

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

## **Abstract**

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

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

## **1 Introduction**

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

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

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

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

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

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

To address these questions, we develop a new system dynamics energy-economy model, called the Green Investment Barrier Model<sup>1</sup> (GIBM) tailored to evaluate different low-carbon electricity transition futures of the UK in terms of macro-economic and electricity system costs. The main purpose of this paper is to provide a holistic and reliable decision-support tool for policy decisions with respect to the speed of decarbonisation of the electricity supply sector. We highlight that GIBM provides only high-level policy insights. That is, it does not assess how to deal with the intermittency of renewables (e.g. by specifying technologies<sup>2</sup>) and the expansion of renewable electricity sources is only restricted by the estimated technical potential of considered renewable sources. Furthermore, we focus on the decarbonisation of the power sector and represent electricity demand from the heating and transport sector exogenously, based on the Green Growth scenario of the National Grid (2018).

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

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

## 2 Methodology

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

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<sup>1</sup> 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)).

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

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

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

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

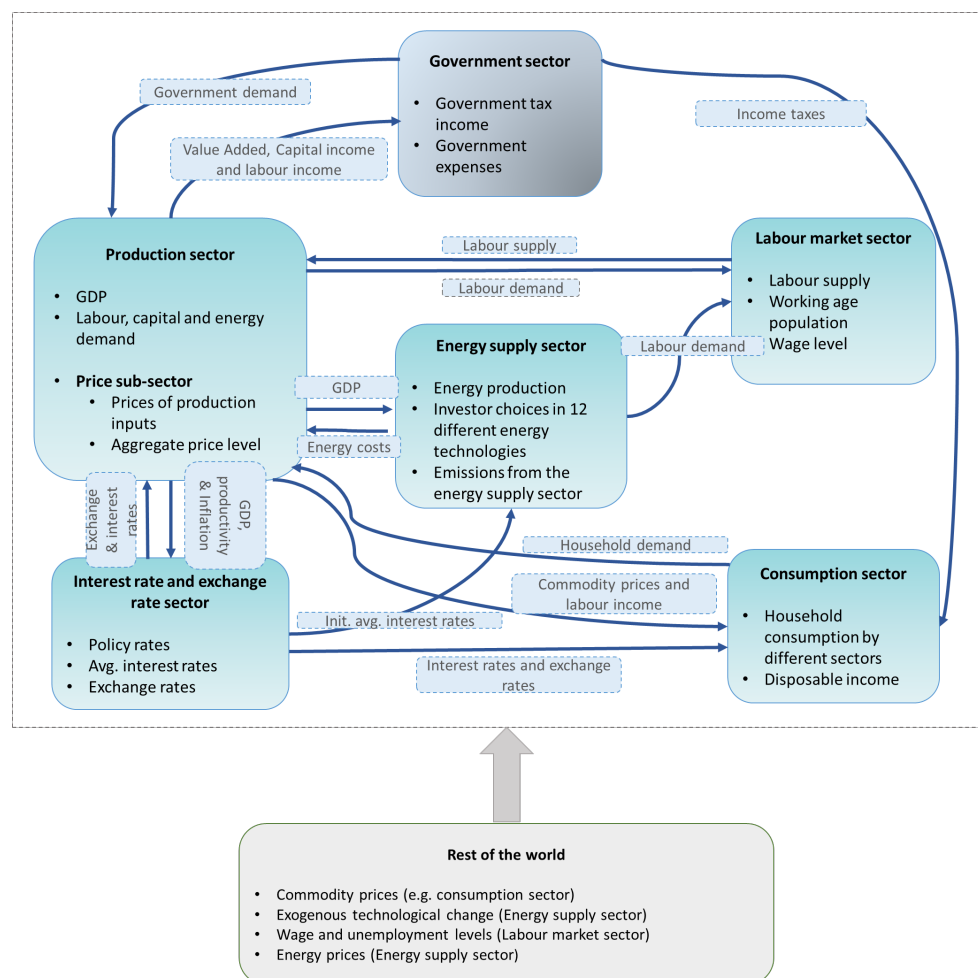
The empirical calibration of the GIBM parameters and initial values for the UK provide a realistic basis for the investigation of the economics of different low-carbon electricity transition pathways. The main data sources used to calibrate the initial conditions, for the UK economy and energy system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

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

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

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

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



## 2.1 Scenario development

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

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

All of these policy scenarios are introduced by assumption and required policies to drive this investment change are not specified in this study. The different scenarios could be interpreted as a situation where government rules mandate nuclear and fossil fuel-fired plants to be phased out and/or shut-down. As mentioned before, we highlight that GIBM does not assess how the higher intermittency of higher shares of renewables can be balanced (e.g. by specifying technologies to deal with this<sup>3</sup>) and that the expansion of renewable electricity sources is only restricted by the estimated technical potential of considered renewable electricity technologies. GIBM only simulates centralised electricity transition scenarios. Also relevant is that the UK low-carbon electricity transition scenarios can include carbon removal technologies (e.g. CCS, see CCC, 2019), however, while GIBM includes CCS Gas, none of our simulated electricity scenarios does include CCS gas in the electricity mix due to the currently high costs of this technology. Finally, all of the tested low-carbon electricity transition policy scenarios are compared against the base-run which represents a no policy scenario. Although the UK has implemented a number of electricity policies these are not used as a base-run as the interest of this study lies in understanding the additional costs of different policy scenarios compared with a base-run under no major climate constraint. Thereby, as investment decisions of energy firms are not only influenced by the costs of different energy production technologies, but also by a behavioural component, the base-run is not necessarily the most cost-effective scenario. We note that the all tested scenarios and the base-run consider a carbon price in the operational costs of fossil fuel-based electricity technologies, as this is not considered as a major policy scheme.

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

## 2.2 Key features and additional remarks

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

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

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

## 2.3 Model boundary and key limitations

GIBM is characterised by the following key limitations:

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

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

include specific storage<sup>4</sup>, other balancing (e.g. demand-management) or import possibilities that help to deal with higher intermittency of renewable electricity sources. In addition, the exploration of decentralised electricity transitions is beyond scope of the current model version.

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

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

### 3 Results

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

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

- Greenhouse gas emissions of the electricity supply system
- GDP
- Unemployed workers plus inactive working age population
- Electricity system costs
- Direct generated employment by the electricity transition
- Implicit carbon price

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

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

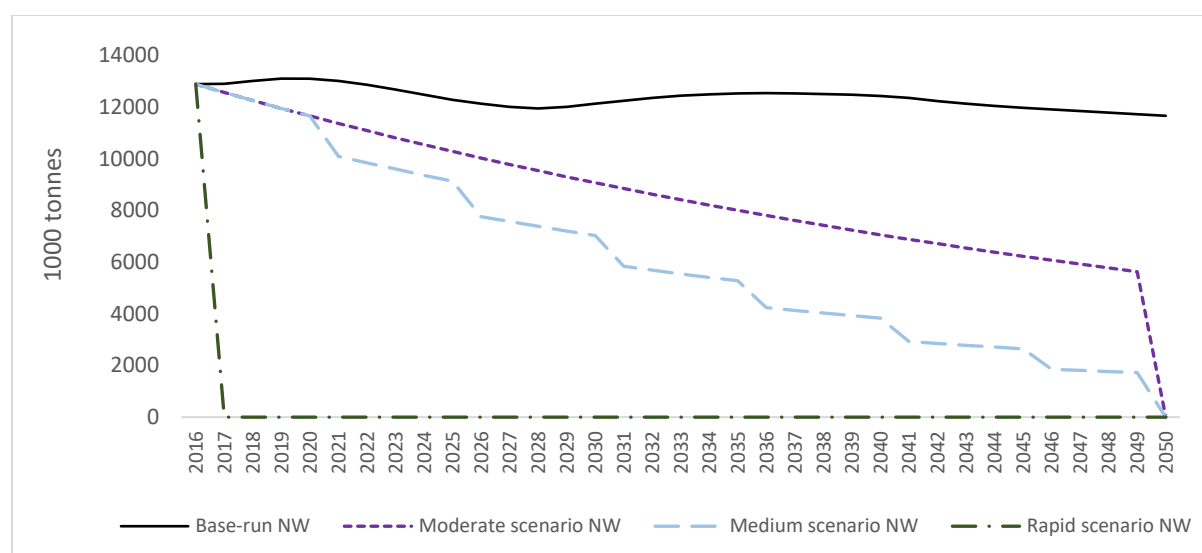
accumulated terms of the chosen policy indicators as percentage against the base-run simulation results.

**Table 1: Overview on policy outcomes of the tested scenarios:** red colour highlights the worst achieved results and the blue colour the best achieved one of all tested low-carbon policy scenarios, impacts on **accumulated** 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

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

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

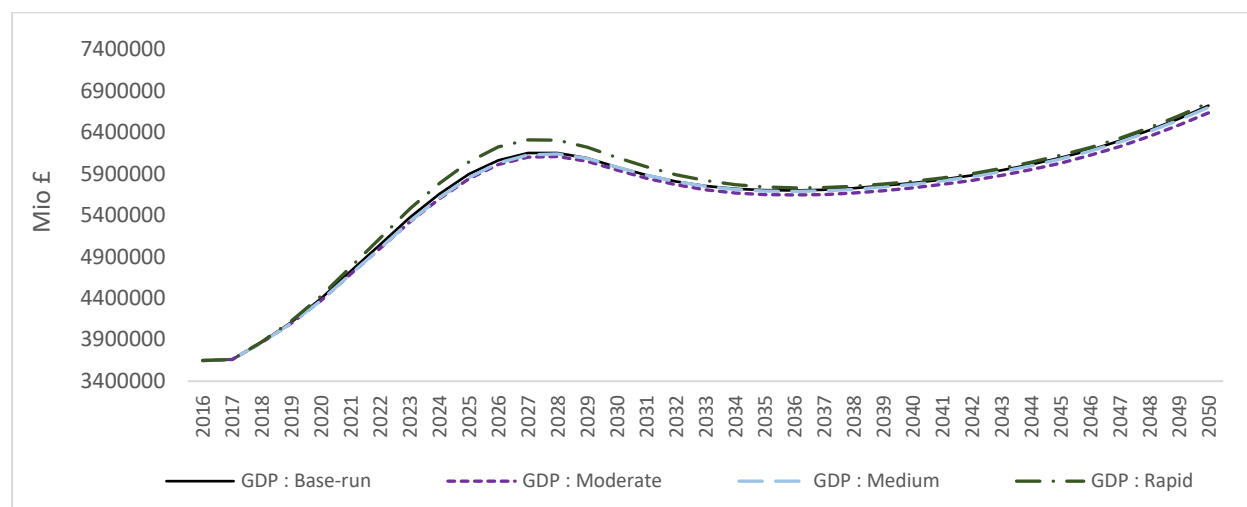


In accumulated terms in 2050, GDP is highest under the rapid scenario – 1.04% higher than the accumulated GDP under the base-run. Moreover, accumulated GDP is lower than under the base-run under the medium (by 0.3%) and moderate (by 0.9%) electricity policy scenarios. In annual terms in 2050, annual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

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

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

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

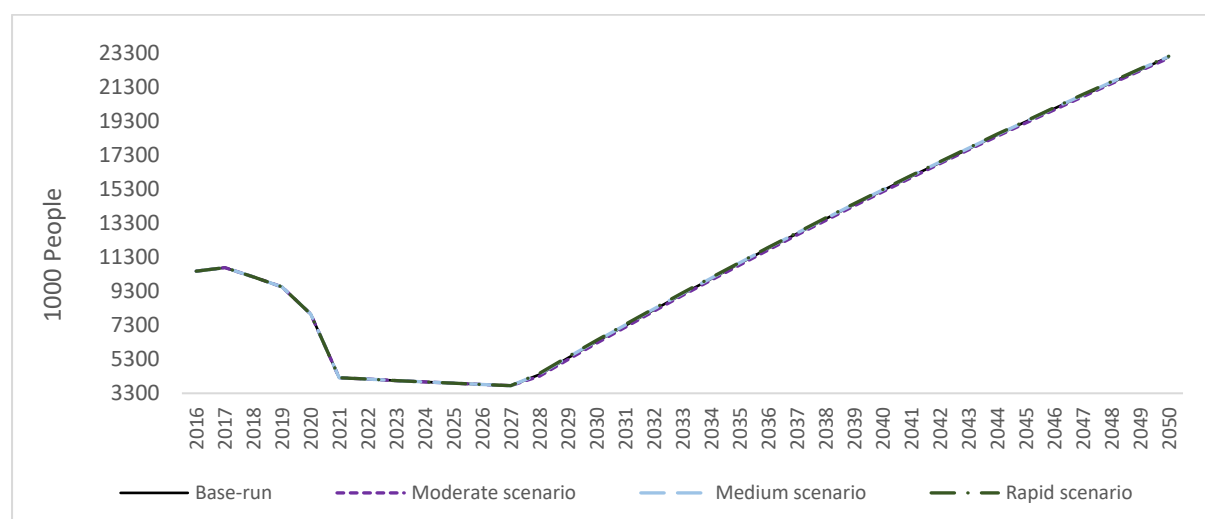


With regard to the policy indicator unemployment, in accumulated terms, the moderate scenario leads to a reduction in accumulated unemployment of 0.41% and the medium scenario of 0.08%. In contrast, cumulative unemployment under the rapid policy scenario increases by 0.08% (always compared to the base-run).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

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

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

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

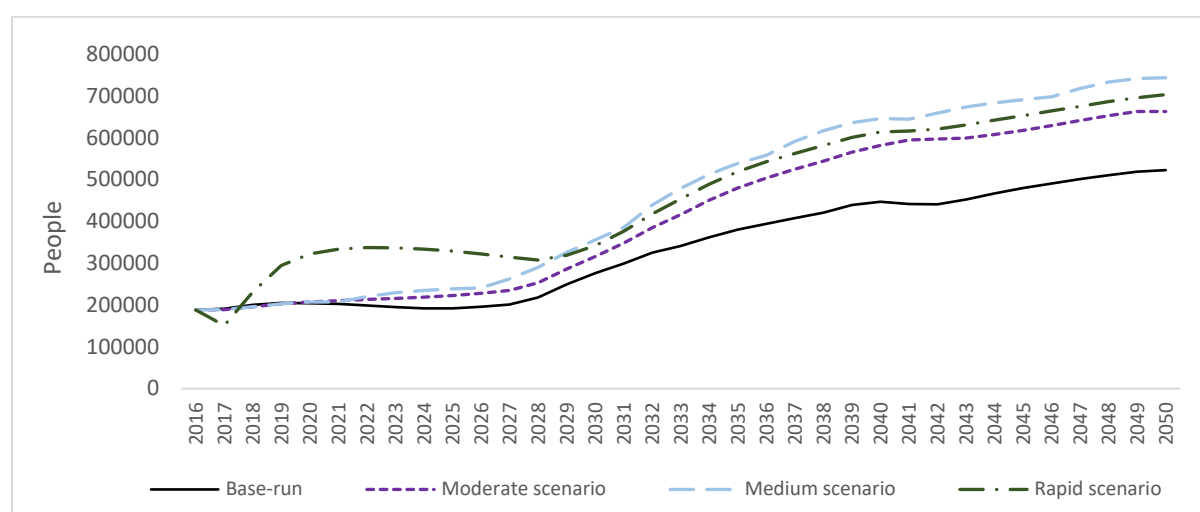


The accumulated generation of direct employment under the rapid energy policy scenario is 38.1% higher as compared to the base-run, and is highest for the tested low-carbon energy transition scenarios. Moreover, accumulated direct employment generated under the medium electricity policy scenario is 35.1%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

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

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

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

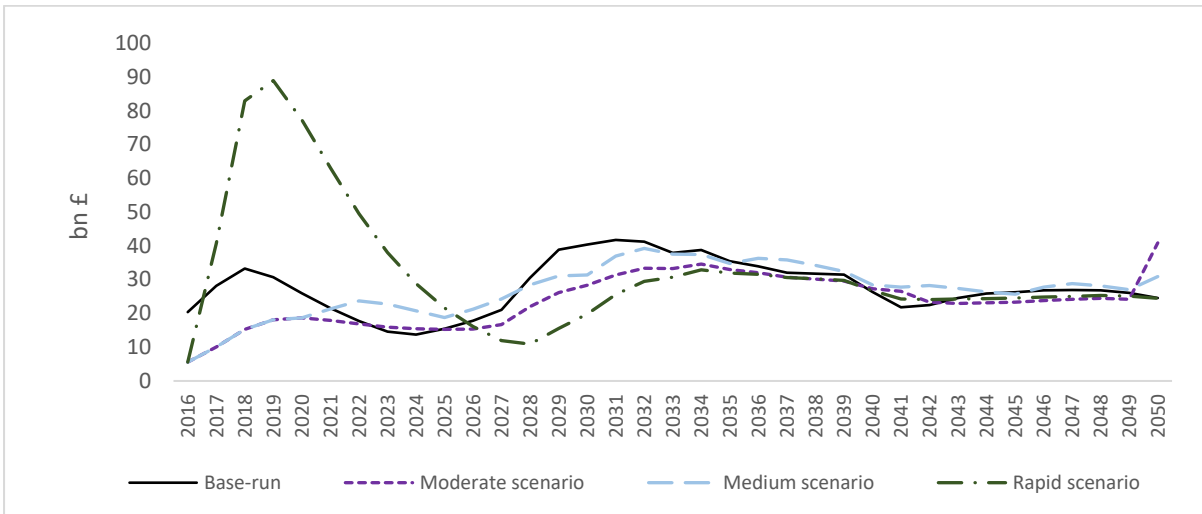


In accumulated terms, the rapid replacement by new low-carbon energy infrastructure leads to around 15.5% higher electricity system costs as compared to the base-run simulation. The accumulated power system costs are 15.9% lower under the moderate scenario and 1.9% lower under the medium scenario. This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

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

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

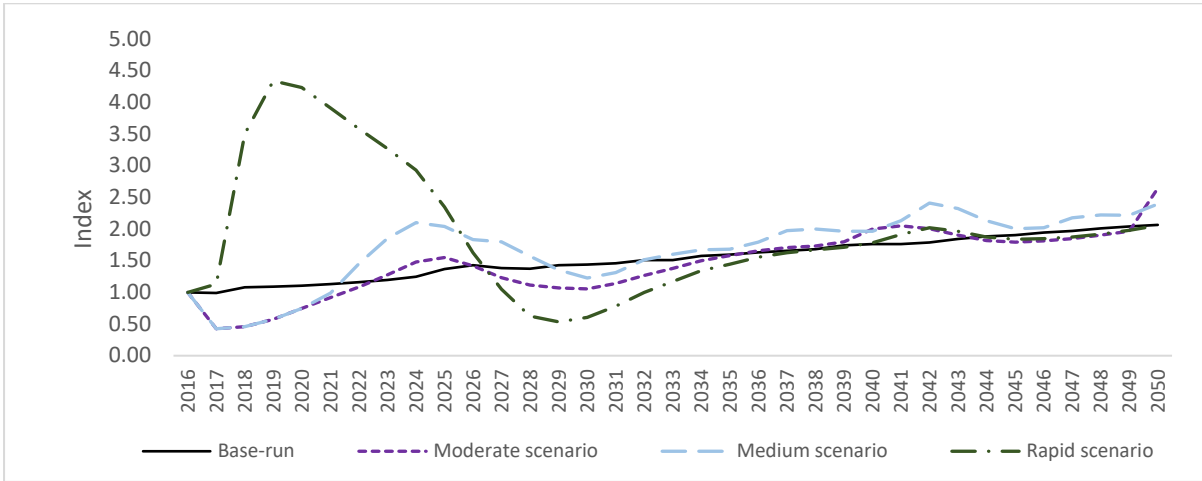
**Figure 6: Electricity system cost**



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

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

**Figure 7: Domestic electricity prices**



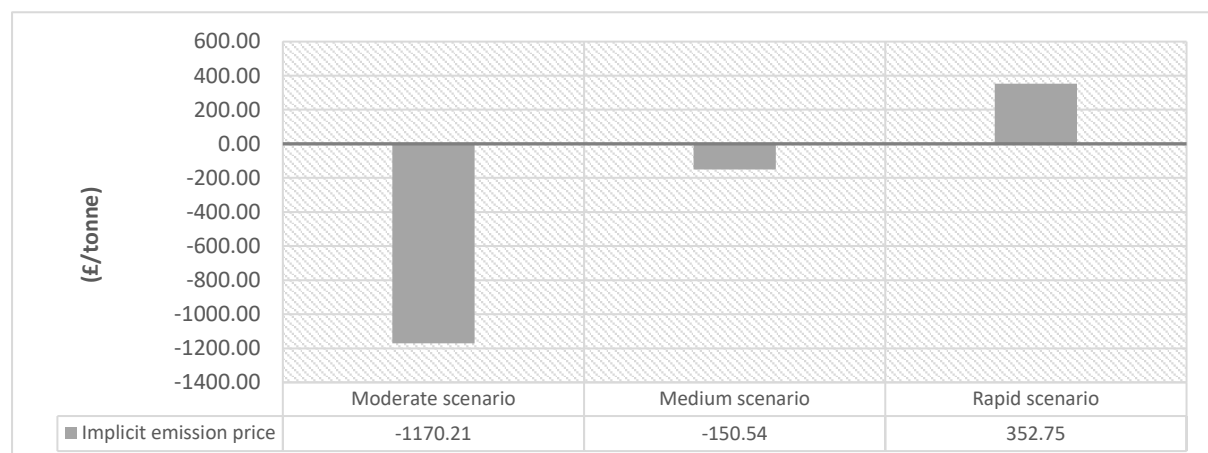
Finally, we introduce a new policy indicator, called the implicit carbon price or carbon price equivalent, in order to effectively communicate related electricity system costs per tonne of reduced emissions. We note that GIBM does not include a carbon price as a policy driver for any of the scenarios,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

The carbon price equivalent is calculated as follows:

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

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

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

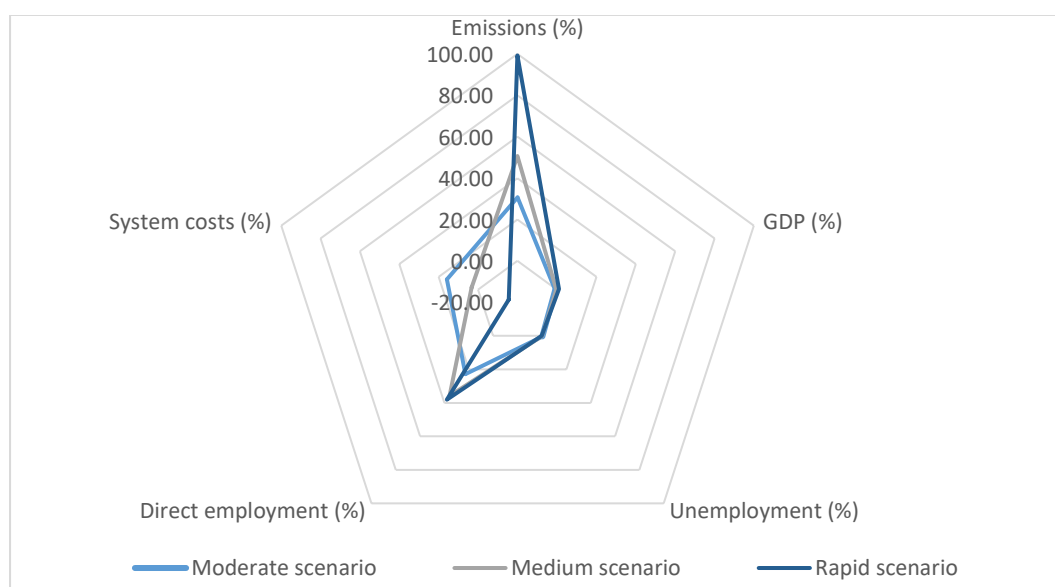


We have conducted sensitivity testing (see appendix). These results generally lead to the same policy conclusions as described in section 5. There are two exceptions to this, which are discussed below.

## 4 Discussion

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

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



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

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

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

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

Model	Study	Time horizon	Geographical scope	Modelling approach	Modelling type	Model sectors
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<b>DSK / Engage</b>	Lamperti et al. (2020)	2000 to 2100	Global	Agent-based modelling	Simulation model / Non-Equilibrium model <sup>5</sup>	Capital goods sector, consumption good sector, energy sector, households, financial system, climate sector.
<b>E3ME</b>	Irena (2016)	2010 to 2030	Global	Macroeconometric simulation model / bottom-up evolutionary technology model.	Simulation model / Non-Equilibrium model	Macroeconomic sectors, and energy, transport, agriculture and heating sectors.
<b>EIRIN</b>	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
<b>EURACE</b>	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.
<b>Eurogreen</b>	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.
<b>GIBM</b>	Current study	2016 to 2020	UK	System Dynamics	Simulation model / Non-Equilibrium model	Macroeconomic sectors, government and electricity supply sector.
<b>LowGrow SFC</b>	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).
<b>MEDEAS</b>	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.
<b>Naqvi, 2018</b>	Naqvi (2018)	100 units	EU	System Dynamics	Simulation model / Non-Equilibrium model	Firms, households (incl. workers and capitalists, government, climate and a banking sector.
<b>PANTA RHEI/GINFORS</b>	Großmann & Lutz (2015)	2000-2020	Germany	Macro-econometric input-output model	Simulation model / Non-Equilibrium model	Macroeconomic sectors, and dwelling, traffic, land-use, material input and energy sector.
<b>Threshold 21/SDGi</b>	UNEP (2011)	2010 to 2050	Global	System Dynamics	Simulation model / Non-Equilibrium model	Society module, Environmental module and Economy module.

<sup>5</sup> 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).

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

**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 nt	Avg. Price level
<b>GIBM</b>	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
<b>E3ME</b>	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).	-
<b>PANTA RHEI/GINFORS</b>	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)
<b>MEDEAS</b>	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
<b>Threshold 21/SDGi</b>	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
<b>EURACE</b>	Feed in tariff price scenario	No policy implemented	Increase of the share of renewables of 10%	-0.267	-	-	Increase	Decrease
<b>Eurogreen</b>	EnM (Energy mix): increases renewable energy sources in production and consumption.	No policy implemented	~ 50	Small decrease	0	-	-	-
<b>DSK/ENGAGE</b>	Increase of renewable	No policy implemented	-37	Decrease	Increase	-	-	-

<b>Naqvi, 2018</b>	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
<b>LowGrow SFC</b>	The GHG Reduction scenario adopts several policy measures (e.g. Carbon price, investments).	No policy implemented	Decrease	Small increase	Decrease	Increase	-	Increase
<b>EIRIN</b>	Green Supporting Factor (GSF)	No policy implemented	Decrease	No change	No change	-	-	Decrease < 1
<b>HMRC model</b>	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

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

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

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

## 5 Conclusions and policy recommendations

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

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

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

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

## 5.1 Data availability

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

## 5.2 Code availability

The Green Investment Barrier model was developed in Vensim 7 DSS<sup>6</sup>. The code for the model can be viewed at: tbc.

## 5.3 Acknowledgements

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

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<sup>6</sup> 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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