

1 Economic impacts of achieving a zero emissions target in the UK power sector

2 Abstract

3 With increasing concerns about climate change, calls for the adoption of net-zero carbon emissions
4 targets are rising. Achieving this target necessitates a radical decarbonisation of the electricity system,
5 including the shut-down of currently operating high-carbon energy infrastructure. In the light of this
6 background, we develop a novel system dynamics energy-economy model to explore the long-term
7 macroeconomic effects, and changes in the power system costs of different low-carbon electricity
8 transition scenarios. Using the UK as a case study, our simulations demonstrate that there is no win-
9 win policy solution. We argue that while the early retirement of a certain amount of brown energy
10 infrastructure is required for the UK to achieve its emissions target, the amount should be determined
11 with care in order to manage the electricity system costs and prices. By using an implicit carbon price,
12 we find that certain trajectories lead to lower energy system costs while achieving the net-zero target.

13 **Keywords:** Energy-transition, system dynamics, energy-economy modelling, climate change, policy

14 1 Introduction

15 Along with increasing concerns on the impact of global warming, calls for adopting a net-zero
16 emissions target rise and social movements, such as Extinction Rebellion (XR), call for an immediate
17 halt in the use of brown energy sources citing a relatively short time horizon in which to stop climate
18 change. In response to the call for net-zero carbon emissions, a growing number of research studies
19 have explored energy transition pathways and their related costs and/or macroeconomic implications.

20 The UK government, as well as the UK independent Climate Change Committee (CCC), predominantly
21 use the well-established macro-hybrid energy-economy UK MACRO Times (successor of the former
22 MACRO MARKAL model) for climate policy analysis and investigating related long-term
23 macroeconomic consequences (Strachan et al., 2007, 2009). This model is a combination of a CGE
24 economic model and a technological-rich bottom-up energy system optimisation model (Strachan et
25 al., 2007; 2008). Another model, the Her Majesty's Revenue and Customs (HMRC) CGE model – initially
26 developed for HMRC to assess tax policy changes – has also been applied to climate policy, including
27 evaluating the economic impacts of the fourth carbon budget (see CCC, 2010). Alternatively, UK policy
28 recommendations are derived based on econometrically-estimated macroeconomic simulation
29 models, notably the UK Energy-Environment-Economy model MDM-E3 (e.g. Barker et al., 2007; Ekins
30 & Etheridge, 2006; Ekins et al., 2011) or the global Econometric Energy-Environment-Economy Model
31 E3ME (see CE, 2019).

32 Other energy transition simulation models in the field of the ecological macroeconomics are
33 increasingly emerging during recent years. Examples of simulation models in this strand of literature
34 include for example MEDEAS (Cappellan-Perez et al., 2017), EUROGREEN (D'Alessandro et al., 2020),
35 SFC low-growth (Jackson & Victor, 2019), EIRIN (Monasterolo & Raberto, 2018), EURACE (Ponta et al.,
36 2018) or the SFC low-growth (Jackson & Victor, 2019) (see Hafner et al., 2020a for a review). These
37 energy-economy models demonstrate different economic (e.g. GDP, employment, inequality)
38 implications of climate policies and reveal a variety of different aspects/implications of low-carbon
39 energy transitions, but to date and our best knowledge, none of them has been applied for the
40 evaluation of a rapid low-carbon energy transition, including the immediate halt of high-carbon
41 electricity infrastructure, as called for by different social movements.

42 In 2019, the UK was the first country to adopt a net-zero emissions target by 2050 (CCC, 2019).
43 Reaching this target requires a radical decarbonisation of the UK energy system. This paper focusses
44 on the UK as a case-study within this context.

45 In the light of this background, we seek to understand the following two questions:

- 46 1) What are the financial costs and the macroeconomic implications of a rapid electricity
47 transition, involving the immediate stop in using all currently still operating brown energy
48 infrastructure?
- 49 2) How do these financial costs and macroeconomic consequences compare to other – less rapid
50 - low-carbon electricity transition scenarios?

51 To address these questions, we develop a new system dynamics energy-economy model, called the
52 Green Investment Barrier Model¹ (GIBM) tailored to evaluate different low-carbon electricity
53 transition futures of the UK in terms of macro-economic and electricity system costs. The main
54 purpose of this paper is to provide a holistic and reliable decision-support tool for policy decisions
55 with respect to the speed of decarbonisation of the electricity supply sector. We highlight that GIBM
56 provides only high-level policy insights. That is, it does not assess how to deal with the intermittency
57 of renewables (e.g. by specifying technologies²) and the expansion of renewable electricity sources is
58 only restricted by the estimated technical potential of considered renewable sources. Furthermore,
59 we focus on the decarbonisation of the power sector and represent electricity demand from the
60 heating and transport sector exogenously, based on the Green Growth scenario of the National Grid
61 (2018).

62 Our study complements and extends earlier studies on the economics of low-carbon energy
63 transitions. First, the studies indicated above tested less radical energy decarbonisation scenarios and
64 to our best knowledge, none of the these has been used to simulate a scenario, involving the
65 immediate shut-down of *all* current high-carbon energy infrastructure in the UK. Indeed, due to the
66 underlying model assumptions, CGE models are generally not applied for the investigation of a net-
67 zero emissions target (IPCC, 2014; 2019). The policy scenario tested in this study aims to fill this gap.
68 Second, this study applies a different model methodology compared to other studies. System
69 dynamics modelling is particularly useful for long-term simulation exercises where the understanding
70 of key feedback loops driving a complex, dynamic system from a holistic perspective is important
71 (Sterman, 2000). By using a different methodology, our study also helps to increase the robustness of
72 previously achieved results on energy transition simulations.

73 This paper is structured as follows: section 2 introduces our methodology and describes the Green
74 Investment Barrier model. Section 3 presents the model results, section 4 discusses the results and
75 compared them with the results achieved by other energy-economy models. Section 5 concludes and
76 indicates future research avenues.

77 2 Methodology

78 The developed system dynamics energy-economy model is built with the system dynamics simulation
79 software Vensim. System dynamics (SD) was elaborated by Jay Forrester in the 1960s at MIT and is

¹ GIBM allows also to test policies that tackle key green investment barriers to scale-up green finance and therefore its name (see Hafner et al., 2020b; Hafner et al. (forthcoming)).

² GIBM does account for the average financial costs of required storage technologies when higher shares of renewables are on the grid (see Supplementary Information).

80 grounded in the theory of non-linear dynamics and feedback control developed in mathematics,
81 physics and engineering (Forrester, 1958). SD uses concepts of those disciplines in its modelling
82 approach. For example, the idea to understand and manage systems through feedback loops draws
83 on control theory from engineering. SD has been applied in various areas, including organisation
84 theory, economics, health care, cognitive and social psychology and conflict research (see Sterman,
85 2000 for case studies). Mathematically, SD is a set of linked differential equations simulated by
86 algorithms. SD models are frequently represented visually through a stock and flow diagram (SFD) or
87 a causal-loop diagram (CLD) (Sterman, 2000). This methodology has been chosen to represent the
88 underlying complexities in both the economy and the energy system, and their interlinkages. In
89 addition, the modelling environment of the system dynamics program is suitable for long-term
90 simulation periods and flexible enough to adjust the developed model relatively easily for new energy-
91 economy related policy challenges.

92 Importantly, this study applies another model approach compared to most studies applied to energy
93 transitions that use CGE (CCC, 2010) or macro-economic modelling (CE, 2019). Specifically, on the one
94 side, in comparison to CGE and other equilibrium models, system dynamics modelling abstracts away
95 from the adoption of (bounded) rational model agents and cleared markets (in the long-term). Instead,
96 the model results are calculated for each time step, and model agents take decisions and form
97 expectations, using heuristics and information on the current state of the model world. On the other
98 side, in comparison to macro-econometric models, system dynamics models can be said to be more
99 flexible. That is, while system dynamics models sometimes apply econometrically estimated
100 parameter values, they also allow parameters and/or parameter values – or changes thereof -
101 informed by qualitative research or expert consultation.

102 The economic model sectors of GIBM can be said to be embedded in a post-Keynesian/ecological
103 macroeconomic framework (Sawyer & Fontana, 2016; Hardt & O'Neill, 2017). Specific model
104 equations build generally on different non-equilibrium modelling approaches, including post-
105 Keynesian economics, ecological economics or system dynamics (e.g. Sterman, 2002), but also
106 equilibrium approaches (e.g. CES production function). Non-equilibrium modelling approaches share
107 a set of common presuppositions or metaphysical beliefs, which cannot be put in formal form, but are
108 part of, and influence, the analytical framework of economic models (Lavoie, 2014). For example, non-
109 equilibrium modelling approaches perceive the economic environment as complex, dynamically
110 evolving, interrelated with other environments (e.g. institutional setting) and characterised by deep
111 uncertainty (i.e. probabilities cannot be assessed) and path-dependency. Model agents do not possess
112 near-perfect information and optimize their outcomes (e.g. utility, profit), but often use simple
113 decision-rules to operate in the complex economic environment (e.g. Mercure et al. 2019).

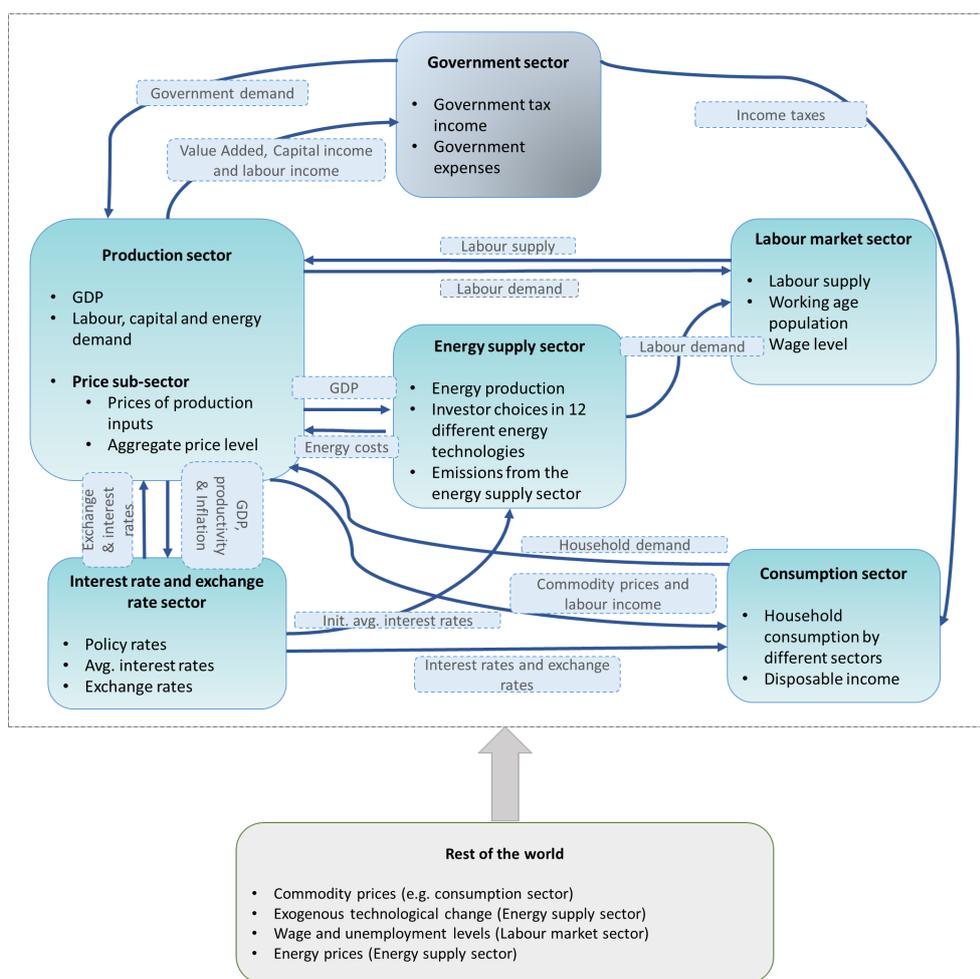
114 The empirical calibration of the GIBM parameters and initial values for the UK provide a realistic basis
115 for the investigation of the economics of different low-carbon electricity transition pathways. The
116 main data sources used to calibrate the initial conditions, for the UK economy and energy system in
117 the year 2016, are from ONS, EUROSTAT and policy reports (in the case for the energy system).

118 GIBM (see Figure 1) includes key macroeconomic sectors (e.g. production, consumption, and labour
119 market), a public sector and an electricity supply sector. The production process at the
120 macroeconomic level is represented with a demand-led CES production function – that is, the
121 production inputs, labour, capital, energy and intermediate inputs are not (necessarily) fully utilised.
122 The production sector also includes the simulation of prices; the consumption sector simulates

123 household consumption per industry; the labour market sector determines employment and
 124 simulates unemployment as the difference between labour demand coming from the production
 125 sector and the available labour force. In addition, the labour market represents the wage level and
 126 includes a sub-sector that simulates the UK working population endogenously; the exchange and
 127 interest rate sector includes the exchange rate between the UK and its main trading partners, and the
 128 average interest rate for credits of UK firms; the public or government sector tracks state income and
 129 expenditure. Finally, the electricity supply sector includes a detailed representation of the electricity
 130 production capacity and determines annual energy produced in the UK. The power supply sector is
 131 differentiated by 12 electricity production technologies, including biomass, hydro, marine, onshore
 132 wind, offshore wind, solar, other thermal and other renewable energies as renewable technologies,
 133 nuclear and CCS gas as other low-carbon technologies and finally coal and gas as brown technologies.

134 These features allow us to understand what the macroeconomics implications and electricity system
 135 costs of different electricity -transition scenarios are. See the Supplementary material for a full
 136 documentation of model equations.

137 **Figure 1: Overview of GIBM** –The main causal relationships between model sectors. GIBM is visualised
 138 in the dashed box. I.e. the rest of the world is outside the GIBM. The model sectors in the parenthesis
 139 in the ‘Rest of the world’ box indicate that additional exogenous inputs from the rest of the world
 140 enter the model.



141

142 2.1 Scenario development

143 All our tested renewable electricity policy scenarios imply that new electricity capacity installations
144 include only renewable electricity sources plus CCS Gas (but no other fossil fuel-fired or nuclear power
145 sources).

146 Our moderate renewable electricity policy scenario includes in addition just enough early retirement
147 of still operating brown electricity infrastructure to reach the net-zero emissions target for the
148 electricity sector by 2050. In other words, the moderate electricity policy scenario corresponds to a
149 scenario that allows the net-zero emissions target by 2050 for the electricity sector to be reached
150 while maximising the use of existing brown (i.e. coal and gas) electricity infrastructure. In addition, in
151 contrast to the rapid electricity policy scenario, the moderate electricity policy scenario adopts the
152 assumption that the shut-down of brown electricity infrastructure by the beginning of 2049 is planned
153 from now on. Accordingly, the installations of the therefore required renewable electricity
154 infrastructure start shortly after 2042, taking planning and construction time periods into account and
155 results in emissions dropping sharply to zero in 2050. The medium electricity policy scenario aims at a
156 linear decrease of installed brown (i.e. coal and gas) electricity capacity and annual emissions from
157 2020 onwards, and leads to net-zero emissions by 2050. The rapid electricity policy scenario further
158 implies that all brown (i.e. coal and gas) capacity is shut-down immediately and that no new fossil fuel-
159 or nuclear-based electricity capacity is installed.

160 All of these policy scenarios are introduced by assumption and required policies to drive this
161 investment change are not specified in this study. The different scenarios could be interpreted as a
162 situation where government rules mandate nuclear and fossil fuel-fired plants to be phased out
163 and/or shut-down. As mentioned before, we highlight that GIBM does not assess how the higher
164 intermittency of higher shares of renewables can be balanced (e.g. by specifying technologies to deal
165 with this³) and that the expansion of renewable electricity sources is only restricted by the estimated
166 technical potential of considered renewable electricity technologies. GIBM only simulates centralised
167 electricity transition scenarios. Also relevant is that the UK low-carbon electricity transition scenarios
168 can include carbon removal technologies (e.g. CCS, see CCC, 2019), however, while GIBM includes CCS
169 Gas, none of our simulated electricity scenarios does include CCS gas in the electricity mix due to the
170 currently high costs of this technology. Finally, all of the tested low-carbon electricity transition policy
171 scenarios are compared against the base-run which represents a no policy scenario. Although the UK
172 has implemented a number of electricity policies these are not used as a base-run as the interest of
173 this study lies in understanding the additional costs of different policy scenarios compared with a base-
174 run under no major climate constraint. Thereby, as investment decisions of energy firms are not only
175 influenced by the costs of different energy production technologies, but also by a behavioural
176 component, the base-run is not necessarily the most cost-effective scenario. We note that the all
177 tested scenarios and the base-run consider a carbon price in the operational costs of fossil fuel-based
178 electricity technologies, as this is not considered as a major policy scheme.

³ GIBM does account for the average financial costs of required GIBM storage technologies when higher shares of renewables are on the grid (see Supplementary Information).

179 2.2 Key features and additional remarks

180 GIBM is smaller than a large-scale model, such as for example the Cambridge Economics E3ME model,
181 but is larger than a stylised mathematical model. While the distinction between large-scale and small
182 and stylised mathematical models is certainly not clear-cut, it can be said that large-scale models
183 involve a large number of variables and equations and cannot generally be solved analytically but are
184 solved numerically. Models are considered as stylized mathematical models if they contain relatively
185 few equations. This latter type of model is more abstract than large-scale models and does not
186 represent details; instead stylised models represent the main mechanisms relevant for a certain
187 question or policy issue.

188 Specially, GIBM includes 313 stock variables and more than 3000 variables in total. The simulation
189 horizon for this study included the period from 2016 to 2050, with time steps of 0.25 years.

- 190 1. It includes a representation of the macroeconomy and a simplified representation of the
191 electricity supply sector from a bottom-up perspective;
- 192 2. Accordingly, it includes the endogenous simulation of key macroeconomic variables, such as
193 GDP or unemployment, emissions (as key environmental indicators) emitted by the electricity
194 supply sector and electricity system costs;
- 195 3. It is calibrated to the UK context and includes the most recent available cost projections for
196 electricity production technologies;
- 197 4. It allows for the simulation of different low-carbon electricity transition scenarios and enables
198 their evaluation in terms of effects on GDP, unemployment, emissions and electricity system
199 costs.

200 2.3 Model boundary and key limitations

201 GIBM is characterised by the following key limitations:

202 The key features and novelties proposed by GIBM are summarized as follows:

- 203 1) *Treatment of the energy supply sector*: Importantly, GIBM represents the electricity supply
204 sector endogenously. Other energy sources for the heating and transport sector are not
205 covered in GIBM. The demand for electricity from the heating and transport sector are
206 introduced exogenously, based on the Green Growth scenario of the National Grid (2018),
207 which assumes an electrification of the heating and transport sector in line with the UK climate
208 targets (see Supplementary Material). In the case of an immediate shut-down of fossil-fuel
209 based power production, we do not assume any shifts from electricity-based heating towards
210 traditional fossil-fuel based heating sources (e.g. gas heater) from the side of the consumers,
211 as this would be ruled out by a decarbonisation scenario demanded for by the different social
212 movements. That is, the economic implications shown by GIBM concern only the decarbonisation
213 of the power supply sector under the assumption of an increased electrification of the transport
214 and heating sector as given in the Green Growth scenario of National Grid (2018).
- 215 2) *Technical feasibility*: GIBM in its current form is not suitable to investigate the technical
216 feasibility of the tested low-carbon electricity transition scenarios. That is, GIBM does not

217 include specific storage⁴, other balancing (e.g. demand-management) or import possibilities
218 that help to deal with higher intermittency of renewable electricity sources. In addition, the
219 exploration of decentralised electricity transitions is beyond scope of the current model
220 version.

221 3) *Stranded assets and instability in the financial system*: GIBM does not represent financial
222 flows. Therefore, the current version of GIBM is not appropriate to assess potential risks of
223 very fast or low green electricity transition on stranded assets and financial instability.

224 4) *Country-scale model*: We opted for a country-scale model and therefore unlike global-scale
225 integrated assessment models, GIBM does not consider global dynamics. The representation
226 of climate change damages, climate change policy intervention of other countries or the
227 representation of resource scarcity depending on global resource use lies beyond scope of the
228 model.

229 3 Results

230 We have developed the Green Investment Barrier Model (GIBM) and applied it to the UK, for the
231 period 2016 to 2050. The different electricity policy scenarios were introduced in 2016. We choose to
232 focus at country scale since national governments are the main decision takers on electricity and
233 climate policies. And as explained previously, the UK is the first country that has adopted a net-zero
234 emissions target for 2050.

235 We show the simulation results for the following key policy indicators:

- 236 • Greenhouse gas emissions of the electricity supply system
- 237 • GDP
- 238 • Unemployed workers plus inactive working age population
- 239 • Electricity system costs
- 240 • Direct generated employment by the electricity transition
- 241 • Implicit carbon price

242 We choose to define ‘unemployed’ in this study as sum of unemployed and inactive workers, as in
243 GIBM, the number of people outside the labour force is dependent on the percentage of
244 unemployment due to the so-called ‘discouraged workers effect’ (e.g. Filatriau & Reynès, 2012). That
245 is, a large part of the inactive labour force consists of individuals who although would desire to work,
246 decided to stay outside the labour force. In our study, we opted to include these otherwise ‘hidden’
247 individuals in our policy evaluation (see also Supplementary Information). Electricity system costs are
248 defined as the sum of the Levelised Costs of Energy (LCOE) for new electricity infrastructure and the
249 storage and interconnections costs of new installations in a particular year. The costs of electricity
250 imports are not included in electricity system costs for simplicity and because they are assumed to be
251 independent from the electricity transition scenario chosen (and thus they have no impact on the
252 difference of electricity system costs between scenarios). We also indicate the results both in annual
253 and accumulated terms (see table 1); thereby, ‘accumulated’ means that the annual amount of each
254 of the chosen policy variables is added up/accumulated from 2016 to 2050 (i.e. over the simulation
255 time horizon). Specifically, table 1 shows the simulation results of the electricity policy scenarios in

⁴ GIBM does include estimated average costs of the storage possibilities required with increasing shares of renewable energy sources on the grid (see Supplementary Information).

256 accumulated terms of the chosen policy indicators as percentage against the base-run simulation
 257 results.

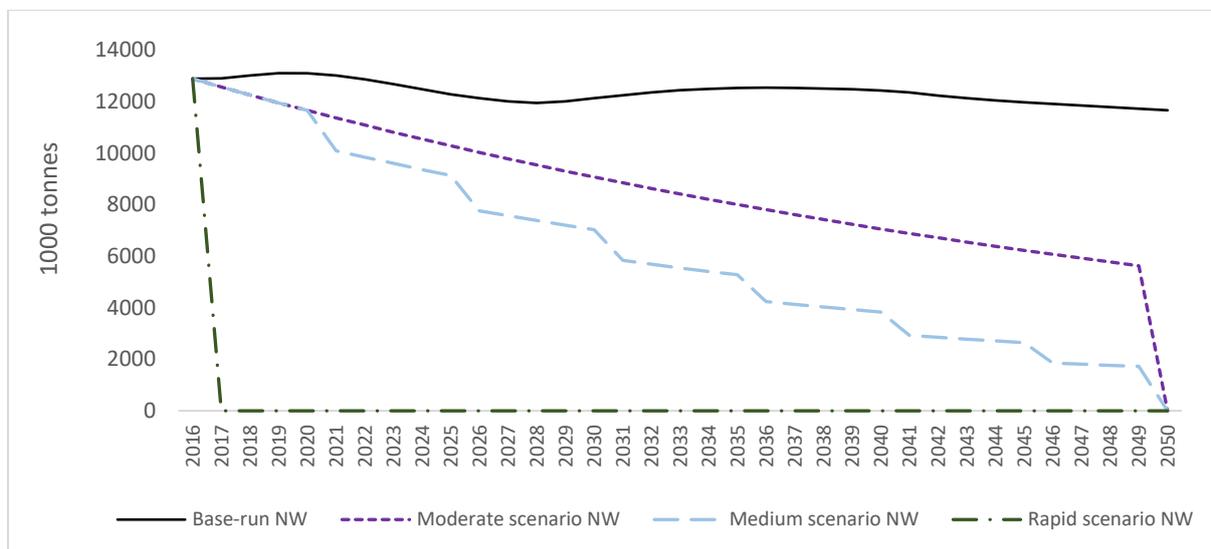
258 **Table 1: Overview on policy outcomes of the tested scenarios:** red colour highlights the worst achieved results
 259 and the blue colour the best achieved one of all tested low-carbon policy scenarios, impacts on **accumulated**
 260 variables from 2020 to 2050 in percentage compared to the base-run.

	<i>Emissions (%)</i>	<i>GDP (%)</i>	<i>Unemployment (%)</i>	<i>Direct employment (%)</i>	<i>Electricity system costs (%)</i>
Moderate scenario	-30.69	-0.8614	-0.41	22.85	-15.88
Medium scenario	-50.66	-0.2925	-0.08	35.89	-3.37
Rapid scenario	-99.23	1.041	0.08	38.08	15.48

261

262 In the following, the achieved results for each policy indicator are described in more detail. The figure
 263 below demonstrates that the target of net-zero carbon emissions for the power system by 2050 is
 264 achieved under all three tested low-carbon electricity policy scenarios. Thereby, the moderate
 265 renewable electricity transition scenario leads to a reduction of around 31% cumulative emissions by
 266 2050. The drop in 2049 is explained by the (planned) halt of all brown electricity infrastructure still in
 267 use by then. The medium policy scenario results in a cumulative emission reduction of 51%. The rapid
 268 low-carbon electricity policy scenario results in almost 100% cumulative emission reduction. This is
 269 because under the rapid electricity -transition scenario all brown (i.e. fossil-fuel and gas) electricity
 270 infrastructure is shut-down immediately and thus there are zero carbon emissions from the moment
 271 the policy is implemented. At the end of the simulation, all scenarios, but the base-run, lead to zero
 272 emissions.

273 **Figure 2: Annual emissions from the UK power supply sector**



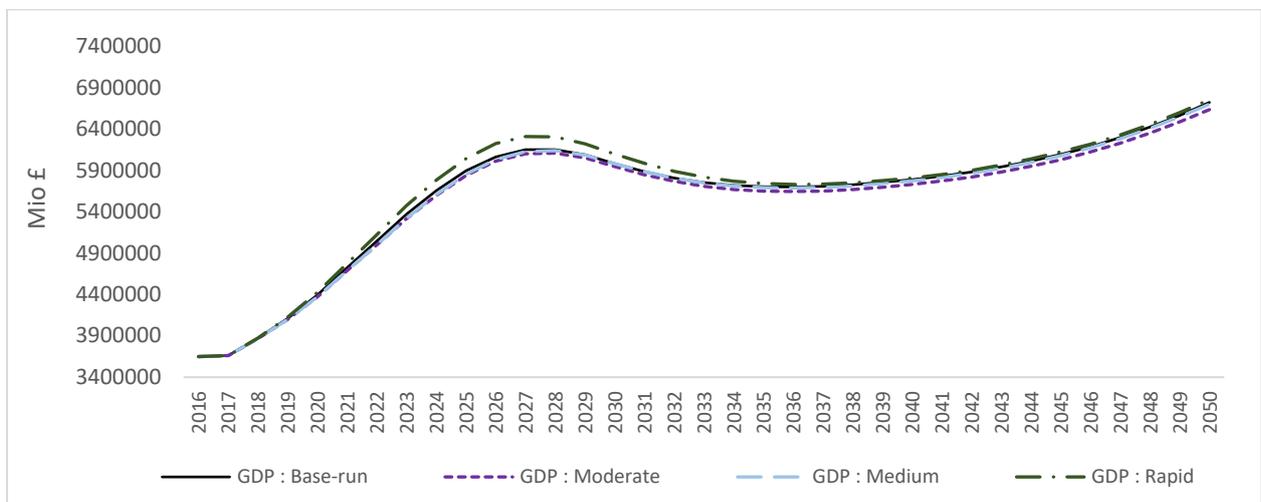
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275 In accumulated terms in 2050, GDP is highest under the rapid scenario – 1.04% higher than the
 276 accumulated GDP under the base-run. Moreover, accumulated GDP is lower than under the base-run
 277 under the medium (by 0.3%) and moderate (by 0.9%) electricity policy scenarios. In annual terms in
 278 2050, annual GDP is 1.3% lower under the moderate scenario, 0.3% lower under the medium scenario
 279 and 0.5% higher under the rapid scenario – always compared to the annual GDP base-run (see figure3).
 280 These numbers can be explained by the following key mechanisms.

281 First, the rapid scenario reaches an especially high annual GDP during the period 2022 to 2032. The
 282 early retirement of brown infrastructure and subsequent rapid installation of renewable electricity
 283 infrastructure during this period leads to higher capital investment and direct employment. This in
 284 turn leads to an increase in aggregate demand and GDP, which is amplified further due the underlying
 285 macroeconomic dynamics. Importantly, the higher power infrastructure costs during this period
 286 translate to higher electricity prices, leading to a higher average price level. As the wage-level is
 287 indexed to the consumer price index (CPI), however, this does not translate to lower real household
 288 income for consumers (see appendix for a scenario where the salary level is not indexed fully to the
 289 CPI). Second, annual GDP under the medium and moderate electricity policy scenario is lower than
 290 under the base-run over the entire simulation horizon. This is because cost projections for renewable
 291 electricity sources, including initial capital investments, are on average lower for renewable power
 292 sources compared to brown electricity sources. This means that in the scenarios with higher shares of
 293 renewable energy sources aggregate demand is lower due the lower capital investments (that are a
 294 part of aggregate demand). That is, additional aggregate demand is lower in case of the medium and
 295 moderate electricity policy scenarios (in comparison to the base-run simulation), leading to lower
 296 GDP.

297 Finally, the simulated behaviour of annual GDP for all scenarios plus the base-run is driven by two
 298 factors: first, the total factor productivity (TFP) is positively dependent on capital investments. Capital
 299 investments increase in all scenarios and therefore TFP and in turn GDP. However, the GIBM adopts a
 300 flattening positive relationship between capital investments and TFP. That is, the impact of capital
 301 investments in TFP decreases, with increasing levels of capital investments. This explains why GDP
 302 increases strongly at the beginning of the simulation horizon and why the increase flattens towards
 303 the second part of the simulation period. Another important driver for GDP outcome of all scenarios
 304 and the base-run is the following: GIBM represents the production of the economy as dependent of
 305 the expected demand (which is dependent on aggregate demand of the previous periods). This means
 306 that if aggregate demand decreases, the production will decrease only with a lag, leading to an
 307 increase in the firms inventory – as the inventory of the firms is higher compared to the actual demand
 308 and its desired inventory, the firms will try to adjust their production to actual demand, which can
 309 lead to small cycles (as displayed in Figure 3).

310 **Figure 3: Annual GDP (in real prices, with base year 2016).**



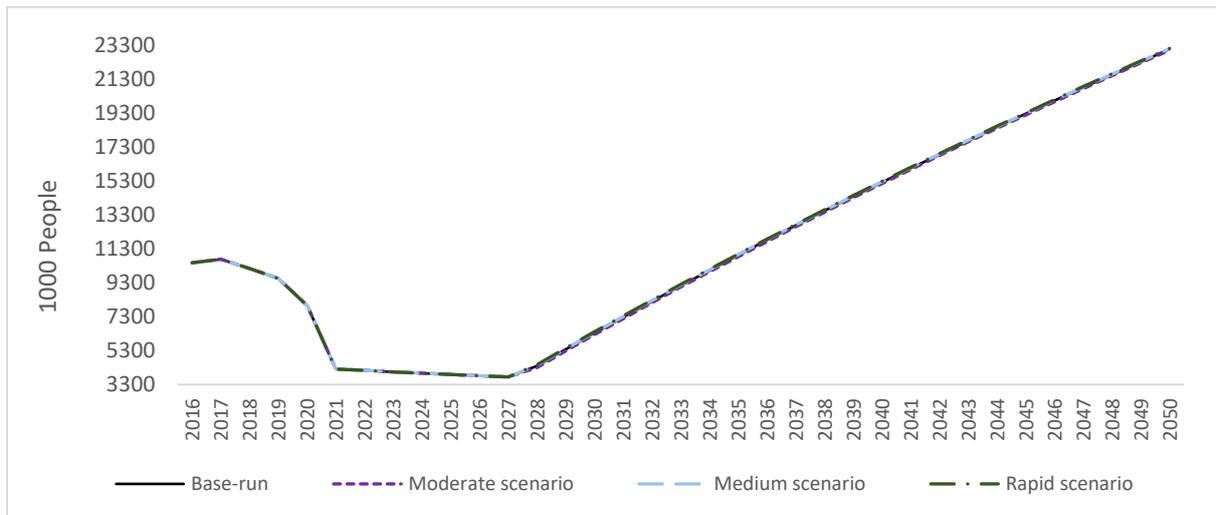
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312 With regard to the policy indicator unemployment, in accumulated terms, the moderate scenario
313 leads to a reduction in accumulated unemployment of 0.41% and the medium scenario of 0.08%. In
314 contrast, cumulative unemployment under the rapid policy scenario increases by 0.08% (always
315 compared to the base-run). In terms of the annual numbers in 2050, unemployment is, compared to
316 the base-run of annual unemployment, 0.18% lower in the moderate scenario, 0.02% higher in the
317 medium scenario and 0.001% lower in the rapid scenario.

318 The higher numbers in cumulative unemployment under the rapid scenario compared to the other
319 scenarios can be explained due to the path-dependency related to changes in the working-age
320 population and the level of unemployment. That is, under the rapid electricity policy scenario, annual
321 GDP and therefore employment possibilities increase very quickly at the beginning of the simulation
322 period as the discard of the brown electricity infrastructure necessitates the installation of a
323 comparable amount of new renewable electricity production capacity. This in turn reduces annual
324 unemployment and increases the wage-level during this initial period, which then leads to increased
325 migration to the UK and therefore to an increase in the working age population. Once the new
326 infrastructure is built, employment possibilities however decrease while the working age population
327 does not decrease significantly, leading to higher accumulated unemployment under the rapid
328 electricity policy scenario in 2050. The moderate and medium scenario instead have a more balanced
329 installation of renewable electricity infrastructure and in the case of the medium scenario discard in
330 brown infrastructure. Therefore, these scenarios are characterised by less path-dependency, leading
331 to lower cumulative unemployment levels in 2050 of these two scenarios.

332 Finally, Figure 4 shows that development of annual unemployment is similar for all scenarios and that
333 differences are small. This is because the development of annual unemployment is closely connected
334 to the development of GDP (when GDP increases, unemployment decreases due to higher labour
335 demand). This explains the decrease in annual unemployment from 2016 to 2027 (Figure 4). From
336 2027 onwards, annual unemployment increases even though GDP increases again slightly after 2038.
337 This is because, as mentioned before, GIBM includes some path-dependency in terms of
338 unemployment level. In addition, in GIBM, UK unemployed are less likely to be employed compared
339 to new (skilled) workers from abroad. This means that whenever GDP increases, but its level is below
340 previous GDP levels, unemployment still decreases.

341 **Figure 4: Annual unemployment in the UK**



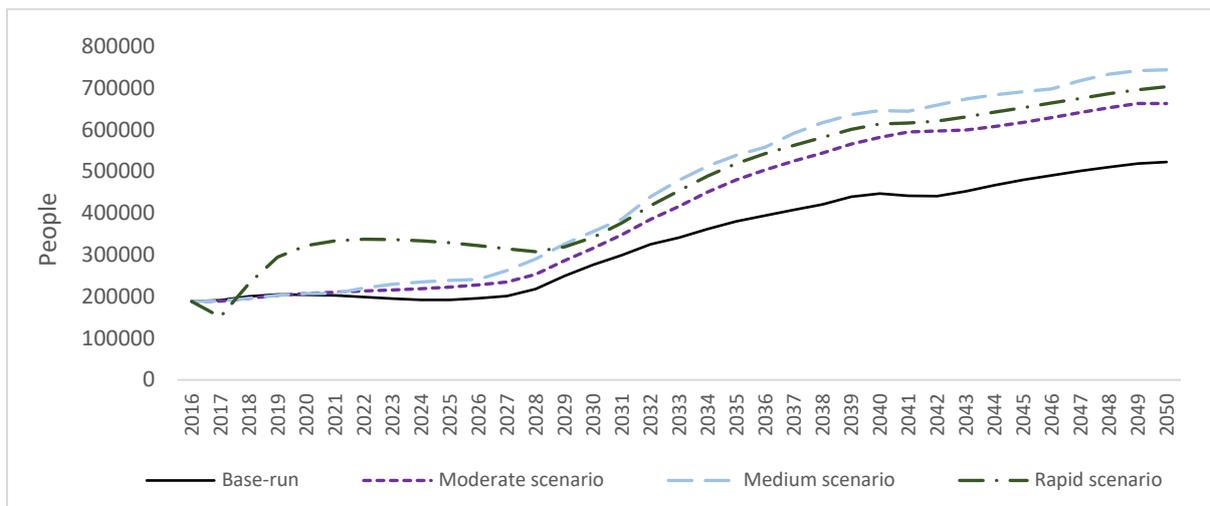
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343 The accumulated generation of direct employment under the rapid energy policy scenario is 38.1%
 344 higher as compared to the base-run, and is highest for the tested low-carbon energy transition
 345 scenarios. Moreover, accumulated direct employment generated under the medium electricity policy
 346 scenario is 35.1% and under the moderate electricity scenario 23.9% higher than accumulated direct
 347 employment under base-run. With regard to the annual numbers in 2050, annual direct generated
 348 employment in comparison to the base-run simulation is 26.8% higher in the moderate scenario,
 349 42.3% higher in the medium scenario and 34.6% higher in the rapid scenario – always compared to
 350 the base-run results of annual direct employment in 2050 (Figure 5).

351 In terms of the key drivers of the observed development of direct employment (Figure 5), the share
 352 of renewables increases over time under all scenarios and the base-run. As direct employment for the
 353 installation of new electricity scenarios is on average higher for renewable electricity infrastructure
 354 (see Wei et al., 2010), the generated direct employment in the power sector increases over time for
 355 all scenarios including the base-run.

356 With regard to the differences between the scenarios, the rapid electricity transition scenario involves
 357 the shut-down of all brown electricity infrastructure and the subsequent installation of the same
 358 amount of low-carbon electricity production capacity – for which labour force is required. Therefore,
 359 annual direct employment is particularly high for the rapid scenario during the period 2016 to 2028.
 360 Subsequently, annual direct employment of the rapid scenario is lower than the medium scenario as
 361 comparatively less new power infrastructure needs to be built (see figure below)

362 **Figure 5: Annual direct generated employment of the power sector**

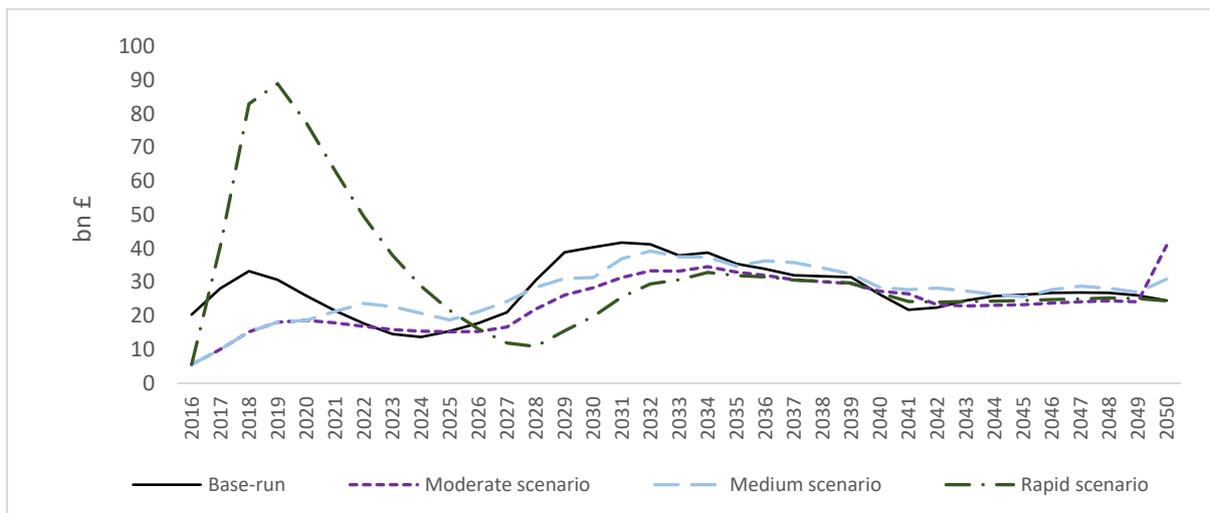


363
 364 In accumulated terms, the rapid replacement by new low-carbon energy infrastructure leads to
 365 around 15.5% higher electricity system costs as compared to the base-run simulation. The
 366 accumulated power system costs are 15.9% lower under the moderate scenario and 1.9% lower under
 367 the medium scenario. This is because the costs of renewable electricity sources are for most cases
 368 lower than for brown electricity sources (as already mentioned and see in the supplementary
 369 information for further details). In annual numbers by 2050, annual electricity system costs are 66.4%
 370 higher under the moderate scenario, 25.8% higher under the medium scenario and 0.3% lower under
 371 the rapid scenario – always compared to the base-run annual power system costs (see figure 6).

372 The high annual electricity system costs under the rapid electricity scenario during the period between
 373 2016 and 2026 are driven by the immediate shut-down of coal and gas electricity infrastructure. In
 374 addition, as the rapid electricity scenario is unplanned and as the replacement of the shut-down
 375 electricity infrastructure with the corresponding renewable electricity infrastructure takes time,
 376 higher electricity imports would likely be required and add to the costs, however, for simplicity we
 377 have not accounted in this model exercise for an increase in electricity imports. The lower annual
 378 system costs from around 2027 are due to the fact that most infrastructure is shut-down and started
 379 or already finished to rebuilt.

380 Over most of the simulation time horizon, annual electricity system costs are lower under the
 381 moderate and medium electricity policy scenario as compared to the rapid electricity scenario and the
 382 base-run simulation. The reason is that compared to the rapid scenario, these scenarios do not involve
 383 a shut-down of all still working born power infrastructure installations and compared to the base-run,
 384 they involve higher shares of renewable power sources that are in average cost-effective compared
 385 to brown power technologies. The increase of the annual system costs of the moderate (and to some
 386 extend medium) scenario at the end of the simulation period is explained as in this scenario the shut-
 387 down of all still available brown infrastructure is shut down and the corresponding renewable power
 388 infrastructure rebuilt.

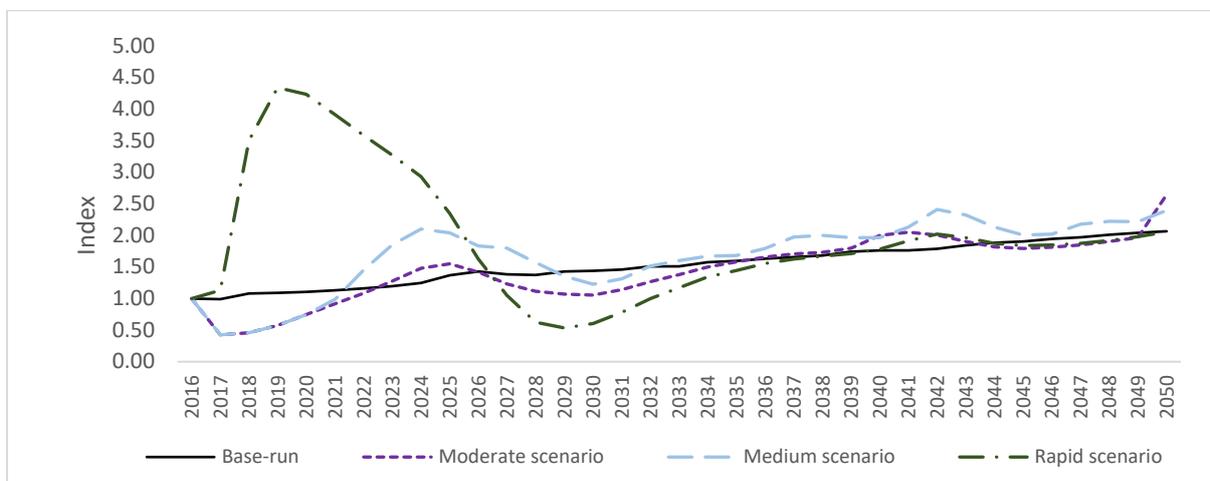
389 **Figure 6: Electricity system cost**



390
 391 In 2050, the domestic electricity price index is 28% higher under the moderate scenario and 16%
 392 higher under the medium scenario. In contrast, it is 0.4% lower under the rapid scenario. This
 393 development is following the simulated outcome of the annual electricity system costs (see figure
 394 above) as higher annual electricity system costs translate generally into higher domestic electricity
 395 prices. For this reason, it is not further explained here.

396 Moreover, under the rapid electricity policy scenario, domestic electricity prices are on average 26.6%
 397 higher; under the medium electricity policy scenario domestic electricity prices are 10% higher and
 398 under the moderate electricity policy scenario domestic electricity prices are on average 5% lower
 399 when compared to the base-run scenario. Importantly, domestic electricity prices under the medium
 400 scenario are on average *higher* than the base-run, yet the electricity system costs under this scenario
 401 are higher than the base-run in accumulated terms. This can be explained due to the case that the
 402 system costs indicate the absolute costs of electricity production while the prices reflect the costs per
 403 produced unit of electricity. Specifically, GDP, and therefore electricity production, is higher under the
 404 base-run as compared to the medium scenario and therefore the average costs per unit of produced
 405 electricity or the electricity system costs per produced unit of electricity are lower under the base-run.

406 **Figure 7: Domestic electricity prices**



407

408 Finally, we introduce a new policy indicator, called the implicit carbon price or carbon price equivalent,
 409 in order to effectively communicate related electricity system costs per tonne of reduced emissions.
 410 We note that GIBM does not include a carbon price as a policy driver for any of the scenarios, however,
 411 a carbon price is included in all scenario and the base-run, but not sufficiently high to reach the zero
 412 carbon emissions by 2050 (see supplementary information). In this study, the implicit carbon price is
 413 defined as the costs (*in terms of accumulated electricity system costs, including the investment and*
 414 *operational costs of the power production infrastructure, and the storage and intermittency costs*) *in*
 415 *comparison to these costs in the base-run*) per tonne of reduced accumulated emissions (from the
 416 electricity supply sector). Importantly, this does not mean that introducing a carbon price of that level
 417 would lead to this particular scenario or the indicated amount of carbon reduction, mainly because
 418 investment decisions included in GIBM involve a behavioural component. As opposed to the carbon
 419 price (marginal costs of carbon), our measure indicates the average power system costs per reduced
 420 tonne of emissions, which is the value we are interested here. We use a different indicator as
 421 commonly applied in model exercises with Computable General Equilibrium (CGE) models or
 422 integrated assessment models (IAM) due to the different methodology of, and in particular due to the
 423 different representation of electricity investment decision in, GIBM as compared to CGEs or IAMs.

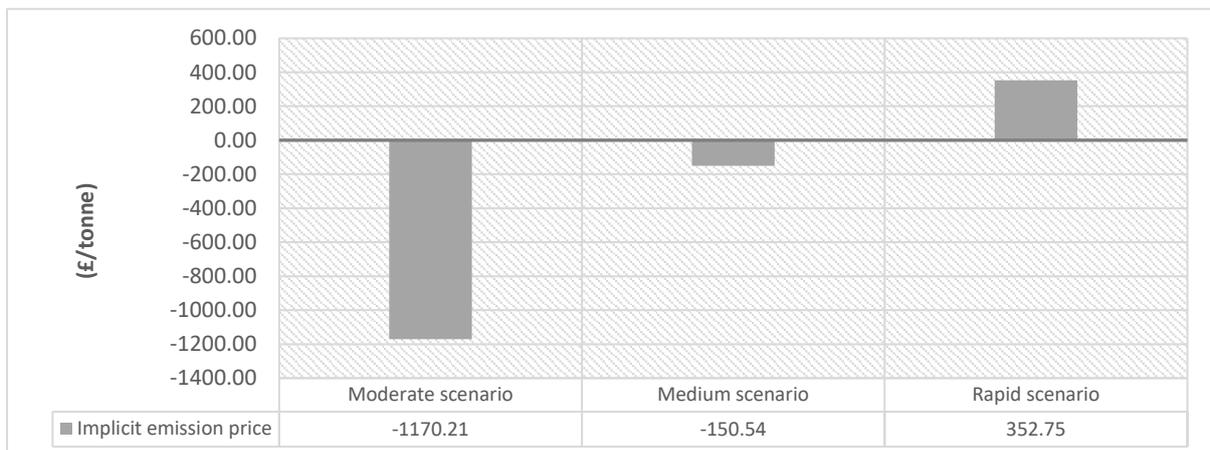
424 The carbon price equivalent is calculated as follows:

425 Carbon price equivalent (£/tonne) = $\frac{\text{Difference acc. energy system costs over simulation period (£)}}{\text{Accumulated emission reduction (tonnes)}}$,

426 The figure below shows that as long as an energy transition is not rapid, the reduction of emissions in
 427 the energy supply sector is in fact profitable, indicated in the table below as a negative carbon price
 428 equivalent. The reason for the negative carbon price under the moderate and medium transition is
 429 that the energy system costs are lower than under the base-run, which in turn is due to the lower total
 430 costs of renewable energy in comparison to brown energy technologies. Under the rapid energy
 431 transition scenario, the carbon price equivalent becomes positive, which is due to the phase-out of all
 432 still operating fossil-fuel based energy technologies and the subsequent installations of renewable
 433 energy infrastructure. That is, for the rapid energy policy scenario the carbon price equivalent
 434 achieved is seen as £760 per tonne. Overall, we emphasise that in the model, it is assumed that storage
 435 or other possibilities to deal with the higher intermittency of RES is available and that related costs lie
 436 within the assumed range of this model exercise.

437 **Figure 8: Carbon price equivalent for different electricity policy scenarios**

438



439

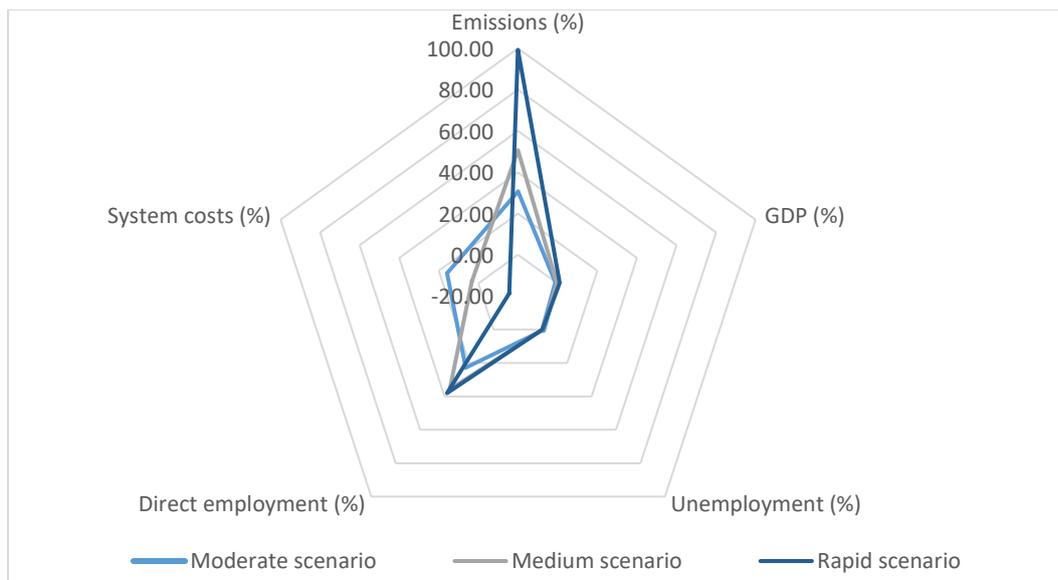
440

441 We have conducted sensitivity testing (see appendix). These results generally lead to the same policy
442 conclusions as described in section 5. There are two exceptions to this, which are discussed below.

443 4 Discussion

444 The simulation results displayed in the previous section suggest that there is no optimal solution i.e. a
445 win-win solution in terms of GDP, unemployment, electricity system costs and emission reduction.
446 Each electricity transition policy scenario generates trade-offs (see figure 9). With regard to the figure
447 below, each axis of the spider diagram shows the chosen policy indicators (GDP, emissions,
448 unemployment etc.) as compared to the base-run simulation, with each policy scenario shown in
449 different colours. A policy scenario that is identical to the base-run would be shown as a 0% difference.
450 The further out the lines – the larger the positive difference and the closer to the centre – the larger
451 the negative difference.

452 **Figure 9: Overview on the different tested electricity transition scenarios:** A reduction is reported as positive
453 numbers in case of the policy indicators, emissions, unemployment and electricity system costs. Accordingly,
454 positive changes can always be interpreted as positive in terms of policy outcomes in the illustration below.
455



456

457 In more detail, while all simulated electricity transition scenarios reach the net-zero emission target
458 by 2050, cumulative emissions are highest under the rapid scenario. Accumulated GDP and
459 accumulated direct generated employment is as well highest under the rapid scenario, however, in
460 terms of negative side-impacts, accumulated unemployment increases and the accumulated
461 electricity system costs are also highest under the rapid scenario (compared to the base-run
462 simulation). On the other hand, the cumulative emission reduction is lowest under the moderate
463 scenario, changes in GDP compared to the base-run are negative and cumulative direct employment
464 generation is the lowest among all scenarios compared to the base-run. However, on the other hand,
465 the accumulated reduction in unemployment compared to the base-run is the highest as well as the
466 reduction in the electricity system costs. The medium scenario is situated somewhere in between
467 these two scenarios.

468 In terms of the carbon price equivalent, our simulation results show that both the moderate and
 469 medium scenario imply negative cost for emission reduction, while the rapid scenario costs around
 470 390£ per tonne of reduced emissions, implying that a very fast transitions, involving the immediate
 471 closure of fossil fuel-based electricity infrastructure, is difficult in terms of managing the financial
 472 costs. An exception to this finding are the results for the implicit carbon price under two sensitivity
 473 scenarios: both ‘scenario low’ where a variety of relevant parameters in the power sector (e.g. learning
 474 rates, cost projections) are not as favourable towards renewable power sources as under the main
 475 scenario and a scenario where the wage level does not react to the average price level lead to a
 476 positive implicit carbon price under the medium policy scenario. That is 127£/tonne in the former and
 477 113£/tonne in the latter sensitivity scenario – which are still substantially lower numbers compared
 478 to the numbers of the implicit carbon price under the rapid scenario (505£/tonne and 509£/tonne).
 479 Overall, this means that our study also shows that low-carbon electricity transitions can be financially
 480 cost-effective (in terms of system costs) due to the decreasing and cost-efficient costs of low-carbon
 481 electricity technologies. That is, the net-zero emission target in the power sector can be achieved cost-
 482 efficient, while even generating the co-benefits of an increase in direct-employment and a reduction
 483 in overall unemployment (see moderate and medium scenario). However, under these two scenarios,
 484 GDP is lower than under the base-run. The reason is that capital investments are lower due to the
 485 lower costs of renewable electricity infrastructure – here, it is also important to recall, that under the
 486 base-run, electricity firms do not always invest in the most cost-efficient technology option, but are
 487 also influenced by behavioural factors, such as past decisions and risk-adversity for example – and
 488 therefore, aggregate demand and therefore GDP is lower under the moderate and medium scenario
 489 in comparison to the base-run. Here, it is important to note, that GDP can be increased by the
 490 government by spending the difference in financial costs in any infrastructure or other project in order
 491 to increase aggregate demand. This is due to the Keynesian demand-led nature of the GIBM (see also
 492 Mercure et al., 2016). That is, changes in GDP due to this reason should not justify the choice of the
 493 rapid electricity transition scenario. This means in a summery, the advantages from a moderate and
 494 medium scenario stem on one hand from the lower electricity system costs and therefore the cost-
 495 efficient low-carbon electricity pathway, and on the other hand from the positive employment-
 496 impacts. Moreover, the reduction of GDP comes from the lower electricity investment costs and can
 497 therefore be compensated by investing the savings to any other area via investment, consumption or
 498 government spending.

499 In the following, we compare our results achieved by GIBM with other simulation models that have
 500 been applied for the evaluation of the macroeconomic implications of a low-carbon electricity
 501 transition (see Hafner et al., 2020a for a review). In addition, results from the HM Revenue and
 502 Customs (HRCM) model, a model that has played an important role for the evaluation of the UK
 503 climate policy (e.g. Ackerman, 2014) are used for comparison. The table below gives an overview of
 504 these models.

505 **Table 2: Overview on the selected model sample**

Model	Study	Time horizon	Geographical scope	Modelling approach	Modelling type	Model sectors
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DSK / Engage	Lamperti et al. (2020)	2000 to 2100	Global	Agent-based modelling	Simulation model / Non-Equilibrium model ⁵	Capital goods sector, consumption good sector, energy sector, households, financial system, climate sector.
E3ME	Irena (2016)	2010 to 2030	Global	Macroeconomic simulation model / bottom-up evolutionary technology model.	Simulation model / Non-Equilibrium model	Macroeconomic sectors, and energy, transport, agriculture and heating sectors.
EIRIN	Dunz et al. (2019)	2018 to 2038	High income country	Stock-Flow Consistent behavioural model	Simulation model / Non-Equilibrium model	Households-, Government-, Commercial banking- and a capital (green & brown) and goods production sector
EURACE	Ponta et al. (2018)	Fictive, 20 years	Advanced economy single-country	Agent-based modelling	Simulation model / Non-Equilibrium model	Macroeconomic, government, central banking, banking and energy sectors.
Eurogreen	D'Alessandro et al. (2018)	2014 - 2050	France	System Dynamics	Simulation model / Non-Equilibrium model	Households, Industries, Population, Government, Energy Resources, Assets, Rest of the Whorls, GHG emission module.
GIBM	Current study	2016 to 2020	UK	System Dynamics	Simulation model / Non-Equilibrium model	Macroeconomic sectors, government and electricity supply sector.
LowGrow SFC	Victor Jackson & (2019)	2017 to 2067	Canada	System Dynamics	Simulation model / Non-Equilibrium model	The model includes the representation of households, firms, banks, government, a central bank and the 'rest of the world' (or 'foreign' sector).
MEDEAS	Nieto et al. (2020)	1995 to 2050	EU	System Dynamics	Simulation model / Non-Equilibrium model	Economy, population, employment, water, land-use, climate, energy and materials sector.
Naqvi, 2018	Naqvi (2018)	100 units	EU	System Dynamics	Simulation model / Non-Equilibrium model	Firms, households (incl. workers and capitalists, government, climate and a banking sector.
PANTA RHEI/GINFORS	Großmann & Lutz (2015)	2000-2020	Germany	Macroeconomic input-output model	Simulation model / Non-Equilibrium model	Macroeconomic sectors, and dwelling, traffic, land-use, material input and energy sector.
Threshold 21/SDGi	UNEP (2011)	2010 to 2050	Global	System Dynamics	Simulation model / Non-Equilibrium model	Society module, Environmental module and Economy module.

⁵ The literature distinguishes between equilibrium vs. non-equilibrium models based on the criteria of the model solution approach of the economic outcomes, which is grounded in the theoretical underpinning of the model (i.e. their scientific paradigm) (Mercure et al., 2019a; Scricciu et al., 2013).

HMRC model	HM Government (2011)	2020 - 2025	UK	Computable General Equilibrium (CGE) model	Equilibrium Optimization approach	/	Macroeconomic sectors (top-down representation of the energy sector).
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506

507 Table 3 displays the achieved results of the different models for the key policy indicators used in this
508 study, including emissions of the power sector (or the entire economy if indicated in Table 3 when
509 power emissions were not indicated in the study), unemployed, induced employment in the power
510 sector, real GDP, power system costs and avg. price level. When no quantitative number is reported,
511 this means that there were no numbers indicated in the consulted study and no entry means that
512 there were no indications on the changes of the policy indicator.

513

514 **Table 3: Comparison of model results**

Model	Energy scenario or policy	Reference case	Emissions -power sector	Unemploy ed	Real GDP	Power system costs	Direct employe ment	Avg. Price level
GIBM	Medium electricity transition scenario	No major policy scheme implemented; but introduced & expected CO2 prices in the UK are considered.	-100	0.02	-32	26	42	16
E3ME	REmap Electrification scenario (RemapE): Increase in investments to expand the renewable energy sector.	Implemented and planned policies, leading to a warming of 2.6 Degree globally.	-15.7	-0.2	1.1	Not indicated	+ 69 (incl. indirect generated employment in the renewable energy sector).	-
PANTA RHEI/GINFORS	The Transition scenario includes an expansion of renewable energy and improvements in energy efficiency.	Based on the assumptions given in the "Energy Scenarios 2010".	-80 to -95	-1.23	0.1	Increase	Increase	0.35 (cost of living)
MEDEAS	Energy Roadmap: EUCO+27	The Base-run assumes no energy constraints and is based on past trends.	- 47.2 (economy)	43.1	-58.7	-	Increase	Increase
Threshold 21/SDGi	G2 Scenario: Increase the renewable energy in power generation and primary energy consumption to reach targets set in IEA's BLUE Map scenario.	BAU2 is modelled on the assumption that current trends will continue. BAU2 assume additional investments of 2% of GDP, as is the case with G2, but these are allocated across the economy in a BAU context.	-64.09	-2.08	15.70	Increase	26	Decrease
EURACE	Feed in tariff price scenario	No policy implemented	Increase of the share of renewables of 10%	-0.267	-	-	Increase	Decrease
Eurogreen	EnM (Energy mix): increases renewable energy sources in production and consumption.	No policy implemented	~ 50	Small decrease	0	-	-	-
DSK/ENGAGE	Increase of renewable	No policy implemented	-37	Decrease	Increase	-	-	-

Naqvi, 2018	Policy where public R&D budget is shifted towards Resource-saving technologies and resource tax.	No policy implemented	-2.3 (economy)	-	-2.7	-	-	2.25
LowGrow SFC	The GHG Reduction scenario adopts several policy measures (e.g. Carbon price, investments).	No policy implemented	Decrease	Small increase	Decrease	Increase	-	Increase
EIRIN	Green Supporting Factor (GSF)	No policy implemented	Decrease	No change	No change	-	-	Decrease < 1
HMRC model	Introduction of carbon prices	No policy implemented	- 50 (entire economy, relative to 1990)	No change	Decrease	Increase	-	Increase

515

516 Results from E3ME, PANTA RHEI, Eurogreen and EIRIN demonstrate that accelerating the deployment
517 of renewable energy fuels economic growth and creates new employment opportunities. This is
518 mostly driven by the increased investment in renewable energy deployment, which subsequently
519 triggers various co-benefits throughout the economy via Keynesian-multiplier effects. Results of
520 EURACE can be said to be similar as the results of the models indicated above, with the caveat that
521 the simulations highlight the crowding-out effect of investments in to renewable energy infrastructure
522 (via the EEG tariffs) on household consumption. While GIBM includes similar mechanisms as E3ME,
523 PANTA RHEI, Eurogreen and EIRIN, the results achieved by GIBM show a different sign of direction
524 (see table above), however, the underlying mechanisms of the achieved results are similar. The
525 difference can be explained because in GIBM, the investments into low-carbon power transitions are
526 in average lower than under the base-run – unless the transition is rapid – due to the cost-effective
527 and decreasing costs of renewable energy infrastructure, leading to lower aggregate demand, GDP,
528 employment and consumption under low-carbon transitions, which is further reinforced by Keynesian
529 multiplier-effects. In other words, when GIBM tests a scenario with increased investments into energy
530 infrastructure compared to the base-run, model results resemble them of E3ME and Pantha Rhei in
531 terms of the direction of the results (i.e. GDP and employment would increase, see rapid scenario
532 tested with GIBM in this study).

533

534 Moreover, DSK (see Lamperti et al., 2020) and the threshold 21 model (see UNEP, 2011) account for
535 climate change damages and pressure on natural resources (the latter only applies to the threshold
536 21 model) – that is, the base-run macroeconomic indicators are affected by climate change damages.
537 For this reason (i.e. due to the (partial) avoidance of climate change damages and pressure on natural
538 resources), the positive macroeconomic impacts of a low-carbon transitions are larger than those
539 achieved by the model introduced before.

540 Further, the MEDEAS model (Nieto et al., 2020) and the LowGrow SFC (Victor & Jackson, 2019) yield
541 negative (or neutral) macroeconomic when simulating of low-carbon transitions. The MEDEAS model
542 simulations are negative in terms of the macroeconomic impacts of an energy transition – thereby,
543 the negative impacts are substantially larger compared to the results of GIBM. This difference can be
544 explained that MEDEAS includes global biophysical constraints (e.g. resource availability). That is, their
545 results illustrate that GDP growth and employment creation can be halted due to energy constraints

546 (even when considering great energy efficiency gains). In the case of the LowGrow SFC model, this is
547 because, in the model, it is assumed that all green investment is non-additional, that is, that green
548 investment displaces other intended investment. Moreover, in LowGrow SFC, the diversion of
549 investment away from the expansion of conventional 'brown' capital implies slower growth in labour
550 productivity, which in turn translates lower GDP compared to the base-run.

551 Naqvi (2018) tests the impact of a centralised 'green' policy that influences resource productivity
552 directly by autonomously increasing the share of public R&D towards resources and that also includes
553 a resource tax. The main drivers of the model results, in particular lower GDP and higher prices, are
554 the redirecting of consumption spending towards government spending to productivity improvement
555 and the higher input costs due to resource taxes.

556 Finally, we compare the achieved results of GIBM with the HM Revenue & Customs (HMRC) model.
557 The HMRC model is characterised as a Computable General Equilibrium (CGE) model and belongs
558 therefore contrary to the other models considered before, to the class of equilibrium models. Similar
559 to E3ME or Phanta Rhei, the HRMC model assumes that low-carbon energy infrastructure as higher
560 costs than the ones of brown energy infrastructure. However, the results for all considered indicators
561 achieved based on the HMRC show a different sign than the indicator results achieved by E3ME or
562 Pantha Rhei. This can be traced back to the different mechanisms inherent in equilibrium models vs.
563 the ones inherent in the introduced demand-led simulation models, such as GIBM, EIRIN or E3ME. Key
564 differences in the model structure between the introduced simulation models and equilibrium
565 models, include generally adoption of a fixed vs. endogenous money supply, adoption of a supply-led
566 vs. demand-led production, treatment of prices, treatment of unemployment and the assumption that
567 the economy operates at full capacity (see Hafner et al., 2020a).

568 5 Conclusions and policy recommendations

569 In this study, we evaluated through the use of the Green Investment Barrier Model (GIBM) macro-
570 economic and electricity system cost impacts of different low-carbon electricity transitions. GIBM is a
571 system dynamics simulation model as opposed to the more common equilibrium (optimization)
572 models. It provides a holistic framework to test different low-carbon electricity transition, including a
573 very rapid transition that includes the immediate shut-down of all current fossil fuel-based electricity
574 infrastructure. That is, our study complements earlier studies on the macroeconomic impacts of low-
575 carbon transitions by testing a more radical electricity decarbonisation scenario, which is increasingly
576 demanded for by various social movement (e.g. Extinction Rebellion). In addition, in contrast to earlier
577 studies, our model is calibrated in a way that renewable electricity production is on average cost-
578 effective compared to fossil-fuel and nuclear based power production, leading to different
579 macroeconomic effects of low-transition scenarios.

580 While there is no clear win-win situation due to policy introduction, drawing on our simulation results,
581 we recommend the implementation of a moderate or medium low-carbon electricity transition
582 scenario rather than reducing emissions in the electricity sector to zero immediately, as called for by
583 for example Extinction Rebellion. The reason is that under these scenarios the net-zero carbon
584 emissions target for the electricity sector is achieved, without increasing electricity system costs or
585 prices. Indeed, the implicit carbon price under both policy scenarios is negative, amounting to --
586 £1170/tonne (moderate scenario) or -£150/tonne (medium scenario) of reduced carbon emissions.
587 However, sensitivity testing revealed that under certain assumptions the implicit carbon price under

588 the medium scenario can become positive. It should be noted that the transition pathway assumed
589 for the medium scenario is a simple linear pathway of brown infrastructure destruction and has not
590 been optimised for the implicit carbon price.

591 In contrast to the rapid scenario, the moderate and medium electricity policy scenario lead to lower
592 electricity infrastructure investments compared to the base-run and therefore to lower GDP and
593 higher unemployment. However, an increase in GDP and decrease unemployment under the
594 moderate or medium electricity transition scenario – or more generally of a less rapid electricity
595 transition scenario - could be achieved by investing in other relevant sectors (e.g. transport, health or
596 housing). In addition, if these investments were balanced over time (i.e. when there is no large peak
597 at some point in time, as is the case in the rapid scenario), unemployment rates do not increase. This
598 is because under a balanced government investment, the working age population would not increase
599 because of better labour market conditions followed by a drop in opportunities leaving many
600 unemployed. This further supports our recommendation for a medium or moderate transition and
601 further implies that the key trade-off among scenarios and policy indicators considered becomes the
602 speed in the reduction of carbon emissions vs. the increase in electricity system costs. That is, the
603 lower the speed in emission reduction, the lower the additional electricity system costs are – and vice-
604 versa. However, we highlight that other factors not included in this study, such as total accumulated
605 emissions or the introduction of intermediate targets, should also be considered in a final choice
606 between different electricity transitions.

607 5.1 Data availability

608 The initial data and the simulation outcomes of the model that support the findings of this study are
609 available at: tbc.

610 5.2 Code availability

611 The Green Investment Barrier model was developed in Vensim 7 DSS⁶. The code for the model can be
612 viewed at: tbc.

613 5.3 Acknowledgements

614 The financial support of the Economic and Social Research Council for the Centre for the
615 Understanding of Sustainable Prosperity (CUSP) (ESRC grant no: ES/M010163/1) is gratefully
616 acknowledged.

⁶ Specifically, GIBM was built in *Vensim 7* (<https://vensim.com/vensim-7-release/>). There may be small differences in the model output if using a different version of Vensim due to different rounding approaches.

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