommissioned. The lifetime of high-carbon assets and their sunk value become important in determining whether financial losses are to be expected. A debate has also emerged regarding whether such transition risks could threaten the stability of the global financial sector with profound socio-economic implications, especially in scenarios of rapid disorderly transition (Battiston et al., 2017; Mercure et al., 2018a; Semieniuk et al., 2021).

The form and shape of decarbonisation policies affect the degree of distributional disparity that their impacts generate (Markkanen & Anger-Kraavi, 2019). Structural changes are by definition unavoidable during a transition from high-carbon (sunset henceforth) industries to low-carbon (sunrise henceforth) industries and activities (Freeman & Louçã, 2001). The degree of mobility of workers, capital and skills between sectors is widely debated but could have large impacts on structural and societal changes (Fallick, 1993; Spencer et al., 2018). As Schumpeter (1947) famously put it,

“That the theorist’s teaching, according to which capital ‘migrates’ from declining to rising industries, is unrealistic is obvious: the capital ‘invested’ in railroads does not migrate into trucking and air transportation but will perish in and with the railroads”

In other words, the common assumption in standard economic theory that capital will re-allocate itself from sunset to sunrise activities may be misleading (Mercure, 2022). As a result, economic expectations will, and perhaps already look bleak in regions that are economically focused on activities that lie in the ageing sunset paradigm of fossil-based energy and carbon-intensive industries. This not only includes industries directly involved with the extraction, transport, and combustion of fossil fuels, but also the manufacturing of internal combustion engines, production of steel, cement and petrochemicals, heavy manufacturing, and plastics industries. These industries are frequently geographically concentrated in regions with large fossil fuel resources. Demand and output reductions in the sunset industries lead to unemployment, reduced aggregate demand, stagnating investment, and ultimately post-industrial decline.

Meanwhile, the future will naturally look bright in regions that are already oriented towards the new sunrise technologies, which could include not only low carbon cleantech (e.g., solar photovoltaics, wind turbines), but also, in a broader emergent tech ecosystem, artificial intelligence, automation, biotechnology, batteries, and electric mobility. This disparity in activity across sectors in turn affects the welfare of citizens through many channels. Post-industrial decline is typically regionally concentrated largely due to either geological reasons (as fossil fuel activities tend to cluster around regions with large hydrocarbon resources) or industrial clustering (as heavy industries benefit from economies of agglomeration, see Arthur (1990)). The ability of agents to adapt depends to a large degree on their social and regional mobility. Price, income, and wealth barriers can emerge within countries between regions of high affluence in comparison to regions affected by post-industrial decline, notably in housing markets, hindering mobility from occupations in the sunset regime towards sunrise ones (Lux & Sunega, 2012; Martin et al., 2016).

Early warning signs of division, disparity and discontent have emerged in various parts of the world. This includes the ‘Gilets Jaunes’ protests in France against new taxes on fuels (Hope, 2019). At face value, this could be interpreted to mean that the ‘political acceptability’ of carbon taxes is low (Jewell & Cherp, 2020). However, a more critical analysis of the structure of socio-economic transformation and sectoral interdependencies can help illuminate why such discontent arises even though the predicted aggregate economic and employment impacts are so moderate.

In this paper, we use three well-established, highly detailed sectoral macroeconomic models to explore the disparities and structural change that emerge within the economy through a net zero transition. This aims to better understand distributional issues between countries and sectors, as well as the process of economic transformation itself. Following on from work by Lefevre et al. (2022) where a new research agenda for global structural change in the mitigation context was proposed,

103 we aim to develop an emergent literature on structural change, which can help the design of resilient,
104 fair, and socially acceptable climate policies towards achieving a 'just transition'. We employ models
105 widely used for impact assessment in policy circles that are built upon different theoretical economic
106 bases (demand-led and supply-driven models, see Mercure et al., 2019) to explore possible ranges,
107 levels and directions of structural change impacts that can be expected in different economic sectors
108 and regions worldwide in the context of the low-carbon transition.

109 To address these research goals, section 2 of this paper reviews the emergent literature on structural
110 change, climate change mitigation, and the just transition, adopting the Great Waves analysis
111 tradition as a theoretical framework. Section 3 outlines the methodology and the theoretical
112 differences between the three modelling frameworks used here. Section 4 presents selected model
113 results exploring key aspects of structural change induced by decarbonisation focusing on specific
114 sectors and regions. Section 5 discusses the model-based projections of section 4, extracting
115 insights for future research. Section 6 concludes the research.

2. Structural change and the low-carbon transition – a framework

2.1. The Great Waves of innovation

Many scholars have noted that economies are characterised by cycles of varying timeframes. Shorter economic cycles, determined by inventory fluctuations and fixed capital investment, include Kitchin cycles (40-59 months) and Juglar cycles (7-11 years) (Köhler, 2012). Work on long cycle theory was pioneered by Nikolai Kondratiev and Joseph Schumpeter and focuses on the occurrence of economic oscillations of around 40-60 years. Both Kondratiev and Schumpeter attribute this cycle to technological change (Barnett, 1998). This was said to be due to the temporal clustering of innovations and the process of 'creative destruction'; where new products and technologies displace older systems, methods, and occupations (Schumpeter, 1939). Freeman & Louçã (2001) identify five technological revolutions or 'Great Waves', from the age of the steam engine at the start of the 19th century to the more recent IT revolution. Whilst the technologies and industries were different, each technological revolution saw a cycle involving (Perez, 2003) (see Mercure, 2022 for a recent update and detailed analysis):

- The development of a new constellation of connected innovations with revolutionary collective potential
- Product innovation and exponential diffusion of the new constellation, starting the displacement of existing ways of doing things in older incumbent industries
- Process innovation, expansion and consolidation in the new technological regime, completing the displacement of previous ways of doing things
- Saturation, growth decline and possible obsolescence of the new regime as innovation opportunities deplete

Saturation in the mature paradigm coincides with the development of a constellation of sunrise industries and a period of co-existence between the two paradigms begins. Here, opportunities and fortunes of the different parts of the economy begin to diverge (Perez, 2003). Process innovation, where entrepreneurs seek ways to achieve the same output at a lower cost, causes unemployment in the sunset industries while accelerated investment and high-profit margins lead to high rates of growth in the sunrise industries. The end of a Great Wave is therefore a turbulent and uneven period and post-industrial decline has been observed and documented in specific sectors and regions towards the end of each of the past five Great Waves (Freeman & Louçã, 2001; Perez, 2003).

These paradigms can also be understood as socio-technical regimes; systems of technologies and people interacting and working together towards specific purposes in industry, production, consumption and societal systems. Transitions of socio-technical regimes have been described along a multi-level perspective, involving new products in niches, multi-actor networks, socio-technical configurations and landscape evolution (Geels 2002).

Meanwhile, the interplay between product and process innovation has been explored empirically by Utterback & Abernethy (1974), in which a lifecycle of products emerges with different focal points for innovative activity: product innovation in the early phases with the aim to maximise performance; process innovation in the intermediate phase with the aim of maximising sales, and upstream process innovation during the late phases to minimise input costs and increase efficiencies when further innovation becomes limited on the product itself.

What emerges from the transitions and Great Waves analysis is a product life cycle that corresponds to a sectoral life cycle, and in turn, this generates an economic cycle that is sectorally, and often regionally, significant. Research and development (R&D) investment inversely relates to the age of sectors (Grubb, 2014), going in decreasing order from biotech, artificial intelligence, computers, chemicals, electricity, steel, engines, other metals, agriculture and so on. This matches six successive industrial revolutions in reverse historical order: biotech and artificial intelligence (2010-present), information technology (1970s-2010), petrochemicals and combustion engines (1920-1970s), heavy engineering and electricity (1870s-1910s), the steam engine (1830s-1870s) and textiles (1770s-1830s) (Freeman & Louçã, 2001; Perez, 2003).

A key question is whether and where the low-carbon transition fits in this historical perspective. While the above industrial revolutions appear to be driven by the private sector, entrepreneurs and

innovation, the low-carbon transition is understood as normatively driven, originating from the need to address climate change (Semieniuk et al., 2021). However, technological change is often accidental (e.g., Garud & Karnøe, 2003), while some of the past transitions have been at least partly driven by the public sector at the time. Notably, the historic decision of the British military to convert its naval fleet from coal to oil-powered had a substantial accelerating impact on the innovation dynamics and the pace of the transition towards the internal combustion engine and petrochemicals, which later came to dominate mobility globally (Ediger & Bowlus, 2018). It is, therefore, not excluded that climate policy could be precipitating a transition that might have happened anyway eventually, but potentially not in time to avoid climate change. Indeed, the transition away from fuel combustion and heat towards electric means of harvesting energy is motivated not only by climate policy, but also by lower wage bills, increased efficiency, and lower operational costs, both of which are traded off against higher capital costs (Ondraczek et al., 2015) to generate return in the long run, typical of innovation-led transitions.

2.2. Sectoral macroeconomics

Just as technologies are interlinked with one another in constellations (Perez, 2003) so too are industries, their related occupations, and labour skills. These linkages are frequently regional too, where whole cities or even countries may have formed and grown around certain industrial activities. For example, Fort McMurray, an urban service area in Northern Canada, might not have existed without the development of the tar sands industry. Similarly, Rotterdam could have been a less prominent city without the development of its petrochemical industry, which powers mobility and many other industrial activities upstream of the Rhine River in Germany and elsewhere.

During transitions, it is common that the demand for particular end-use and intermediate products gradually declines and disappears. For example, horses, carriages and related equipment, inputs and components went out of use over a very short period in the US between 1910 and 1930 (Nakicenovic, 1986). The deployment of electric vehicles and heat pumps in Germany will inevitably have an important cross-border impact on the petrochemical complex of Rotterdam through large changes in demanded volumes and trade for petrol, diesel, and other liquid petroleum fuels. However, since the electric motor and the heat pump are significantly more efficient than the internal combustion engine in converting energy into movement, and the gas boiler in generating heat (Knobloch et al., 2020), this loss of energy production volume will thus not be replaced by an equivalent gain in the volume of energy produced elsewhere as this loss is typically larger than demand growth.

More broadly, many countries will see a net gain in employment and economic activity as a result of the transition, while others will see a net loss. Notably, the Middle Eastern oil and gas producers, which typically have low levels of economic diversification and high dependence on fossil fuel export revenues, could suffer drastic reductions in economic output and generalised loss of income spending across the economy (Hafner & Tagliapietra, 2020). In parallel, large energy importers could see a positive change in their trade balance, with money previously spent on expensive fuel imports becoming spent domestically, generating a double dividend. However, outcomes for countries such as Australia, Canada, and the US is less obvious (Mercure et al., 2021b), with significant energy production and both fossil fuel and renewable energy resources.

This reflects the general purpose of product and process innovation at the industry or end-use levels: reductions in the inputs to production for generating comparable usable outputs. Process innovation leads to incremental loss of employment upstream that corresponds in macroeconomic terms to the reductions in inputs to production. However, excess income, originating from profits made on innovation, spent in the economy generally increases demand for other products, which in turn creates new demands for labour and increases income. Over the very long term, the global economy grows at an approximately constant rate (Jarvis, 2018), but over the medium term, it goes through deep sectoral and regional highs and troughs.

2.3. Post-industrial decline and the Just Transition

Deindustrialisation and the associated post-industrial decline have been widely studied, especially in the context of the closure of coal mines, steel, chemical and textile industries in the latter part of the 20th century in the North of England (Mah, 2009; Martin et al., 2016; Thorleifsson, 2016;

Johnstone & Hielscher, 2017; Gherhes et al., 2020), Scotland (Lever, 1991; Walsh et al., 2010), elsewhere in Europe (Walsh et al., 2010) and the Great Lakes region in the US and Canada (Mah, 2009). Deindustrialisation leads not only to loss of income and poverty but also to a loss of identity (Mah, 2009; Thorleifsson 2016; Johnstone & Hielscher, 2017). Working-class communities working in the mines, mills and factories typically develop tight-knit cultures around organised industrial work. The loss of those industries has led historically to migration and depopulation, and for those who have not or could not leave, socio-economic decline and challenges (Mah, 2009). Regions affected by deindustrialisation in Europe rank lowest for health and life expectancy in each country (Walsh et al., 2010). The disappearance of once dominant large industries can also leave communities with stymied entrepreneurial capabilities, hindering their recovery in the long run (Gherhes et al., 2020), which reinforces socio-economic divergence within countries (Gardiner et al., 2013; Martin et al., 2016).

Meanwhile, transitions are commonly characterised by strong resistance from incumbent industries and actors (Geels, 2002; Fouquet, 2016; Markard et al., 2020). From the perspective of the actors at the losing end of the transition, the motivating factors are straightforward: loss of affluence, income, employment, purpose, and social status (Baran et al., 2020). Just as companies, investors and entrepreneurs invest in long-lived capital to create productive capacity, individuals and societies invest in long-lived human capital (skills), to innovate, generate income, raise families, and accumulate wealth (World Bank, 2021). With a working life of around 40 years (Jarvis et al., 2015), it is highly likely that a substantial number of individuals, young and old, will see their skills become obsolete during a rapid transition before the end of their working lives. Furthermore, since industries are typically geographically clustered (Arthur, 1990), this process leads to regional concentrations of similar or related skills becoming obsolete in large numbers (e.g., coal miners), making it challenging for the local economy to absorb into new occupations required for the sunrise sectors and activities.

The challenge is therefore not just about re-training. For workers unwilling or unable to migrate, without substantial opportunities, a skills excess glut can imply long-term involuntary unemployment and subsequently further persisting social dislocation. Furthermore, any sustainability transition is likely to not only impact those directly employed in fossil fuel industries but also workers in other industries and businesses indirectly. For instance, Marchand (2012) finds that, in Western Canada, for every 10 jobs created in hydrocarbon extraction, 9.5 jobs are created in other industries, demonstrating the wider impact fossil fuel industries can have on local and regional economies and labour markets. This has resulted in a growing awareness of the potential for 'stranded regions' (Spencer et al., 2018); areas that are unable to capture many of the socio-economic benefits of the transition and instead, undergo a process of post-industrial decline as the costs of the transition accumulate.

In perhaps one of the most infamous examples, the UK coal transition of the 1980s transformed the socio-economic landscape of many former coal mining communities, with long-standing impacts. Despite previously being one of the UK's most important strategic industries of the early 20th century (Mitchell, 1984), by the 1960s, UK coal mines were facing increasing competition from other fuels that offered economic and environmental advantages. Policymakers adopted a policy of 'controlled rundown' of the coal mining industry in response (Ashworth & Pegg, 1986). Following the miners' strike of 1984-1985, major job losses occurred, leading many workers to take early retirement and others to receive incapacity benefits (Foden et al., 2014). Over 30 years on, former coal mining areas still lag far behind the UK average for metrics including employment and education and have rates above the national average for deprivation, state benefit claimants, and chronic health conditions (Beatty et al., 2019). This kind of persisting social dislocation is not unique to the UK's coal transition and can also be witnessed in Detroit and the Great Lakes region following the partial decline of the automobile industry there (Draus et al., 2010).

Whilst most of the literature has focused on the decline of the coal industry in a sustainability transition, communities dependent on the oil and gas industries will soon face similar challenges (Carley & Konisky, 2020). However, this is not to say that post-industrial decline is an unavoidable consequence of climate policy and a low-carbon transition. In what can be regarded as an exemplar of mitigating the socio-economic impacts of structural change, Germany's Ruhr region transitioned from an economy largely geared around the coal extraction and steel manufacturing industries to a

276 region dominated by a knowledge-based service-oriented economy. Strategic economic
277 diversification managed by the regional and federal governments as well as trade union involvement
278 and comprehensive retraining schemes led to an economic transition that avoided widespread social
279 dislocation (Galgóczy, 2014).

280 Literature has emerged on the so-called 'Just Transition', a movement that seeks strategies for
281 climate policy to both address climate change and mitigate present and expected new inequalities
282 (Markkanen & Anger-Kraavi 2019). Originating from the US labour movement of the late 1990s, the
283 just transition concept has evolved to address issues of equity and justice surrounding the mitigation
284 of climate change, gaining considerable attention through the UN's Sustainable Development Goals
285 (SDGs) and the Paris Agreement (Bang et al., 2022) as well as national climate transition strategies.
286 This literature addresses some of the issues that have been hindering progress in rolling out climate
287 policies, typically related to regional communities predominantly employed in high-carbon industries.
288 For example, due to the expected impacts of European climate policy on the coal-producing country
289 of Poland, the latter has lobbied the European Commission considerably and negotiated with other
290 member states for concessions, otherwise threatening to block further climate policies at the
291 European level (Brauers & Oei, 2020). Similar socio-economic challenges may also be at the root of
292 political polarisation around climate policy in some countries (Kurz et al., 2010; Vona, 2019). Last
293 and not least, the Gilets Jaunes protests in France illustrate the divisions that can arise with the
294 implementation of price-based climate policy even in nations less dependent on fossil fuel-related
295 industries.

296

297 3. Methods

298 Section 2 highlights the need to better anticipate the rise and decline of economic sectors in certain
299 geographical areas. We propose a first step in this direction - exploring the possible ranges, levels,
300 and directions of structural change in different economic sectors and regions in a net zero scenario
301 through the application of multi-sectoral macroeconomic models. This analysis aims to provide
302 insights that go beyond the conventional assessment of economic impacts at the aggregate level
303 and helps to capture structural change and distributional impacts, which must be mitigated in a just
304 transition. In this section, we first provide an overview of how macroeconomic models can offer
305 insights into structural changes before presenting a brief description of the three macroeconomic
306 models used in this study.

307 3.1 Modelling low-carbon transition impacts

308 Obtaining quantitative insights on the sectoral and regional impacts of a net zero transition using
309 macroeconomic models requires a high level of sectoral and regional disaggregation of industrial
310 output, demand for goods and services, international trade, employment by socio-economic groups,
311 and an adequate temporal resolution. Advanced representations of innovation and technological
312 change dynamics disaggregated across the economy are also required. Furthermore, international
313 trade and sectoral interdependencies are crucial as they provide the necessary interconnections
314 linking agents, products, industries, and regions to one another. This means that many of the
315 integrated assessment models that are frequently used for the assessment of climate change
316 mitigation scenarios are ill-equipped to answer important questions about structural change effects
317 in the economy induced by decarbonisation. Questions could include whether jobs created in sunrise
318 industries will be of the same quantity and in the same regions as jobs destroyed in sunset industries,
319 or the extent to which particular baskets of climate policies exacerbate or mitigate structural change-
320 induced social dislocation.

321 Macroeconomic models also frequently report impacts of climate policy that vary both in terms of the
322 magnitude and even the direction of change. In some models, stringent climate policy results in a
323 short-run reduction in GDP relative to a counter-factual baseline whereas in other models, the
324 opposite occurs, and climate policy can drive a short-run GDP boost. The main source of this short-
325 run divergence stems from the economic theoretical underpinnings of the models which can be
326 broadly categorised as equilibrium (supply-led) economics and non-equilibrium (demand-led)
327 economics (Mercure et al., 2019). Here, we use models from both paradigms to analyse structural
328 change in a net zero transition.

329 3.2 Macroeconomic model descriptions

330 E3ME-FTT is an advanced non-equilibrium macro-econometric model based on a demand-led
331 economic framework. It covers the world in 71 regions with a sectoral disaggregation of 70 sectors
332 of industrial production in the EU and 44 sectors for non-EU regions. Intermediate production in
333 supply chains is represented through a combination of input-output relationships between sectors
334 and bilateral trade relationships between regions. It features both financial and physical energy flows
335 in its econometric representations based on IEA data in 22 fuel user types (Cambridge
336 Econometrics, 2019). FTT (Future technology transformation) is a family of evolutionary models of
337 detailed decision-making and S-curve technology diffusion processes. It represents technological
338 decision-making by heterogeneous agents in specific sectors, and the evolution of fleets of
339 technologies from birth to death. Currently, the FTT family covers the power, road transport,
340 residential heating, and iron and steel sectors (Mercure et al., 2018b; Lee et al., 2019;
341 Mukhopadhyay, 2021).

342 GEM-E3-FIT is an advanced Computable General Equilibrium (CGE) model, hybrid with bottom-up
343 energy, electricity, and transport modules, ensuring that the economic system in all scenarios
344 remains in general equilibrium. It represents the global economy as a set of 46 interconnected
345 regional and national economies, each composed of 52 production sectors (also connected by input-
346 output and bilateral trade links). Prices determine the interactions between a group of representative

firms and a representative household for each regional (or national) economy. Here, prices are also used to minimize production costs and to allow households to maximise their intertemporal welfare whilst conforming to a budget constraint (Capros et al., 2013; Paroussos et al., 2019). The model formulates production technologies in an endogenous manner allowing for a price-driven derivation of all intermediate consumption and the services from capital and labour. In the electricity sector, a bottom-up approach is adopted for the representation of the different power-producing technologies (Fragkos et al., 2021). On the demand side, the model formulates consumer behaviour and distinguishes between durable (equipment) and consumable goods and services and explicitly represents energy-related technologies in buildings and road transport.

Imaclim-R is a multi-sectoral Computable General Equilibrium (CGE) model, hybrid with bottom-up sectoral modules (fossil fuel extraction, electricity, buildings, and transport). It represents the global economy as a set of 12 interconnected regional and national economies, each composed of 19 production sectors (also connected by input-output and trade links). It features consistent input-output accounting of both economic and physical energy flows. The model simulates dynamic trajectories in yearly steps through the recursive and hard-linked succession of static macroeconomic equilibria and bottom-up sectoral modules. It explicitly represents the constraints affecting technical flexibilities and their interplay with macroeconomic trajectories by describing economic patterns in a world with market imperfections, partial use of production factors (labour and capital) and imperfect expectations for investment decisions. Within macroeconomic equilibria, a representative household in each regional economy maximizes its utility under both economic and time budget constraints. Productive sectors supply for demand under short-run technical and productive capacity constraints. Between two economic equilibria, bottom-up modules simulate technical adjustments to demand and price changes under imperfect foresight with explicit technologies for the electricity and transport sectors. In the electricity sector, a bottom-up approach is adopted for the representation of the different power-producing technologies. For the demand side, the model represents energy-related technologies in buildings and road transport.

Some of the key model characteristics and differences in theory and assumptions are summarised in table 1. E3ME-FTT is a demand-driven, non-equilibrium model that assumes that both labour and capital are not fully utilized, whereas GEM-E3-FIT and Imaclim-R are supply-driven, general equilibrium models that assume capital is fully utilised in the baseline scenario. In addition, GEM-E3-FIT and Imaclim-R, in their standard macroeconomic closure¹, assume that investment is exclusively financed by savings and there are no savings unused. Therefore, decarbonisation that requires larger investment volumes will lead to the “crowding-out” of investment in other productive sectors. Meanwhile, E3ME-FTT assumes that financing for projects is not constrained by the financing of other projects elsewhere in the economy, and therefore that investment is not directly constrained by the saving behaviour of agents. Involuntary unemployment is recognised in all three models. For further comparison of equilibrium and non-equilibrium modelling paradigms, see Mercure et. al (2019). For further comparison of the E3ME-FTT, GEM-E3-FIT, and Imaclim-R models, see Lefèvre et al (2022).

3.3 Study design

To explore possible ranges, levels, and directions of structural change impacts in a low-carbon transition, we develop baseline and global net zero emission scenarios for the macroeconomic models mentioned above. The baseline only includes currently implemented energy and climate policies without intensification in the future (Van Soest et al., 2021; Lefevre et al, 2022). Net zero scenarios show the impact of ambitious climate and energy policies on economic structural change. In all three models, the net zero scenario includes a combination of market-based (e.g., carbon pricing) and regulatory (e.g., clean technology support) policies. The scenarios are compliant with a carbon budget of between 600-700 GtCO₂ and reach global net zero emissions between 2060-2065. This is considered compatible with the Paris Agreement goal to limit global warming to below 1.5°C by 2100 (Riahi et al., 2021). All scenarios include the short-term socio-economic impacts of the

¹ GEM-E3-FIT can adopt a financial mechanism that relaxes this constraint. See Paroussos et al. (2019) for more detail.

397 COVID-19 pandemic. We develop a consistent aggregation of economic sectors and include results
398 for major fossil fuel exporter and importer economies.

	E3ME-FTT	GEM-E3-FIT	Imaclim-R
Model type	Macro-econometric/ evolutionary model	CGE model	CGE model
Macro-innovation theory branch	Non-equilibrium (Demand driven)	Equilibrium (Supply driven)	Equilibrium (Supply driven)
Sector coverage	43 (70 in the EU)	52	19
Regional coverage	71 countries and regions	46 countries and regions	12 countries and regions
Net zero scenario policies	Market-based and regulatory	Market-based and regulatory	Market-based and regulatory

399 **Table 1.** Overview of the key macroeconomic model similarities and differences.

4. Results

4.1. Regional socio-economic impacts of a net zero transition

We find crucial differences in the economic output projections between the models that illustrate alternative possible storylines of the net zero transition. These differences are linked to different visions and economic theories embedded in the models related to: i) the flexibility of the economy, socio-technical, labour, and energy systems in the short to medium run, ii) the availability of capital for low carbon investments and the resulting stimulus effect in sunrise sectors, and iii) alternative visions and databases for modelling fossil fuel markets and the distribution of declining production between countries.

Whilst a net zero transition will inevitably generate different impacts in different parts of the world, we can identify four broad country groups that display similar trajectories in a net zero transition. These four groups are described in table 2 and are determined largely by the carbon intensity of economies and their position in the global fossil fuel trade. Group 1 contains fossil fuel exporting countries with a high economic carbon intensity (Russia, Saudi Arabia). Group 2 also includes fossil fuel exporters, though these countries have a more moderate carbon intensity and are more economically diversified (Brazil, Canada, US). Groups 3 and 4 are net fossil fuel importers. Group 3 contains developed Global North fossil fuel importing regions with a low carbon intensity (EU, Japan), whilst group 4 consists of Global South fossil fuel importing countries with a higher carbon intensity (China, India).

Group	Countries	Economic Carbon intensity	Fossil fuel Importer/exporter status	Degree of model convergence	Aggregate GDP impacts
1	Russia, Saudi Arabia	High	Exporter	High	Large negative impacts
2	Brazil, Canada, US	Medium	Exporter	Medium	Small to moderate positive or negative impacts
3	EU, Japan	Low	Importer	Medium	Small positive or negative impacts
4	China, India	High	Importer	Low	Large positive or negative impacts

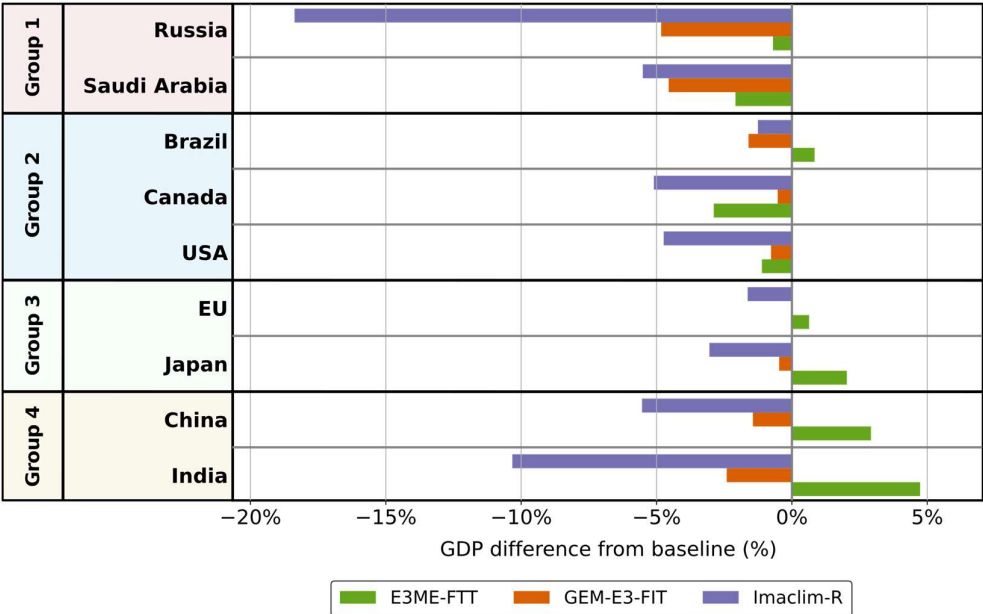
Table 2. Description of four common country groups derived from economic carbon intensity, fossil fuel exporter/importer status, and the size of the aggregate GDP changes in a net zero transition.

As figure 1 shows, and in line with other models featured in IPCC AR6, a net zero scenario in each of the models generates mostly small to moderate impacts on aggregate GDP (IPCC, 2022). Regions in group 1 exhibit some of the most severe losses on account of their large share of fossil fuel activity in their economies. For regions in group 2, a net zero transition leads to mostly GDP losses across all models. Although these regions are net fossil fuel exporters, their economies are well diversified and have a medium carbon intensity, limiting the extent of the mitigation costs. In both groups, the results of the models display a moderate-high level of convergence. Model result convergence is much lower in groups 3 and 4, with E3ME-FTT projecting a boost to aggregate GDP

429 in fossil fuel importing regions, whilst the other models continue to project activity losses. This
430 convergence is particularly low in group 4, developing regions with high carbon intensities and net
431 fossil fuel importers.

432 This difference in the trajectory of aggregate output between E3ME-FTT and the two other models
433 is largely due to the absence of crowding-out of low-carbon investments on other investments
434 combined with a flexible supply to adapt to the demand and evolution of technical systems and the
435 capital stock. Furthermore, a stimulus effect is generated from the investment required to develop
436 low-carbon technologies and sectors. Fossil fuel importer countries are key winners of the transition
437 in E3ME-FTT, witnessing a positive shock from reducing oil and gas import bills. This benefits most
438 countries worldwide since fossil fuel production is concentrated in a limited number of countries. The
439 reverse effect occurs in fossil fuel exporting countries in E3ME-FTT, where the loss of activity
440 amplifies through drastic losses of investment, with scrapped capital not assumed to be recycled
441 towards other activities. In addition, E3ME-FTT adopts a representation of fossil fuel markets based
442 on a detailed extraction costs dataset (Mercure et al., 2021a) that penalizes the high-cost producers
443 (USA, Canada) in a more pronounced way than the other models, with low-cost producers flooding
444 the declining market in the net zero scenario.

445 Whilst Imaclim-R and GEM-E3-FIT both project GDP reductions across all regions in a net zero
446 scenario, such reductions are generally larger in Imaclim-R. This is due to the higher flexibility of
447 technical systems as embedded in the CES (constant elasticity of substitution) production functions
448 and in the bottom-up modules to represent energy and transport systems in GEM-E3-FIT (Fragkos
449 & Fragkiadakis, 2022). Additionally, a more flexible labour market in GEM-E3-FIT limits short to
450 medium-run transition costs. Overall, the three macroeconomic models agree that economies with
451 a low carbon intensity and a high energy import dependence will tend to face more positive impacts
452 from decarbonisation relative to major fossil exporters and countries with a high carbon intensity.



453

454 **Figure 1.** Discounted cumulative GDP differences from baseline (3% discount rate) in 2050 for each
455 study region in E3ME-FTT, GEM-E3-FIT, and Imaclim-R.

4.2 Structural change in a net zero transition

Whilst the economic impacts of a net zero transition might well appear relatively moderate for most countries at the aggregate level, we find substantial sectoral variation regarding the direction and magnitude of change in both output and employment. This reflects the potential for climate policy to induce large-scale structural change, with uneven impacts between sectors and regions (Lefèvre et al., 2022). Figure 2 shows the absolute differences in output in the net zero scenarios relative to the baseline scenarios for all common regions and sectors. Despite the different theoretical underpinnings of the models, a common narrative of structural change in a net zero transition emerges.

In line with the premise of the study, where fossil fuels need to be phased out through climate policy, the fossil fuel sector's share of total GDP falls rapidly in every region. This contraction in contribution to overall GDP is particularly considerable in the fossil fuel exporter economies in group 1 that are currently less well economically diversified. A lack of economic diversification away from fossil fuels is likely to lead to significant challenges and large activity, income, and employment losses. Figure 3 also shows that employment in the fossil fuel sector falls in every region in all models in the net zero scenarios, consistent with the sectoral output. Again, the most substantial losses are projected in large fossil fuel-producing regions, where a greater portion of the total workforce is currently employed in the fossil fuel sector.

Trade plays an important role in this deindustrialisation process, given that fossil fuels are produced in only a few regions but are used everywhere. As figure S5 (supplementary material) shows, the fossil fuel trade balance (exports-imports) generally worsens in fossil fuel exporter countries as their hydrocarbon exports decrease. Simultaneously, the fossil fuel trade balance generally improves in importer countries, as decreased demand for fossil fuels reduces their import bill. Export losses are particularly severe amongst higher-cost fossil fuel producers such as the US, Russia and Canada who are unable to compete with low-cost producers such as Saudi Arabia in a rapidly contracting global market for oil and gas.

The electricity sector witnesses an increase in its share of total GDP in almost all regions as electrification of the road transport and heating sectors accelerate as these sectors decarbonise. This is also reflected in an increase in electricity sector employment in all regions. At the same time, the energy-intensive sector's share of total GDP also increases across most regions. In GEM-E3-FIT, this is largely driven by an increased demand for critical materials on account of a greater share of solar photovoltaics in electricity systems and electric vehicles in the road transport fleet. The policies utilised in the net zero scenarios of the three models also drive the growth in the agriculture sector, where demand for biomass and biofuels increases to replace fossil fuel energy supply, particularly in hard-to-electrify transport segments, including freight transport, aviation, and navigation.

A key feature in the process of decline in high-carbon industries is the impact on the intermediate production of goods and services that occurs across those value chains, which goes far beyond the fossil fuel sector itself. This includes output losses in manufacturing and construction for projects that do not happen (relative to a counterfactual baseline scenario). This also includes vehicles and machinery that are never produced, fuel that is never distributed, steel for pipelines that is never ordered, and so on. Therefore, downward pressure in many sectors develops, particularly amongst fossil fuel exporters in construction and all other industries due to the loss of activity in the fossil fuel sector.

A substantial part of this contraction of GDP stems from the services sectors, which provide a rough barometer of the general economic situation. This is because the services account for the largest share of GDP globally and they generally become the end recipients of income generated in most other sectors as salaried workers spend their wages (e.g., on food, clothing, etc.). In fossil fuel importer economies, however, the models show different trajectories for the services sector, due to the different ways they portray the creation of (or competition for) financial resources for the investment required for decarbonisation. For fossil fuel importer countries in groups 3 and 4, E3ME-

FTT generally projects increased service sector output and employment in a net zero scenario whilst GEM-E3-FIT and Imaclim-R typically project a somewhat limited contraction induced by the decline in overall GDP levels. This is a direct result of the respective assumptions regarding economic equilibrium and crowding-out effects in these models, where a stimulus effect from building activity related to low-carbon technologies in E3ME-FTT drives an increase in demand.

Meanwhile, in GEM-E3-FIT and Imaclim-R, the cost of the transition reduces the demand for services as financial resources are limited and additional investment requirements for decarbonisation puts stress on the capital markets (“crowding-out” effect), cancelling investment in other productive sectors and increasing the price of capital in the entire economy (Fragkos & Paroussos, 2018). These changes in output are directly reflected in employment projections of the models (see figure 3). There are similarly contrasting outcomes in the construction sector, where in E3ME-FTT, output and employment increase relative to a baseline scenario. This is due to climate policy that induces large-scale investment in low-carbon capital in the form of renewable infrastructure. In GEM-E3-FIT and Imaclim-R, the impact of a net zero transition on the construction sector is slightly negative for most regions, as the negative impacts of GDP losses counterbalance the increased demand for construction to build the new low-carbon infrastructure (e.g., renewable energy plants, enhanced renovation of buildings, recharging infrastructure etc.).

Finally, the modelling results indicate that China and India show the largest degree of model divergence, with E3ME-FTT projecting output and employment gains across several sectors and the other two equilibrium models projecting almost an economy-wide decline relative to a baseline scenario. As fossil fuel importers, China and India have an opportunity in the transition to greatly improve their trade balances by reducing their reliance on expensive imports of fossil fuels, allowing for increased domestic investment in low-carbon technologies and infrastructure. However, the direction and magnitude of change in other sectors are less clear. For instance, the services sector in E3ME-FTT grows both in terms of output and employment whilst the opposite occurs in GEM-E3-FIT and Imaclim-R. Again, this is due to decreased economic growth driven by climate policy under the strict closure rule of General Equilibrium models.

Percentage share of output difference from baseline

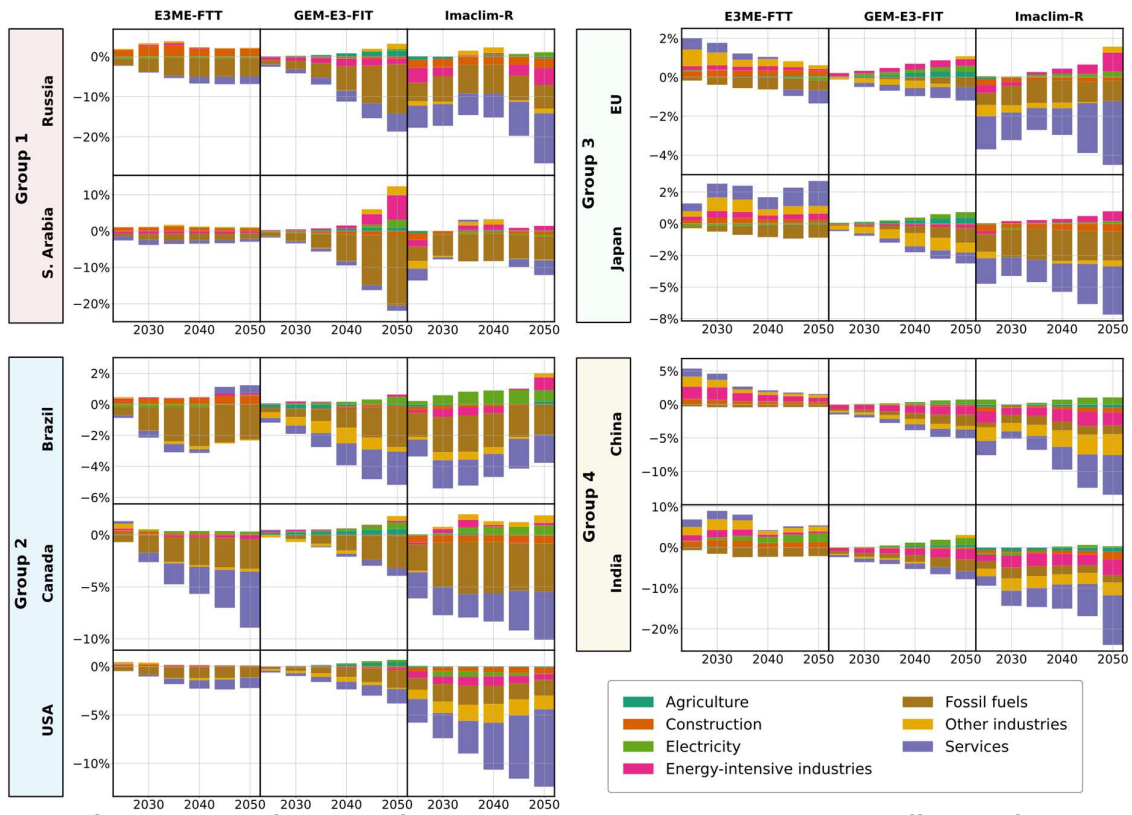


Figure 2. Contributions of a range of sectors to the relative aggregate output difference from baseline in a net-zero scenario for E3ME-FTT, GEM-E3-FIT, and Imaclim-R.

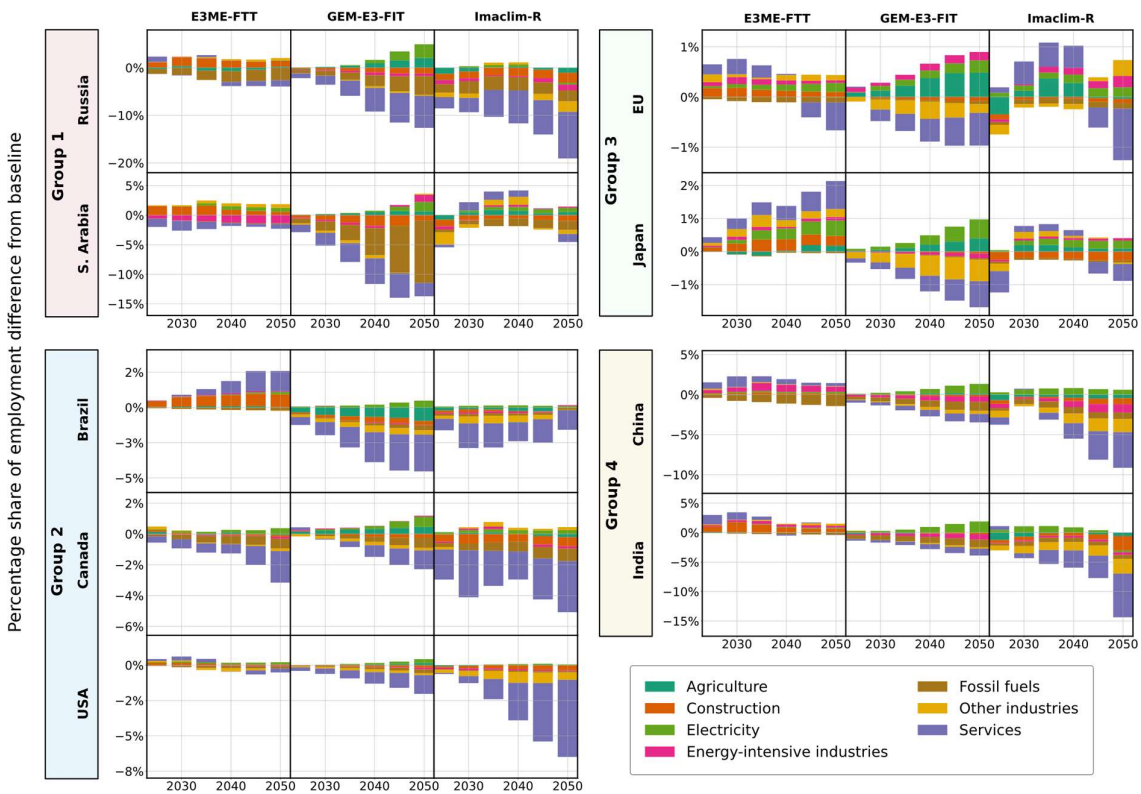


Figure 3. Contributions of a range of sectors to the relative aggregate employment difference from baseline in a net-zero scenario for E3ME-FTT, GEM-E3-FIT, and Imaclim-R.

5. Discussion

Using three sectorally and regionally disaggregated macroeconomic models of different theoretical foundations, we show that the transition to a low-carbon economy will generate substantial uneven impacts on economic output, employment, and trade both within and between economies. The models not only agree that large-scale unemployment will emerge in the fossil fuel sectors, especially in fossil fuel exporting regions, but also that employment losses could be witnessed in other areas of the economy, through supply chain linkages with the sunset sectors. There is still significant uncertainty regarding the degree of losses in the service sectors in particular, as the three models present often contrasting directions of change due to their different theoretical positions concerning the creation of investment capital and their degree of optimism regarding the flexibility of sociotechnical systems. It is not possible at this stage to claim with any degree of certainty which trajectory the future will be closer to. In fact, since investment capital is neither limitless (as in E3ME-FTT) nor fully crowded-out (as in GEM-E3-FIT and Imaclim-R), the future trajectory of the economy is likely to lie between the boundaries delimited by these models.

The primary insight of this study is that structural change is much larger in magnitude than the aggregate impacts of a net-zero transition. For an ordinary household, emerging economic pressures will depend starkly upon which sector(s) and region its working family members live and work in, in contrast with any definition of a representative agent (or average person) as commonly used in economic and Integrated Assessment modelling. The decarbonisation impacts on financial, economic, social, health and standard of living metrics for certain households could be extreme, even if 'average' or 'median' impacts across households are moderate or zero. This means that the frequently used aggregate metric of 'consumption loss' or 'GDP loss' as used in standard policy assessments could be misleading, as it could be interpreted as the amount of consumption or income lost by all households in a region because of climate policy. In contrast, we show here that moderate aggregate consumption loss can mean important benefits for some households (e.g., increased income for those working in renewable energy sectors), simultaneous to the end of entire livelihoods and communities for others (e.g., employees in coal or oil-dependent regions), even within the same regions. Those differences in turn can fuel societal inequality, socio-economic division, and political polarisation. It is important to note that although the models do not have sub-national resolution, output losses from the transition are typically geographically concentrated at the municipal or county level following the regional concentration of fossil fuel industries (McDowall et al., 2022).

Regardless of whether stringent climate policies adequate to achieve ambitious emission reduction targets are developed and implemented, technology is constantly changing in a transition towards higher energy efficiency, renewable energy sources, and increasing electrification in the present economic trajectory. With ambitious climate policies, the accelerated rate of structural change could destabilise many parts of the economy from the incumbent supply chains, labour markets, and financial markets. This rapid evolution of the socio-technical regime must be recognised as it could become the dominant source of socio-economic transformation for the next few decades, driving key socio-economic indicators and even political processes.

Due to the large structural changes induced by climate policy both across sectors and regions, there is a pressing need to move beyond considerations of only aggregate measures of change in discussions of climate policy. Such a coarse focus risks overlooking significant regional and sectoral disparities that are masked by otherwise limited or moderate changes at the aggregate level. This risks contributing to a transition that is inherently unjust and is in danger of creating stranded capital, labour, skills, and even entire regions that become precluded from many of the opportunities presented by the sunrise sectors. This could also severely limit the social and political acceptance of climate policies. Regional stranding and subsequent potential post-industrial decline could be reminiscent of the long-standing and persisting socio-economic challenges that remain in many former coalfield communities in the UK caused by an unjust transition in the 1980s (Foden et al., 2014). These impacts are typically observed in inequalities of wealth, infrastructure, health, life expectancy, as well as educational and professional attainment (Beatty et al., 2019).

592 Whilst the approach presented here offers a first quantification of the potential ranges of structural
593 changes in a net zero transition across countries and production sectors, we recognise that the
594 impacts are likely to be even more severe within these sectors and regions, especially considering
595 the tendency of similar industries to cluster (Arthur, 1990). This means that the impact of the
596 transition is likely to vary substantially within countries, something particularly pertinent for large
597 countries including many presented here. Obtaining more pertinent insights into the risk of post-
598 industrial decline in an economic transition towards a low-emission economy will require approaches
599 that have an even greater regional and sectoral disaggregation (e.g., McDowell et al., 2022).

600 More research work is needed to establish what effective mitigation of transition-induced structural
601 change should look like. It is clear that adequate policy frameworks will be highly region and sector
602 dependent. Processes towards identifying these through science-policy interfaces should assess
603 both risks and opportunities involved in all proposed strategies (Mercure et al., 2021a). Analysis and
604 evidence generation could include the assessment of appropriate economic diversification policies
605 for regional and national economies as well as vocational training and relocation schemes for
606 displaced workers in sunset industries and related supply chains. Such schemes can be (at least
607 partly) funded by increasing carbon tax revenues. International mechanisms can play a role too, as
608 demonstrated by the recent Just Energy Transition Partnership, where the governments of France,
609 Germany, the United Kingdom, and the United States, as well as the European Union, financially
610 support the acceleration of South Africa's energy system decarbonisation. This partnership explicitly
611 acknowledges calls for a just transition, placing focus on supporting affected communities in this
612 transition (European Commission, 2021). Other similar partnerships providing financial support to
613 Indonesia, India, Senegal, and Vietnam have been announced (IISD, 2022).

614 Research to further investigate the regional disparities both between and within countries is also
615 needed to help inform future discussions on structural change induced by ambitious climate policy.
616 Coupled with this, advanced modelling tools that offer a high sectoral and regional disaggregation
617 of outputs embedded in economy-wide frameworks with endogenous trade impacts are required to
618 identify risks and opportunities for national and subnational regions and sectors and to support
619 effective decision-making and design of efficient and just industrial, labour, climate, and economic
620 policy.

6. Conclusion

Analysis of the economic impacts of climate policy in a sustainability transition must evolve to examine both regional and sectoral disparities caused by the transformation away from fossil fuels and related carbon- and energy-intensive industries. This paper aims to kickstart an investigation of structural change in a low-carbon transition by comparing the disaggregated outputs of three leading sectorally disaggregated macroeconomic models of contrasting economic schools of thinking. We find that structural change impacts, when measured on a sectoral and regional basis, are much stronger and more drastic (either positive or negative) than the impacts observed at the aggregate economy-wide level.

Given that aggregate level impacts are typically moderate, this suggests that socio-economic impact assessments of decarbonization could usefully move their focus away from aggregate metrics such as GDP or consumption and towards detailed sectoral and regional analyses. However, assessment outcomes also vary depending on which model is used under which theoretical framework, which suggests that attention must be given to better identify the sources of investment and growth available to economic sectors and geographical regions. We call for the development of modelling tools and analytical practices that can explore, with ever greater detail, the regional and sectoral impacts and societal transformations induced by climate policy and innovation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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831 8. Supplementary Material

832 Structural change in a baseline scenario

833 We assess and compare the extent of structural change in a baseline scenario (i.e., with no
834 additional climate policy) in E3ME-FTT, GEM-E3-FIT, and IMACLIM-R. Figure S1 shows the relative
835 change from 2020 in aggregate GDP, employment, investment, and exports in each study region. In
836 aggregate, the three models agree on the direction of change for all metrics in almost all regions.
837 GDP, investment, and exports continue to grow in all regions, whereas employment falls in China
838 and Japan with mixed results for the EU. Projected working age population change is a major driver
839 of aggregated employment declines.

840 Figures S2-S4 show the sectorally disaggregated GDP values from figure S1 for each of the three
841 models. In relative terms, many sectors exhibit significant changes in their share of total economic
842 output. In all three models, the contribution of the fossil fuel and energy-intensive sectors in GDP
843 falls in almost every region. Meanwhile, the services sector sees relative growth in almost every
844 region. This suggests that, even without further ambitious climate policy, structural change is
845 expected to occur as developing countries such as India move further toward a service-based
846 economy (with reduced shares of agriculture) and demand for fossil fuels is gradually replaced by
847 renewable energy technologies which see continued cost declines.

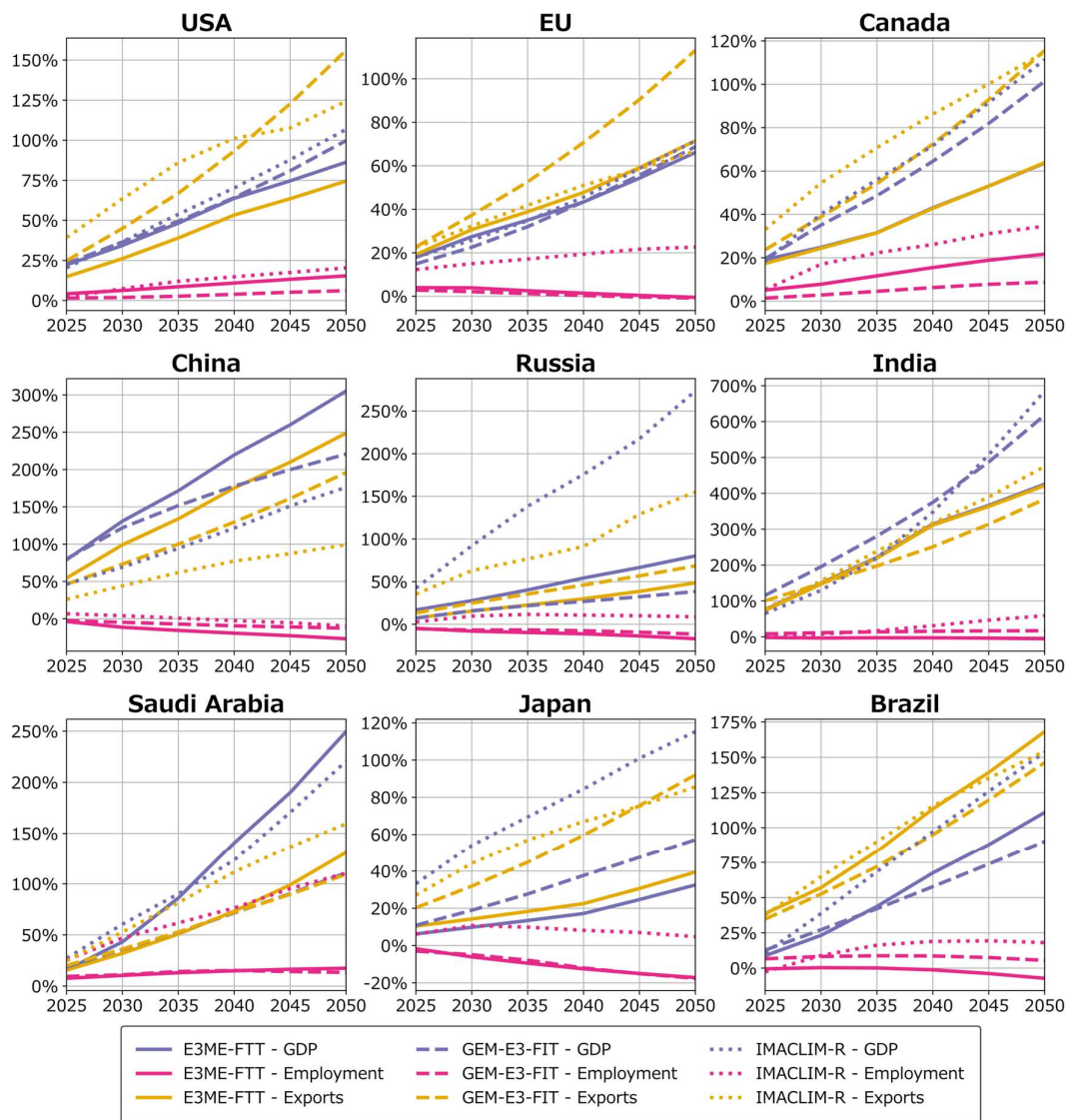


Figure S1. Relative differences from 2015 in a baseline scenario for E3ME-FTT (solid lines), GEM-E3-FIT (dashed lines), and IMACLIM-R (dotted lines) for a range of aggregate economic measures

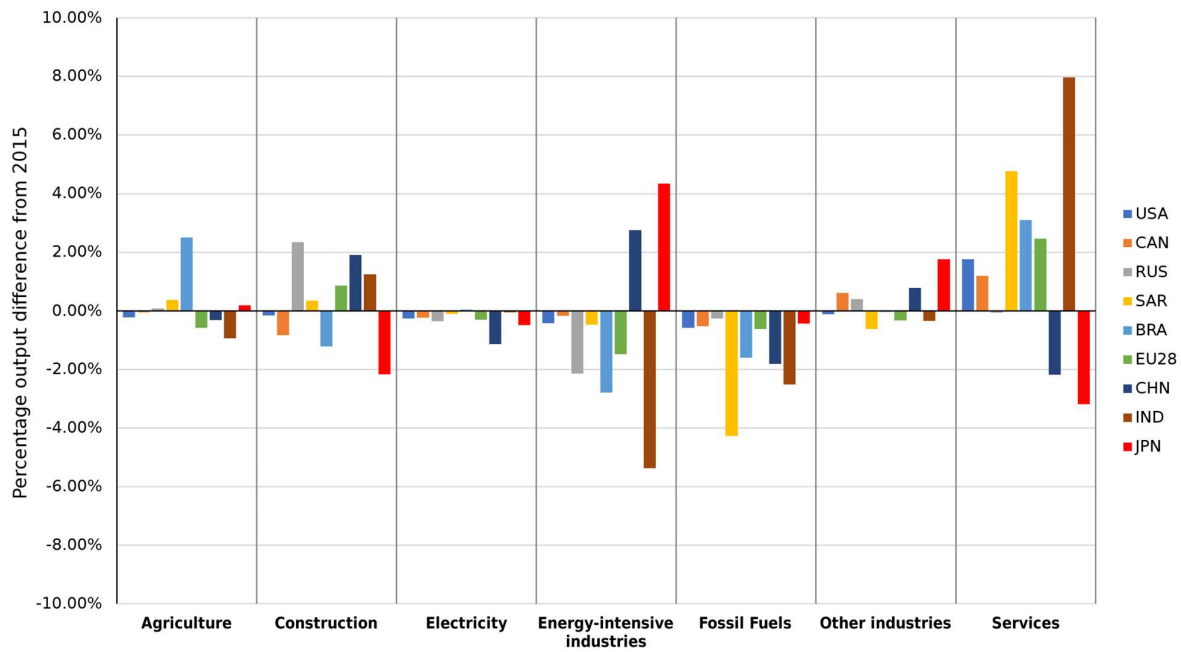


Figure S2. Relative changes in economic structure in E3ME-FTT between 2015 and 2050 in a baseline scenario

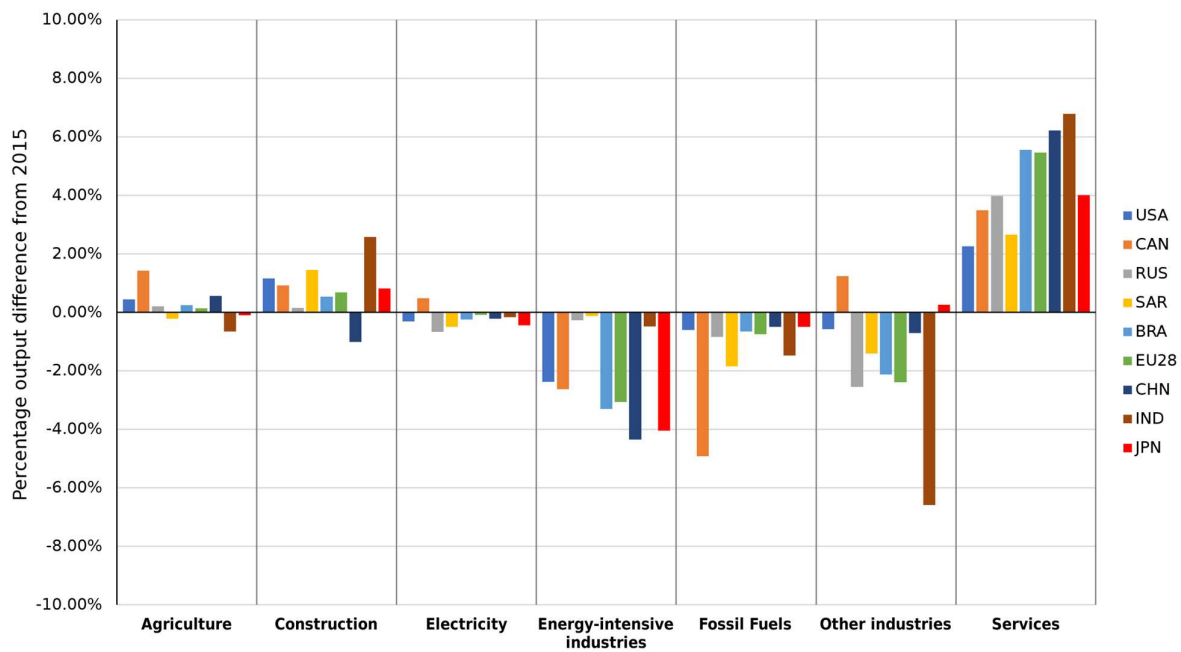


Figure S3. Relative changes in economic structure in GEM-E3-FIT between 2015 and 2050 in a baseline scenario

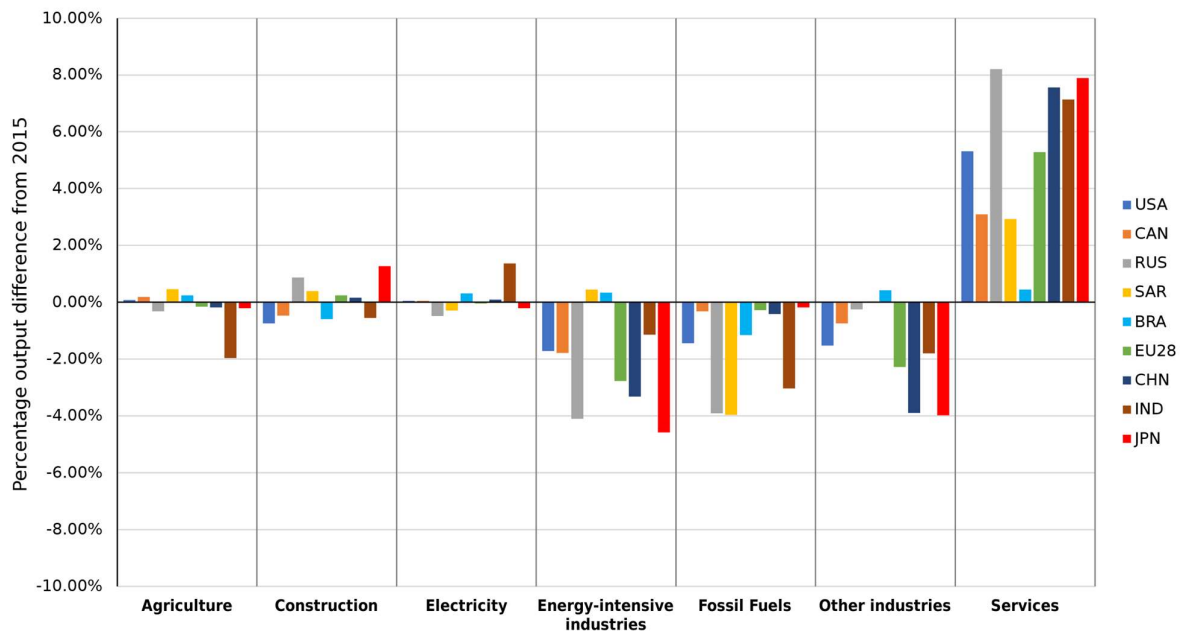


Figure S4. Relative changes in economic structure in Imacsim-R between 2015 and 2050 in a baseline scenario

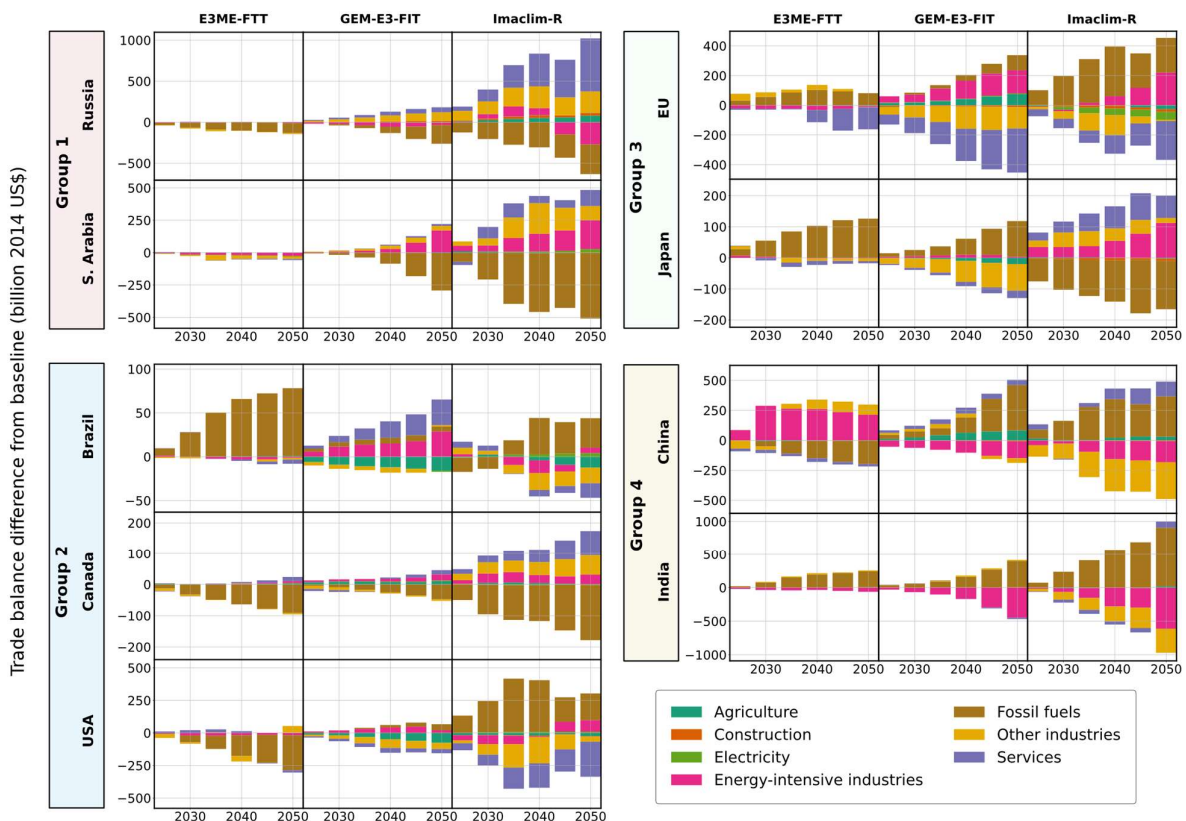


Figure S5. Absolute differences from baseline in the balance of trade (billion USD 2014) (sector exports – sector imports) in a range of sectors in a net-zero scenario for E3ME-FTT, GEM-E3-FIT and IMACIM-R. Negative values indicate either loss of exports or gains of imports, while positive values conversely indicate losses of imports or gains in exports.