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

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16 Abstract

17 A net zero transition is likely to generate substantial and irreversible economic transformation. High-
18 carbon industries and their related occupations will disappear, while new low-carbon industries and
19 occupations will be created. In the aggregate, the impact of the transition on GDP and employment
20 is commonly projected to be relatively moderate. However, such estimates hide drastic distributional
21 issues that are sectorally and regionally concentrated. Here, we use three sectorally detailed and
22 regionally disaggregated macroeconomic models to explore the possible levels and impacts of
23 structural change in a net zero transition consistent with the well below 2°C goal of the Paris
24 Agreement. In addition to the expected decline in the carbon-intensive industries, we observe
25 secondary impacts, particularly in the services sectors, that vary significantly between models. The
26 risks entailed with structural change involve worsening economic disparity and societal division that
27 could exacerbate existing socioeconomic and political polarisation. Impact assessments of
28 decarbonisation should consider such distributional issues to avoid post-industrial decline and
29 widening socioeconomic inequalities.

31 Keywords

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

34 1. Introduction

35 The low-carbon transition necessary to achieve the objectives of the Paris Agreement for mitigating
36 climate change is, by design, transformative for the global economy (Mercure et al., 2021a; IPCC,
37 2022a). The energy supply sector, together with industry, transport, and households must evolve to
38 use new methods and low-carbon technologies and strive to reduce aggregate energy and material
39 use. At the same time, old systems, carbon-intensive manufacturing and fossil-based production
40 processes, durable goods and their value chains must be phased out (Geels et al., 2017).

41 For the economy and the well-being of workers and citizens, the transition could have impacts more
42 pervasive than could be foreseen by simple aggregate economic models, including some
43 established Integrated Assessment Models (IAMs). While the impacts of the transition on aggregate
44 variables including global GDP and employment are projected to be relatively moderate in many
45 models (ILO, 2018; IEA, 2021; IPCC, 2022a), significant disparities could be created both between
46 and within countries and sectors due to the simultaneous birth and death of industries and
47 occupations (Carley & Konisky, 2020; Fragkos et al., 2021).

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

54 The common assumption in standard economic theory that capital will re-allocate itself from sunset
55 to sunrise activities may be misleading (Mercure, 2022). As a result, economic expectations will, and
56 perhaps already look bleak in regions that are economically focused on activities that lie in the ageing
57 sunset paradigm of fossil-based energy and carbon-intensive industries (Carley & Konisky, 2020).
58 This not only includes industries directly involved with the extraction, transport, and combustion of
59 fossil fuels, but also the manufacturing of internal combustion engines, production of steel, cement
60 and petrochemicals, heavy manufacturing, and plastics industries. These industries are often
61 geographically concentrated (Arthur, 1990; Krugman, 1991; Caldecott et al., 2017). Such regions
62 could therefore be at risk of post-industrial decline and the ability of agents to adapt depends to a
63 large degree on their social and regional mobility. Price, income, and wealth barriers can emerge
64 within countries between regions of high affluence in comparison to regions affected by post-
65 industrial decline, notably in housing markets, hindering mobility from occupations in the sunset
66 regime towards sunrise ones (Lux & Sunega, 2012; Martin et al., 2016).

67 Meanwhile, the future will naturally look bright in regions that are already oriented towards the new
68 sunrise technologies. This could include not only low-carbon cleantech (e.g., solar photovoltaics,
69 wind turbines), but also, in a broader emergent tech ecosystem, artificial intelligence, automation,
70 biotechnology, batteries, and electric mobility. Early warning signs of division, disparity and
71 discontent have emerged in various parts of the world. This includes the 'Gilets Jaunes' protests in
72 France against new taxes on fuels (Hope, 2019). At face value, this could be interpreted to mean
73 that the 'political acceptability' of carbon taxes is low (Jewell & Cherp, 2020), yet a more critical
74 analysis of the structure of socio-economic transformation and sectoral interdependencies can help
75 illuminate why such discontent arises even though the predicted aggregate economic and
76 employment impacts are so moderate. What must also be recognised is that, without such a
77 transformation, the physical effects of climate change will drive stark inequalities (Hallegatte &
78 Rozenberg, 2017) and have impacts across the economy (IPCC, 2022b).

79 In this paper, we use three well-established, highly detailed sectoral macroeconomic models to
80 explore the disparities and structural change that emerge within the economy through a net zero
81 transition. This aims to better understand distributional issues between countries and sectors and to
82 contribute to an emergent literature on structural change, which can help the design of resilient, fair,
83 and socially acceptable climate policies towards achieving a just transition. We build on work by
84 Lefèvre et al. (2022) where a new research agenda for global structural change in the mitigation
85 context was proposed, to investigate the possible ranges, levels and directions of structural change
86 impacts that can be expected in different economic sectors and regions in a net zero transition. We
87 employ models widely used for impact assessment in policy circles that are built upon different
88 theoretical economic bases (demand-led and supply-driven models, see Mercure et al., 2019).

89 To address these research goals, we begin in Section 2 by drawing from the Great Waves framework
90 to provide a historical perspective on disruptive innovation and the characteristics of economic
91 transformation. We then situate this perspective in the context of the low-carbon transition. Section
92 3 outlines the methodology and the theoretical differences between the three models used. Section
93 4 presents model results, exploring the key aspects of structural change focusing on specific sectors
94 and regions. Section 5 discusses the model-based projections of Section 4, extracting insights for
95 future research. Section 6 concludes the research.

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

97 2.1. The Great Waves of innovation

98 Many scholars have noted that economies can be characterised by cycles of varying timeframes.
99 Work on long cycle theory was pioneered by Nikolai Kondratiev and Joseph Schumpeter and
100 focused on the occurrence of economic oscillations of around 40-60 years. Both Kondratiev and
101 Schumpeter attributed this cycle to technological change (Barnett, 1998). This was said to be due to
102 the temporal clustering of innovations and the process of ‘creative destruction’; where new products
103 and technologies displace older systems, methods, and occupations (Schumpeter, 1939).

104 Freeman & Louçã (2001) identify five technological revolutions or ‘Great Waves’, from the age of the
105 steam engine at the start of the 19th century to the more recent IT revolution. Whilst the technologies
106 and industries were different, each technological revolution saw a cycle involving (Perez, 2003) (see
107 Mercure, 2022 for a recent update and detailed analysis):

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

116 In all these technological revolutions, saturation in the mature paradigm coincides with the
117 development of a constellation of sunrise industries, beginning a period of co-existence between the
118 two paradigms. At this time, the opportunities and fortunes of different parts of the economy begin
119 to diverge (Perez, 2003). Process innovation, where entrepreneurs seek ways to achieve the same
120 output at a lower cost, causes unemployment in the sunset industries while accelerated investment
121 and high-profit margins lead to high rates of growth in the sunrise industries. The end of a Great
122 Wave is therefore a turbulent and uneven period and post-industrial decline has been observed and
123 documented in specific sectors and regions towards the end of each of the past five Great Waves
124 (Freeman & Louçã, 2001).

125 What emerges from the transitions and Great Waves analysis is a product life cycle that corresponds
126 to a sectoral life cycle, and in turn, this generates an economic cycle that is sectorally, and often
127 regionally, significant. Research and development (R&D) investment inversely relates to the age of
128 sectors (Grubb, 2014), going in decreasing order from biotech, artificial intelligence, computers,
129 chemicals, electricity, steel, engines, other metals, agriculture and so on. This matches six
130 successive industrial revolutions in reverse historical order: biotech and artificial intelligence (2010-
131 present), information technology (1970s-2010), petrochemicals and combustion engines (1920-
132 1970s), heavy engineering and electricity (1870s-1910s), the steam engine (1830s-1870s) and
133 textiles (1770s-1830s) (Freeman & Louçã, 2001; Perez, 2003).

134 A key question is how and where the low-carbon transition fits in this historical perspective. While
135 the above technological revolutions appear to be driven in many cases by the private sector,
136 entrepreneurs and innovation, the low-carbon transition is understood as normatively driven,
137 originating from the need to address climate change (Semieniuk et al., 2021). Yet technological
138 change is often accidental (e.g., Garud & Karnøe, 2003) and the public sector has been influential
139 in developing many technologies (Mazzucato, 2018) and even at least partially driving some past
140 transitions (e.g., the decision of the British military to convert its naval fleet from coal to oil-powered
141 accelerating the pace of the transition towards the internal combustion engine and petrochemicals
142 (Ediger & Bowlus, 2018)). Therefore, it is possible that climate policy is accelerating a transition that
143 might have occurred naturally over time, but not soon enough to mitigate climate change.

144 Indeed, the transition away from fuel combustion and heat towards electric means of harvesting
145 energy is motivated not only by climate policy, but also by lower wage bills, increased efficiency, and
146 lower operational costs (Way et al., 2022), traded off against higher capital costs (Ondraczek et al.,
147 2015). Moreover, renewable technologies, in particular solar photovoltaics, could be fast

148 approaching a tipping point where their levelized cost is at parity with or below the fossil fuel
149 equivalents (Nijse et al., 2023). In the Great Waves framing, this could point to a period of co-
150 existence between paradigms. Process innovation, saturation, and overall exhaustion of opportunity
151 characterise the carbon-intensive sectors, while the cleantech sectors are defined by high growth
152 and a jump in productivity over the old paradigm. This raises questions about what we can expect
153 to happen in regions and communities aligned with and dependent on the old carbon-intensive
154 paradigm. Looking at historical transitions can provide some insight.

155 **2.2. Post-industrial decline and the just transition**

156 Deindustrialisation and the associated post-industrial decline have been widely studied, especially
157 in the context of the closure of coal mines, steel, chemical and textile industries in the latter part of
158 the 20th century in the North of England (Mah, 2009; Martin et al., 2016; Thorleifsson, 2016;
159 Johnstone & Hielscher, 2017; Gherhes et al., 2020), Scotland (Lever, 1991; Walsh et al., 2010),
160 elsewhere in Europe (Walsh et al., 2010) and the Great Lakes region in the US and Canada (Mah,
161 2009). Deindustrialisation leads not only to loss of income and poverty but also to a loss of identity
162 (Mah, 2009; Thorleifsson 2016; Johnstone & Hielscher, 2017) as communities typically develop tight-
163 knit cultures around organised industrial work. The loss of those industries has led historically to
164 migration and depopulation, and for those who have not or could not leave, socio-economic decline
165 (Mah, 2009).

166 Regions affected by deindustrialisation in Europe rank lowest for health and life expectancy in each
167 country (Walsh et al., 2010). The disappearance of once dominant large industries can also leave
168 communities with stymied entrepreneurial capabilities, hindering their recovery in the long run
169 (Gherhes et al., 2020) and reinforcing socio-economic divergence within countries (Gardiner et al.,
170 2013; Martin et al., 2016). Meanwhile, transitions are commonly characterised by strong resistance
171 from incumbent industries and actors (Geels, 2002; Fouquet, 2016; Markard et al., 2020). From the
172 perspective of the actors at the losing end of the transition, the motivating factors are straightforward:
173 loss of affluence, income, employment, purpose, and social status (Baran et al., 2020).

174 With a working life of around 40 years (Jarvis et al., 2015), it is highly likely that a substantial number
175 of individuals, young and old, will see their skills become obsolete during a rapid transition before
176 the end of their working lives. Furthermore, since industries are typically geographically clustered
177 (Arthur, 1990), this process leads to regional concentrations of similar or related skills becoming
178 obsolete in large numbers (e.g., coal miners), making it challenging for the local economy to absorb
179 into new occupations required for the sunrise sectors and activities. The challenge in transitions is
180 therefore not just about re-training. For workers unwilling or unable to migrate, without substantial
181 opportunities, a skill excess glut can imply long-term involuntary unemployment and subsequently
182 further persisting social dislocation.

183 In perhaps one of the most infamous examples of post-industrial decline, the UK coal transition of
184 the 1980s transformed the socio-economic landscape of many former coal mining communities, with
185 long-standing impacts. Despite previously being one of the UK's most important strategic industries
186 of the early 20th century (Mitchell, 1984), by the 1960s, UK coal mines were facing increasing
187 competition from other fuels that offered economic and environmental advantages. Policymakers
188 adopted a policy of 'controlled rundown' of the coal mining industry in response (Ashworth & Pegg,
189 1986). Following the miners' strike of 1984-1985, major job losses occurred, leading many workers
190 to take early retirement and others to receive incapacity benefits (Foden et al., 2014). Over 30 years
191 on, former coal mining areas still lag far behind the UK average for metrics including employment
192 and education and have rates above the national average for deprivation, state benefit claimants,
193 and chronic health conditions (Beatty et al., 2019). This kind of persisting social dislocation is not
194 unique to the UK's coal transition and can also be witnessed in Detroit and the Great Lakes region
195 following the partial decline of the automobile industry there (Draus et al., 2010).

196 For the most part, these historical transitions were not supported by policy to account for disparities
197 and the uneven impacts of structural change and therefore created new and exacerbated existing
198 inequalities. In the current low carbon transition, literature has emerged on the need for a 'just
199 transition' (Abraham, 2017; Spencer et al., 2018; Weller, 2019). This is a movement that seeks
200 strategies for climate policy to both address climate change and mitigate present and expected new

201 inequalities (Markkanen & Anger-Kraavi, 2019). Originating from the US labour movement of the late
202 1990s, the just transition concept has evolved to address issues of equity and justice surrounding
203 the mitigation of climate change, gaining considerable attention through the UN's Sustainable
204 Development Goals (SDGs) and the Paris Agreement (Bang et al., 2022) as well as national climate
205 transition strategies. Initiatives to promote a just transition have included financial support for the
206 unemployed, regional training schemes, and international transition fund schemes (Krawchenko &
207 Gordon, 2021).

208 This literature addresses some of the issues that have been hindering progress in rolling out
209 ambitious climate policies, typically related to regional communities predominantly employed in high-
210 carbon industries. For example, due to the expected impacts of European climate policy on the coal-
211 producing country of Poland, the latter has lobbied the European Commission considerably and
212 negotiated with other member states for concessions, otherwise threatening to block further climate
213 policies at the European level (Brauers & Oei, 2020). Similar socio-economic challenges may also
214 be at the root of political polarisation around climate policy in some countries (Kurz et al., 2010;
215 Vona, 2019).

216 In the context of the low carbon transition, most of the literature on deindustrialisation and social
217 dislocation has focused on the decline of the coal industry (Burke et al., 2019; Weller, 2019; Baran
218 et al., 2020; Svobodova et al., 2021; Young et al., 2023). Communities dependent on the oil and gas
219 industries will soon face similar challenges (Carley & Konisky, 2020) and broader concerns exist
220 surrounding the potential extent of spill-over effects to other areas of the economy (Raimi et al.,
221 2022). These challenges must also be considered alongside the socioeconomic impacts and
222 inequalities that climate change is already causing through natural disasters (Rusca et al., 2023;
223 Smiley et al., 2022), biodiversity loss (Pörtner et al., 2023), disease epidemics (Ebi & Hess, 2020),
224 and more.

225 However, this is not to say that post-industrial decline is an unavoidable consequence of climate
226 policy and a low-carbon transition. The Ruhr region in Germany transitioned from an economy
227 geared around the coal extraction and steel manufacturing industries to a region dominated by a
228 knowledge-based service-oriented economy. Strategic economic diversification managed by the
229 regional and federal governments as well as trade union involvement and comprehensive retraining
230 schemes led to an economic transition that avoided widespread social dislocation (Galgóczi, 2014;
231 Arora & Schroeder, 2022; Dahlbeck et al., 2022).

232 3. Methods

233 Section 2 highlights the need to better anticipate the rise and decline of economic sectors in certain
234 geographical areas. We propose a first step in this direction – using macroeconomic models to
235 explore the possible ranges, levels, and directions of structural change in different economic sectors
236 and regions in a net zero transition. This analysis aims to provide insights that go beyond the
237 conventional assessment of economic impacts at the aggregate level to capture structural change
238 and distributional impacts which must be mitigated in a just transition. We begin this section by first
239 providing an overview of how macroeconomic models can offer insights into structural changes
240 before presenting a description of the three macroeconomic models used in this study.

241 3.1 Modelling low-carbon transition impacts

242 Obtaining quantitative insights on the sectoral and regional impacts of a net zero transition using
243 macroeconomic models requires a high level of sectoral and regional disaggregation of industrial
244 output, demand for goods and services, employment, and an adequate temporal resolution.
245 Advanced representations of innovation and technological change dynamics disaggregated across
246 the economy are also required. Furthermore, international trade and sectoral interdependencies are
247 crucial as they provide the necessary interconnections linking agents, products, industries, and
248 regions to one another. Unlike many of the IAMs frequently used for the assessment of climate
249 change mitigation scenarios, the models included in this study (E3ME-FTT, GEM-E3-FIT and
250 Imaclim-R) include many of the features that mean they are useful tools to obtain insights into
251 decarbonization induced structural change effects.

252 Macroeconomic models also frequently report impacts of climate policy that vary both in terms of the
253 magnitude and even the direction of change. In some models, without accounting for the financial
254 consequences of climate change, stringent climate policy results in a short-run reduction in GDP
255 relative to a counter-factual baseline whereas in other models, the opposite occurs, and climate
256 policy can drive a short-run GDP boost. The main source of this short-run divergence stems from
257 the economic theoretical underpinnings of the models which can be broadly categorised as
258 equilibrium (supply-led) economics and non-equilibrium (demand-led) economics (Mercure et al.,
259 2019). Here, we use models from both paradigms to allow us to consider a wider range of potential
260 impacts and to capture macroeconomic uncertainties.

261 3.2 Macroeconomic model descriptions

262 E3ME-FTT is an advanced non-equilibrium macro-econometric model based on a demand-led
263 economic framework. It covers the world in 71 regions with a sectoral disaggregation of 70 sectors
264 of industrial production in the EU and 44 sectors for non-EU regions. Intermediate production in
265 supply chains is represented through a combination of input-output relationships between sectors
266 and bilateral trade relationships between regions. It features both financial and physical energy flows
267 in its econometric representations based on IEA data in 22 fuel user types (Cambridge
268 Econometrics, 2022). FTT (Future Technology Transformation) is a family of evolutionary models of
269 detailed decision-making and S-curve technology diffusion processes. It represents technological
270 decision-making by heterogeneous agents in specific sectors, and the evolution of fleets of
271 technologies from birth to death. Currently, the FTT family covers the power, road transport,
272 residential heating, and steel sectors (Mercure et al., 2018; Lee et al., 2019; Vercoulen et al., 2023).

273 GEM-E3-FIT is an advanced Computable General Equilibrium (CGE) model, hybrid with bottom-up
274 energy, electricity, and transport modules, ensuring that the economic system in all scenarios
275 remains in general equilibrium. It represents the global economy as a set of 46 interconnected
276 regional and national economies, each composed of 52 production sectors (also connected by input-
277 output and bilateral trade links). Prices determine the interactions between a group of representative
278 firms and a representative household for each regional (or national) economy. Here, prices are also
279 used to minimize production costs and to allow households to maximise their intertemporal welfare
280 whilst conforming to a budget constraint (Capros et al., 2013; Paroussos et al., 2019). The model
281 formulates production technologies in an endogenous manner allowing for a price-driven derivation

282 of all intermediate consumption and the services from capital and labour. In the electricity sector, a
283 bottom-up approach is adopted for the representation of the different power-producing technologies
284 (Fragkos et al., 2021). On the demand side, the model formulates consumer behaviour and
285 distinguishes between durable (equipment) and consumable goods and services and explicitly
286 represents energy-related technologies in buildings and road transport.

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

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

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

	E3ME-FTT	GEM-E3-FIT	ImacliM-R
Model type	Macroeconometric (E3ME), hybrid with bottom-up evolutionary modules (FTT)	CGE model, hybrid with bottom-up modules	CGE model, hybrid with bottom-up modules
Macroeconomic theory branch	Non-equilibrium (Demand driven)	Equilibrium (Supply driven)	Equilibrium (Supply driven)
Technological change	Endogenous (power, road transport, domestic heat, and steel sectors)	Endogenous (power, road transport, heating)	Endogenous (power, road transport) with high inertia
Labour market representation	Imperfect and flexible labour markets	Imperfect and flexible labour markets, 5 skill levels are represented	Imperfect labour markets with limited flexibility
Investment & Finance	No crowding out, no fixed limit on finance	Crowding-out, finance is constrained	Crowding-out, finance is constrained
Sector coverage	43 (70 in the EU)	52	19
Regional coverage	71 countries and regions	46 countries and regions	12 countries and regions

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

318 **3.3 Study design**

319 To explore possible ranges, levels, and directions of structural change impacts in a low-carbon
320 transition, we develop baseline and global net zero emission scenarios for the macroeconomic
321 models mentioned above. The baseline only includes currently implemented energy and climate
322 policies without intensification in the future (see Lefèvre et al., 2022 for more detail on structural
323 change in a baseline scenario). Net zero scenarios show the impact of ambitious climate and energy
324 policies on economic structural change up to 2050.

325 The scenarios are compliant with an end of century carbon budget of between 600-700 GtCO₂ and
326 reach global net zero emissions between 2060-2065. We consider this to be in line with the Paris
327 Agreement target to limit warming to well below 2°C, with similar budgets featured in such scenarios
328 in IPCC’s AR6 Working Group III (IPCC, 2022a). In all three models, the net zero scenario includes
329 a combination of market-based (e.g., carbon pricing) and regulatory (e.g., clean technology support)
330 policies. Table S1 (supplementary material) shows the policy packages in each of the net zero
331 scenarios. The amount of cumulative global negative emissions is limited to below 50 GtCO₂ in 2050.
332 Between 2020-2050, the average annual global carbon intensity reductions in the net zero scenarios
333 are between 5.8 and 7.5 percent. All scenarios include the short-term socio-economic impacts of the

334 COVID-19 pandemic. We develop a consistent aggregation of economic sectors (described in Table
335 S2 – supplementary material) and include results for major fossil fuel exporter and importer
336 economies.

337 4. Results

338 We begin this section by describing and contrasting the trajectories the three models describe at the
339 economy-wide level in a net zero scenario. In the second part of this section, we show the impact of
340 a net zero transition on disaggregated metrics including sectoral output and employment.

341 4.1. Regional socio-economic impacts of a net zero transition

342 At the aggregate level, we find considerable differences in the economic output projections between
343 the models that illustrate alternative possible storylines of the net zero transition. These differences
344 are linked to different visions and economic theories embedded in the models. We note three key
345 differences: i) the flexibility of the economy, socio-technical, labour, and energy systems in the short
346 to medium run, ii) the availability of capital for low carbon investments and the resulting stimulus
347 effect in sunrise sectors, and iii) alternative visions and databases for modelling fossil fuel markets
348 and the distribution of declining production between countries.

349 4.1.1. Aggregate level differences between regions and models

350 While a net zero transition will inevitably generate different impacts in different parts of the world, we
351 identify four broad country groups (Table 2) according to i) the degree to which the models report
352 similar outcomes and ii) the aggregate GDP impacts of a net zero transition presented in Figure 1.
353 Group 1 represents regions where the model results are similar, with all models projecting some of
354 the most significant negative impacts on GDP in a net zero transition. Countries in Group 1 are major
355 fossil fuel exporter economies with a high carbon intensity (Russia, Saudi Arabia). In Group 2, GDP
356 impacts are less severe. The trajectories described by the models are still fairly similar, where
357 negative GDP impacts are still mostly reported. Like the regions in Group 1, Group 2 consists of
358 fossil fuel exporters, though these countries have a more moderate carbon intensity and are more
359 economically diversified than those in Group 1.

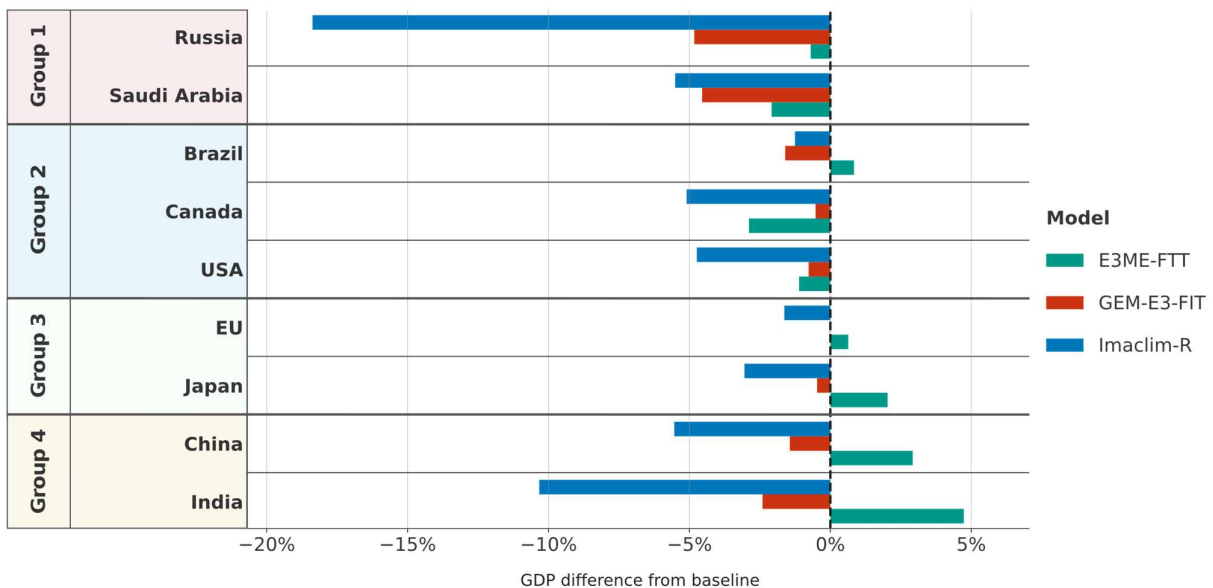
360 The transition trajectories described by the models begin to diverge across models in Group 3.
361 E3ME-FTT, the simulation-based non-equilibrium model, describes positive GDP impacts while the
362 equilibrium models continue to project net costs. Overall, GDP impacts (positive or negative) are the
363 most limited in Group 3 which describes developed Global North fossil fuel importing regions with a
364 low carbon intensity (EU, Japan). Group 4 exhibits the lowest level of model result similarity with
365 strong positive GDP impacts in E3ME-FTT in contrast to notable losses in the other models. This
366 group represents emerging economies that are fossil fuel importers with a higher carbon intensity
367 (China, India).

368 Altogether, as Figure 1 shows, and in line with other models featured in IPCC AR6, a net zero
369 scenario in each of the models generates mostly small to moderate impacts on aggregate GDP
370 (IPCC, 2022a). The models largely agree that fossil fuel exporter economies will witness a negative
371 GDP impact in a net zero transition. This is mainly driven by the loss of exports due to lower global
372 demand for fossil fuels. As a result, countries in Group 1 fare the worst as they are more dependent
373 on fossil fuel rents than the exporters in Group 2, who have more diversified exports. Furthermore,
374 the models also mostly agree that impacts, whether positive or negative, are particularly limited in
375 economies with lower carbon intensities (Groups 2 and 3). The picture is more nuanced in fossil fuel
376 importer economies, where E3ME-FTT projects that a net zero transition has the potential to
377 increase GDP.

Group	Degree of model similarity	GDP impacts	Countries	Fossil fuel importer or exporter	Economic Carbon intensity
1	High	Largest negative impacts	Russia, Saudi Arabia	Exporter	High
2	High/medium	Small - moderate positive or negative impacts	Brazil, Canada, US	Exporter	Medium
3	Low/medium	Smallest positive or negative impacts	EU, Japan	Importer	Low
4	Low	Largest positive or negative impacts	China, India	Importer	High

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

380



381

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

384 4.1.2. Drivers of aggregate level model result difference

385 The difference in the trajectory of aggregate GDP between E3ME-FTT and the two other models
386 described in Section 4.1.1 is largely due to the absence of crowding-out of low-carbon investments
387 on other investments. There is no limit on the availability of the money supply or finance in E3ME-
388 FTT. The model also has a flexible supply that can more readily adapt to the demand and evolution
389 of technical systems and the capital stock than the other models.

390 Furthermore, a stimulus effect is generated from the investment required to develop low-carbon
391 technologies and sectors. Fossil fuel importer countries are key winners of the transition in E3ME-
392 FTT as decarbonisation facilitates improved trade balances. This effect benefits most countries
393 worldwide since fossil fuel production is concentrated in a limited number of countries. The reverse
394 effect occurs in fossil fuel exporting countries in E3ME-FTT, where the loss of activity amplifies
395 through drastic losses of investment, with scrapped capital not assumed to be recycled towards
396 other activities. In addition, E3ME-FTT adopts a representation of fossil fuel markets based on a
397 detailed extraction costs dataset (Mercure et al., 2021b) that penalizes the high-cost producers
398 (USA, Canada) in a more pronounced way than the other models.

399 While the largest differences between models can be explained by the contrasting macro-innovation
400 theory representation, the two equilibrium models also often project GDP impacts of differing
401 magnitude. Both GEM-E3-FIT and Imaclim-R project negative GDP impacts in all regions in a net
402 zero scenario, but such impacts are almost always more negative in Imaclim-R. This is due to the
403 higher flexibility of technical systems as embedded in the CES (constant elasticity of substitution)
404 production functions and in the bottom-up modules to represent energy and transport systems in
405 GEM-E3-FIT (Fragkos & Fragkiadakis, 2022). This means that the energy system in Imaclim-R is
406 characterised by greater inertia. Additionally, a more flexible labour market in GEM-E3-FIT limits
407 short to medium-run transition costs.

408 4.2 Structural change in a net zero transition

409 Whilst the economic impacts of a net zero transition might well appear relatively moderate for most
410 countries at the aggregate level, we find substantial sectoral variation regarding the direction and
411 magnitude of change in both output and employment. This reflects the potential for climate policy to
412 induce large-scale structural change, with uneven impacts between sectors and regions (Lefèvre et
413 al., 2022). The sectoral impact of a net zero transition on output is shown in Figure 2, expressed as
414 the percentage difference from baseline. Despite the different theoretical underpinnings of the
415 models, a common narrative of structural change in a net zero transition emerges, where the models
416 report similar sectoral trajectories.

417 4.2.1 A common storyline of structural change

418 First, in line with the aim of the net zero scenarios, the fossil fuel sector's share of total GDP falls
419 rapidly in every region. This contraction in contribution to overall GDP is particularly considerable in
420 the fossil fuel exporter economies in Group 1 that are currently less well economically diversified.
421 Figure 3 also shows that employment in the fossil fuel sector falls in every region in all models in the
422 net zero scenarios, consistent with the sectoral output. Again, the most substantial losses are
423 projected in large fossil fuel-producing regions, where a greater portion of the total workforce is
424 currently employed in the fossil fuel sector. Furthermore, the fossil fuel trade balance (exports-
425 imports) generally worsens in fossil fuel exporter countries as their hydrocarbon exports decrease
426 (Figure S1 – supplementary material). Simultaneously, the fossil fuel trade balance generally
427 improves in importer countries, as decreased demand for fossil fuels reduces their import bill.

428 Meanwhile, the electricity sector witnesses an increase (albeit limited) in its share of total GDP in
429 almost all regions as electrification of the road transport and heating sectors accelerates as these
430 sectors decarbonise. This is also reflected in an increase in electricity sector employment in all
431 regions. The energy-intensive sector's share of total GDP also increases across most regions. In

432 E3ME-FTT and GEM-E3-FIT, this is largely driven by an increased demand for critical materials on
433 account of a greater share of solar photovoltaics in electricity systems.

434 **4.2.2 Net zero transition impacts beyond the fossil fuel sector**

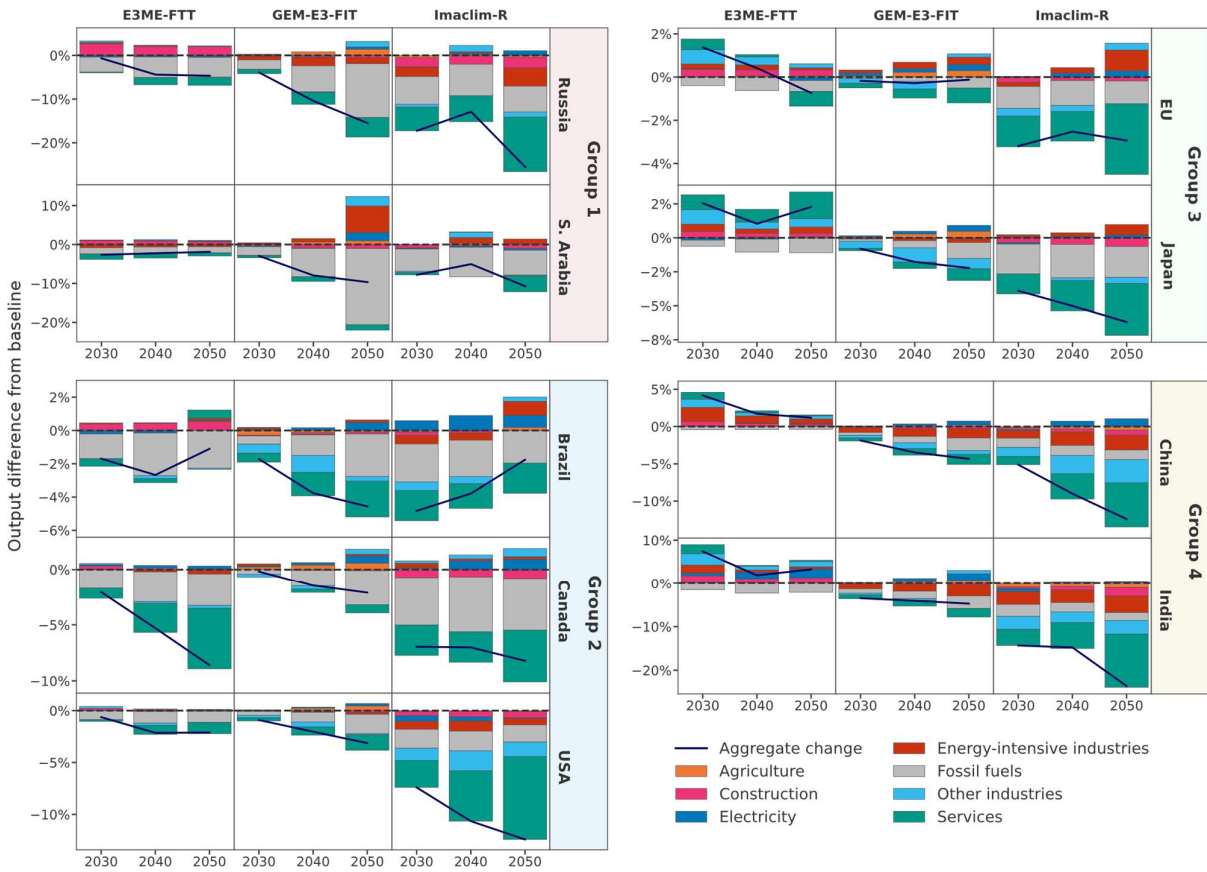
435 A key feature in the process of decline in high-carbon industries is the impact on the intermediate
436 production of goods and services that occurs across those value chains, which goes far beyond the
437 fossil fuel sector itself. This includes output losses in manufacturing and construction for projects
438 that do not happen (relative to a counterfactual baseline scenario). This also includes vehicles and
439 machinery that are never produced, fuel that is never distributed, steel for pipelines that is never
440 ordered, and so on. Therefore, downward pressure in many sectors develops, particularly amongst
441 fossil fuel exporters due to the more significant loss of activity in the fossil fuel sector. At the same
442 time, rapid growth occurs in the renewable energy sectors driven by net zero policy which also has
443 knock-on effects in other areas of the economy though these are less pronounced in GEM-E3-FIT
444 and Imaclim-R due to the crowding-out of investment assumed in CGE models.

445 Figure 2 shows that in many countries a substantial part of this contraction of GDP stems from the
446 services sectors, which provide a rough barometer of the general economic situation. This is
447 because the services account for the largest share of GDP globally and they generally become the
448 end recipients of income generated in most other sectors as salaried workers spend their wages
449 (e.g., on food, clothing, etc.). In fossil fuel importer economies, however, the models show different
450 trajectories for the services sector, due to the different ways they portray the creation of (or
451 competition for) financial resources for the investment required for decarbonisation. For fossil fuel
452 importer countries in Groups 3 and 4, E3ME-FTT generally projects increased service sector output
453 and employment in a net zero scenario whilst GEM-E3-FIT and Imaclim-R typically project a
454 somewhat limited contraction.

455 This is, again, a direct consequence of the assumptions around economic equilibrium and crowding-
456 out effects, where a stimulus effect from building activity related to low-carbon technologies in E3ME-
457 FTT drives an increase in demand. Meanwhile for GEM-E3-FIT and Imaclim-R, the cost of the
458 transition reduces the demand for services as financial resources are limited and additional
459 investment requirements for decarbonisation puts stress on the capital markets ("crowding-out"
460 effect). This cancels investment in other productive sectors and increases the price of capital in the
461 entire economy (Fragkos & Paroussos, 2018). These changes in output are directly reflected in
462 employment projections of the models (see Figure 3).

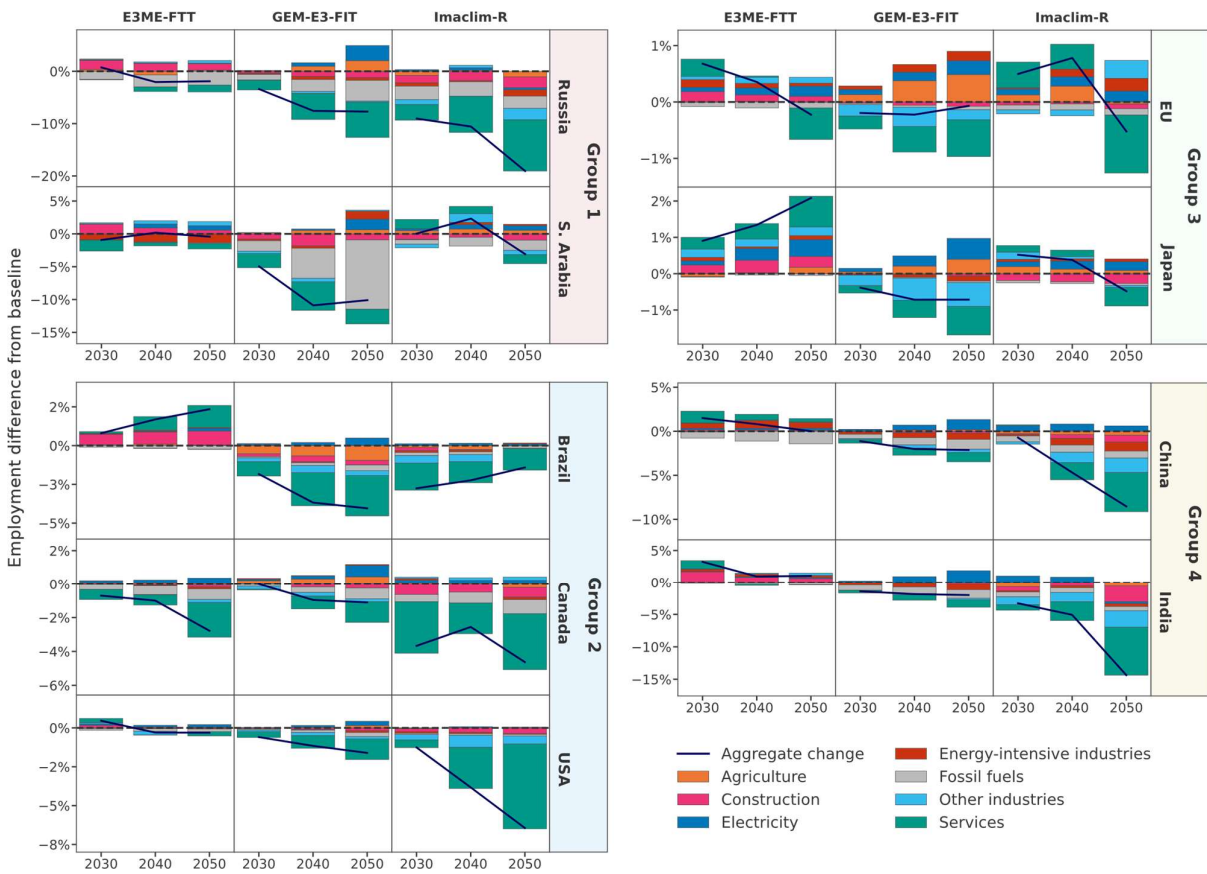
463 There are similar contrasting outcomes in the construction sector, where in E3ME-FTT, output and
464 employment increase relative to a baseline scenario. This is due to climate policy that induces large-
465 scale investment in low-carbon capital in the form of renewable infrastructure. In GEM-E3-FIT and
466 Imaclim-R, the impact of a net zero transition on the construction sector is slightly negative for most
467 regions, as the negative impacts of GDP losses counterbalance the increased demand for
468 construction to build the new low-carbon infrastructure (e.g., renewable energy plants, enhanced
469 renovation of buildings, recharging infrastructure etc.).

470 As indicated in Section 4.1.1, the model results are the most different for China and India, where
471 E3ME-FTT projects output and employment gains across several sectors while the two equilibrium
472 models project almost an economy-wide decline relative to a baseline scenario. While the models
473 agree that China and India can both improve their trade balances in a net zero transition by reducing
474 their imports of fossil fuels, the direction and magnitude of change in other sectors are less clear.
475 For instance, the services sector in E3ME-FTT grows both in terms of output and employment whilst
476 the opposite occurs in GEM-E3-FIT and Imaclim-R. Once again, this is due to decreased economic
477 growth driven by climate policy under the strict closure rule of General Equilibrium models.



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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.



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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.

484 **5. Discussion**

485 Using three sectorally and regionally disaggregated macroeconomic models of different theoretical
486 foundations, we show that the transition to a low-carbon economy will generate substantial uneven
487 impacts on economic output (Figure 2), employment (Figure 3), and trade (Figure S1) both within
488 and between economies. The results described in Section 4 show that, in a net zero transition, some
489 sectoral trends are more certain than others. Most notably, large-scale unemployment will emerge
490 in the fossil fuel sector, especially in fossil fuel exporting regions. Employment losses could be
491 witnessed in other areas of the economy, through supply chain linkages with the sunset sectors.

492 There is still significant uncertainty regarding the degree of losses in the service sectors in particular,
493 as the three models present often contrasting directions of change due to their different theoretical
494 positions concerning the creation of investment capital and their degree of optimism regarding the
495 flexibility of sociotechnical systems. It is not possible at this stage to claim with any degree of
496 certainty which trajectory the future will be closer to. In fact, since investment capital is neither
497 limitless (as in E3ME-FTT) nor fully crowded-out (as in GEM-E3-FIT and Imaclim-R), the future
498 trajectory of the economy could lie between the boundaries delimited by these models (Pollitt &
499 Mercure, 2018). It is also important to highlight that because these models do not consider the
500 physical impacts of climate change and their economic consequences, further inaction on climate
501 change will lead to additional socioeconomic impacts and inequalities that are not represented here.
502 Therefore, delaying or avoiding all policy to support the transition on the grounds of justice is ill
503 considered.

504 **5.1 Limits of aggregate metrics**

505 An important insight of this study is that structural change is much larger in magnitude than the
506 aggregate impacts of a net zero transition. For an ordinary household, emerging economic pressures
507 will depend starkly upon which sector(s) and region its working family members live and work in, in
508 contrast with any definition of a representative agent (or average person) as commonly used in
509 economic and Integrated Assessment modelling. The decarbonisation impacts on financial,
510 economic, social, health and standard of living metrics for certain households could be extreme,
511 even if 'average' or 'median' impacts across households are moderate or zero. Additionally, these
512 disparities could be particularly important in post-growth and degrowth scenarios given that these
513 scenarios not only project more significant aggregate GDP impacts (due in part to less ambitious
514 requirements for technological change) (Keyßer and Lenzen, 2021; Nieto et al., 2020), but also
515 require a differentiated down- or upscaling of different sectors depending on ecological and social
516 importance (Hickel et al., 2021).

517 The frequently used aggregate metric of 'consumption loss' or 'GDP loss' as used in standard policy
518 assessments could therefore be misleading, as it could be interpreted as the amount of consumption
519 or income lost by all households in a region because of climate policy. In contrast, we show here
520 that moderate aggregate consumption loss can mean important benefits for some households,
521 simultaneous to the end of entire livelihoods and communities for others (e.g., employees in regions
522 that rely significantly on the fossil fuel industry), even within the same regions. Those differences in
523 turn can fuel societal inequality, socioeconomic division, and political polarisation.

524 Regardless of whether stringent climate policies adequate to achieve ambitious emission reduction
525 targets are developed and implemented, technology is constantly changing in a transition towards
526 higher energy efficiency, renewable energy sources, and increasing electrification in the present
527 economic trajectory (Way et al., 2022; Nijssen et al., 2023). With ambitious climate policies, where
528 the aim of a just transition is ignored, the accelerated rate of structural change could destabilise
529 many parts of the economy from the incumbent supply chains, labour markets, and financial markets
530 (Semieniuk et al., 2021). Destabilisation could also be significant in alternative pathways looking at
531 low or degrowth transitions (Hickel et al., 2021) or in scenarios with limited mitigation and strong
532 climate change impacts across the economy. This rapid evolution of the socio-technical regime must
533 be recognised as it could become the dominant source of socio-economic transformation for the next
534 few decades, driving key socio-economic indicators and even political processes.

535 **5.2 Post-industrial decline in a net zero transition**

536 Focusing only on the aggregate impacts of climate policy could risk contributing to a transition that
537 is unjust and is in danger of creating stranded capital, labour, skills (Mercure et al., 2021c), and even
538 entire regions (Spencer et al., 2018) that become precluded from many of the opportunities
539 presented by the sunrise sectors. As highlighted in Section 2.2, similar industry tends to cluster due
540 to an agglomeration effect (Arthur, 1990). This means that whole cities or even countries may have
541 formed and grown around certain industrial activities. For example, Fort McMurray, an urban service
542 area in Northern Canada, might not have existed without the development of the tar sands industry.
543 Similarly, Rotterdam could have been a less prominent city without the development of its
544 petrochemical industry, which powers mobility and many other industrial activities upstream of the
545 Rhine River in Germany and elsewhere.

546 This concentration of industry will lead to regionally concentrated output and employment losses in
547 a net zero transition. In such regions, output losses are unlikely to be confined to the high-carbon
548 industries and they will instead likely impact the service sectors too (Raimi et al., 2022) as
549 households have less disposable income to spend on food, retail, and other goods. Just as regions
550 aligned with the sunset technological paradigms in previous transitions were (Freeman & Louçã,
551 2001), regions currently highly dependent on carbon-intensive activities could be at serious risk of
552 post-industrial decline in a net zero transition. Left unmitigated, this could mean such areas become
553 left behind by the transition, potentially unable to take advantage of the economic opportunities
554 offered by the sunrise cleantech industries.

555 **5.3 Implications for climate policy and future work**

556 Addressing post-industrial decline after the fact is challenging, as evidenced by the persistence of
557 poor socioeconomic outcomes in many former industrial areas (Draus et al., 2010; Beatty et al.,
558 2019). Where programs have been successful, they have been at high cost (Arora & Schroeder,
559 2022). While lessons can be learned from previous examples of economic transitions, adequate
560 policy frameworks should be highly region and sector-dependent (Dahlbeck et al., 2022). Vocational
561 training and relocation schemes for displaced workers in sunset industries and related supply chains
562 are likely to be important tools to address disparities. Such schemes can be (at least partly) funded
563 by increasing carbon tax revenues.

564 However, redistributive policy alone is unlikely to be adequate to deal with post-industrial decline,
565 especially considering that fossil fuel exporter economies in particular will be faced with a reduced
566 fiscal space (as shown by Figure S1 – supplementary material) from which to fund transition support
567 initiatives due to losses of exports. Instead, transformative economic policy could be more effective
568 to enable former fossil fuel dependent regions to capture the opportunities of the transition. This
569 could include economic diversification schemes that utilise existing regional economic capabilities
570 to develop new export opportunities (Mealy & Teytelboym, 2022).

571 International mechanisms can play a role too, as demonstrated by the recent Just Energy Transition
572 Partnerships, where the European Union and other countries in the Global North financially support
573 the acceleration of energy system decarbonisation in the Global South. The partnerships explicitly
574 acknowledge calls for a just transition, placing focus on supporting affected communities in this
575 transition (European Commission, 2021). Such partnerships are currently supporting transition
576 efforts in Indonesia, Senegal, South Africa, and Vietnam (Simpson et al., 2023).

577 Research to further investigate the regional disparities both between and within countries is also
578 needed to help inform future discussions on structural change induced by ambitious climate policy.
579 Coupled with this, advanced modelling tools that offer a high sectoral and regional disaggregation
580 of outputs embedded in economy-wide frameworks with endogenous trade impacts are required to
581 identify risks and opportunities for national and subnational regions and sectors and to support
582 effective decision-making and design of efficient and just industrial, labour, climate, and economic
583 policy. Finally, given the call to explore alternative pathways with different growth assumptions, e.g.
584 degrowth and post-growth scenarios (Li et al., 2023), the same methodology could be applied in

585 future research to investigate potential levels of structural change and disparities in such disruptive
586 development pathways (Lefèvre, 2023).

587 **6. Conclusion**

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

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

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609

610 **Declaration of Competing Interest**

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

613

614 **CRedit authorship contribution statement**

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616 **Yeliz Simsek:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft.

617 **Jean-François Mercure:** Conceptualization, Methodology, Software, Formal analysis, Writing –
618 original draft, supervision, project administration, funding acquisition.

619 **Panagiotis Fragkos:** Conceptualization, Methodology, Writing – review & editing, project
620 administration, funding acquisition.

621 **Julien Lefèvre:** Conceptualization, Methodology, Writing – review & editing, project administration,
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628 **Femke Nijse:** Conceptualization, Methodology, Writing – review & editing.

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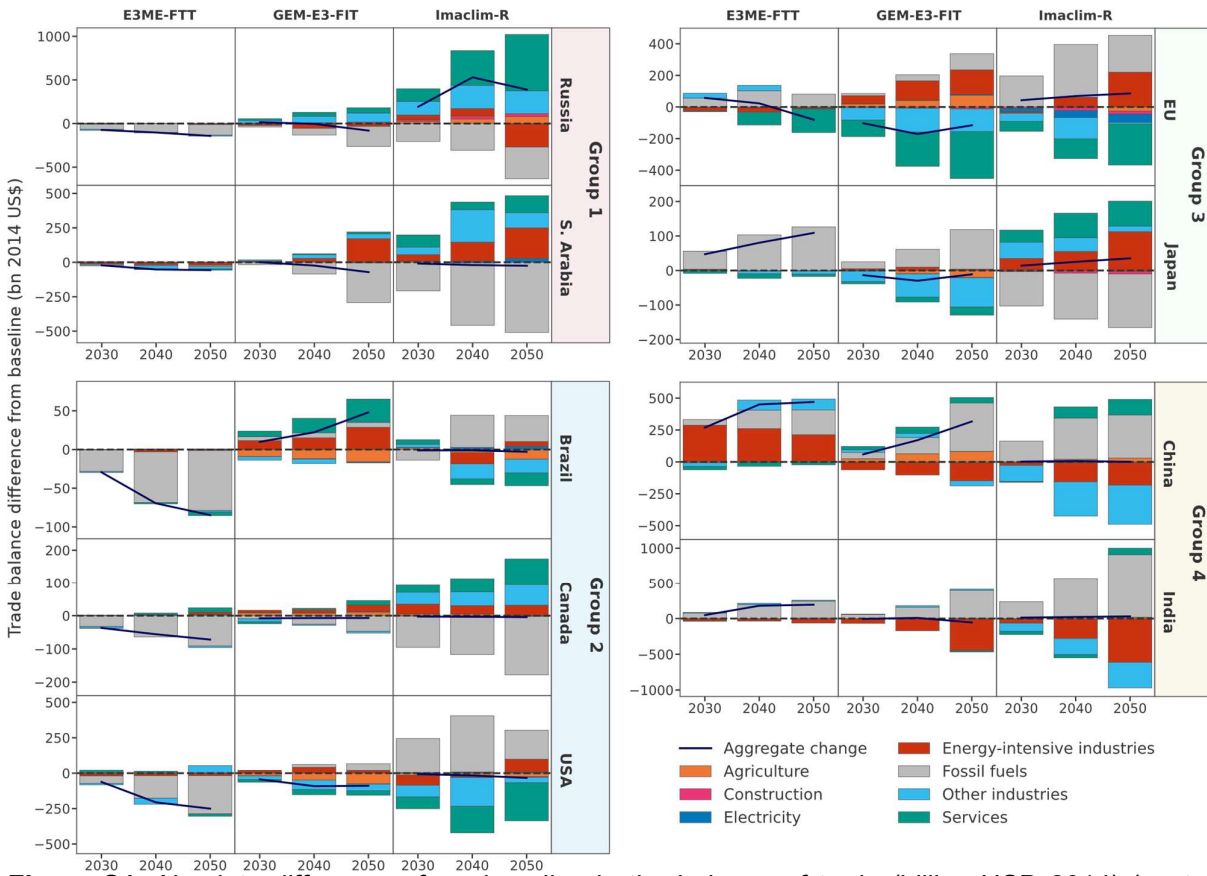
829 **8. Supplementary Material**

	E3ME-FTT	GEM-E3-FIT	Imaclim-R
Emission pricing	Yes – excluding households and road transport	Yes - all sectors	Yes – all sectors
Phase out regulations	Yes – power, domestic heating, road transport, and steel sectors	Yes - through changes in fuel shares in demand sectors	No
Feed-in-tariff	Yes	No	No
Technology subsidies	Yes - power, domestic heating, road transport, and steel sectors	Yes, in heating and transport	No
Kick start procurement schemes	Yes – power and transport sectors	No	No
Fuel efficiency policy and regulations	Yes	Yes - especially in transport and buildings sectors	No

830 **Table S1.** Policies included in the net zero scenarios of each of the three models compared to the
831 baseline scenario.

Sector	Description
Agriculture	Activities related to crop and livestock production and fishing.
Construction	General and specialized construction of buildings and civil engineering works.
Electricity	Activities related to the generation and distribution of electricity.
Energy-intensive industries	Heavy industry including iron and steel, non-metallic minerals, chemicals, non-ferrous metals, paper and pulp.
Fossil fuels	Activities related to the extraction, processing, and supply of coal, gas, and oil.
Other industries	Other manufacturing industries that are not included in the energy-intensive category.
Services	Tertiary sector.

832 **Table S2.** Description of the study sectoral classification.



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Figure S1. 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 IMACLIM-R. Negative values indicate either loss of exports or gains of imports, while positive values conversely indicate losses of imports or gains in exports.