

Modelling the macroeconomic implications of a ‘closing the green finance gap’ policy scenario within a low-carbon energy transition

Abstract

Reaching the UK net-zero emissions target translates into substantial investment requirement in low-carbon energy infrastructure. However, investors are currently not investing at sufficient scale and pace in renewable energy capacity, leading to the so-called green finance gap. While current energy-economy models reveal key macroeconomic implications of low-carbon energy transitions, they mostly do not test policies designed to scale-up finance. In the light of this background, we extend the energy-economy Green Investment Barrier Model (GIBM) with the insights from a qualitative study to investigate the macroeconomic implications of a policy scenario designed to close the green finance gap in the UK in combination with and without a scenario to decarbonise the power sector. We also compare the achieved results with results simulated by other models that focus on the financing the low-carbon transition. We find that closing the green finance gap based on a systems policy approach alongside a low-carbon power scenario leads to the co-benefits of lower power system costs and unemployment, and increases in GDP.

Keywords: Green finance gap, Energy transition, Energy-economy model, System dynamics, Policy scenario

1. Introduction

The UK aims at decarbonising its electricity sector by 2050 (CCC, 2019). This translates into low-carbon electricity infrastructure investment requirements in the range of £300 billion by 2030 (Vivid Economics, 2012; CCC, 2019). The scale of these investment requirements significantly exceeds the funding possibilities of conventional funding sources (e.g. electricity developers) and the UK government. Therefore, the financial sector has a crucial role to play in the transformative change of the electricity sector towards a net-zero economy (HM Treasury & Department for Business, Energy & Industrial Strategy, 2019). However, the increase of investment flows by private investors, institutional investors or banks is hampered by various green investment barriers, leading to the so-called green finance gap, which describes the current lack of investments required for the realisation of a green trajectory (Hafner et al., 2019; 2020a).

In response to the UK’s commitment to reducing emissions by 2050, a growing number of research studies have explored low-emission strategies and their economic impacts. Computable general equilibrium (CGE) energy-economy-environment (E3) models are the predominant modelling approach applied for the UK climate policy analysis (e.g. UK Times model, HMRC model or see Vandyck et al., 2016 for an application on EU level). However, in particular after the Great Financial Crisis in 2008, criticism of models based on a neoclassical or equilibrium framework emerged as these models involve a variety of restrictive assumptions, including but not limited to the assumption of cleared markets or (bounded) rational optimising agents (Hafner et al., 2020b). Alternatively, UK policy recommendations are also derived based on econometrically estimated macroeconomic models, such as the Cambridge Econometrics MDM-E3 model (e.g. Ekins et al., 2011) or more recently their E3ME model (CE, 2019). Other energy transition simulation models in the field of the ecological

macroeconomics which relax most of the restrictive assumptions highlighted above have been increasingly emerging following the 2008 financial crisis. Examples of simulation models in this strand of literature include EIRIN (Monasterolo & Raberto, 2018, 2019), EUROGREEN (D'Alessandro et al., 2020; Bernardo & D'Alessandro, 2016) or the EURACE (Ponta et al., 2018) (see Hafner et al., 2020b for a review).

While current energy-economy models reveal a variety of different aspects/implications, and apply a large range of different foci, of low-carbon energy transitions, to date to the author's best knowledge none of them demonstrate what the related macroeconomic implications of policy approaches/scenarios aimed at scaling up the necessary green investment are¹. Our study aims to fill this gap and thus to extend the current existing energy-economy modelling landscape. We focus on the UK as case study and on the following question:

What are the macroeconomic implications of a policy scenario designed to close the green finance gap with and without the additional implementation of low-carbon energy transition scenario?

To address this question, we extend and apply the UK energy-economy Green Investment Barrier Model (GIBM) (presented in Hafner et al., 2021). The original energy-economy model represents the main macroeconomic mechanisms as well as the diffusion process of renewable energy technologies in the power sector endogenously. The extended model applies different mark-ups for the interest rates of renewable energy technologies, which are also dependent on the key investment barriers found in Hafner et al. (2019; 2020a). Relatedly, the availability of green finance in GIBM is influenced by these green investment barriers. However, GIBM does not include a full finance sector (e.g. it does not track the finance flows). Therefore the model does not capture possible impacts of tested policy scenarios on the finance sector (other than on the interest rates and availability of green finance) and neither knock-on effects from the finance sector on the economy. Furthermore, the tested policy scenario designed 'to close the green finance gap' in this study is based on the high-level policy insights of Hafner et al. (2020a). While Hafner et al. (2020a) point out the relevance of adopting a systems perspective instead of focusing on single sectors or policy interventions (e.g. energy regulations, carbon price or green supporting factor) in order to close the green finance gap, they do not propose specific policy interventions (e.g. carbon price in combination with green supporting factor). Finally, GIBM uses the system dynamics methodology which is applied to complex problems and a strength of this methodology lies in the presentation of so-called soft-parameters (i.e. parameters that are difficult to measure) and insights gained from qualitative research. This makes it a suitable tool for our investigation.

The remainder of this article is organised as follows. Section 2 introduces the methodology of our study. Section 3 highlights the main results and is followed by a discussion in section 4. In addition, in section 4, we also show comparison of the results achieved by GIBM with those of other models that address similar questions. Section 5 states conclusions and key policy implications.

¹ We note that the extended Stock-Flow consistent EIRIN macroeconomic model presented in Dunz et al. (2018; 2019) is a first step to represent policies that help to close the green finance gap. EIRIN allows to test the effect of a Green Supporting Factor (GSF) on green investments in the real economy.

2. Methodology

This study uses system dynamics (SD) as research methodology. System dynamics is a modelling approach that was elaborated by Jay Forrester in the 1960s at MIT and that is grounded in the theory of non-linear dynamics and feedback control developed in mathematics, physics and engineering (Forrester, 1958). SD is a suitable tool to investigate key mechanisms of complex systems that are characterised by feedback loops, uncertainty and path-dependency, and to manage and/or improve these systems by intervening at leverage points that either strengthen desirable or weaken undesired feedback loops. Mathematically, SD models are a set of linked differential equations simulated by algorithms and often shown visually through a stock-and-flow diagram (SFD) or a causal-loop diagram (CLD) (Sterman, 2000). This methodology is well suited to represent the underlying complexities in both the economy and the energy system, and their interactions. In addition, the modelling environment of the system dynamics program is suitable for the inclusion of insights/soft-variables indicated in qualitative studies and for long-term simulation periods. While the representation of the key dynamics causing a particular research or policy challenge and so-called soft-variables is accepted as one of the key strengths of system dynamics, we acknowledge that the model results are often not as precise as those from other models (e.g. econometric or CGE models). In addition, the estimation of exact values of so-called soft-variables (i.e. variables that are difficult to measure, such as personal preferences) is often based on expert-judgement, which may bias model results. That is, overall the strength of system dynamics lies on the identification of the key mechanisms rather than the specification of exact parameter values (see Hafner et al., 2020b).

The remainder of this section is structured as follows: the first subsection introduces the qualitative investigation on the green finance gap, and the second subsection presents the macroeconomic system dynamics Green Investment Barrier Model (GIBM), explains how the qualitative investigation has been included in GIBM and introduces the tested policy scenarios.

2.1 Qualitative investigation on the green finance gap

The qualitative investigation on the green finance gap includes a systematic review of academic literature, an evaluation of policy reports, and the conduction of interviews with financial investors and investment experts.

Policy reports

The policy reports were found by an internet search, using of the following set of keywords (see Hafner et al., 2019):

(Investment OR invest OR finance) AND energy AND (renewable OR green OR “low-carbon” OR climate)

Moreover, the following criteria for inclusion of policy reports were applied (Hafner et al., 2019):

- Published since 2009
- Applied to developed countries
- Include specific reference to barriers in large-scale clean energy infrastructure investment
- Published by multi-stakeholder groups, or an organisation, either public or private, that regularly consults multiple parties across the investment community

Overall, the identified sample of policy reports is representative for this type of literature and captures the current state (Hafner et al., 2019). The evaluation of policy reports on the green finance gap identified a set of key investment barrier themes (see table 1), which were used to derive a set of code words, describing each of the key investment barrier topics, and subsequently used for the identification of green investment barrier topics in the systematic review of academic literature (see next section and Hafner et al., 2020a for further details).

Table 1: Themes and code words identified through the analysis of the practice policy reports

Nr.	Theme	Code words
1	Lack of a stable climate change policy frameworks and policy direction	Policy framework; Policy direction; Long term; Policy uncertainty; Stable regulatory framework; Policy stability; Certainty
2	Policies are in favour of 'brown' energy-infrastructure (e.g. fossil fuel subsidies or limited pricing of carbon emissions)	Fossil fuel subsidies; Carbon price; Perverse incentives; Distorted
3	Constraints on decision making within investor companies	Fiduciary duty; Trust; Investor perceptions; Awareness; Short term; Accounting; Solvency
4	Perceptions that returns of renewable infrastructure investments are too low and require high initial capital investment	Risk return
5	Requirement that projects need a certain credit rating so that it is possible to invest	Credit rating; Risk rating; Credit worthy
6	Technology-risk associated with uncertain technologies	Technology risk
7	Disclosure on climate related risks and integrating them into financial decision-making or a lack of standardised ESG-data	Climate disclosure; Standards; ESG; Benchmark
8	Limited projects with acceptable risk-return profiles or lack of liquidity in markets	Liquidity; Liquid market; Scale
9	Lack of suitable financial vehicles/financial instruments	Financial vehicle; Financial instruments
10	High transaction costs or fees	Transaction costs; High fees
11	Lack of knowledge/technical advice on green infrastructure investment	Technical advice; Technical knowledge
12	Other barriers	Barrier

Source: Retrieved with permission from Hafner et al. (2019)

Systematic literature review

For this review, a similar set of criteria and keywords as for the search of the policy reports was used but was in addition combined with the code words shown in table 1 (see Hafner et al., 2020a for further details). Research articles were searched in the databases Isi Web of Science and Scopus and the following set of key words were used to search these databases:

(Investment OR invest OR finance) AND energy AND (renewable OR green OR "low-carbon" OR climate) AND ("one of the code words")

Only, academic articles published since 2009 were considered.

Interviews with financial investors and experts

Interviews were conducted with private investors, asset-owners and asset-managers, banks and pension funds representatives, actuaries, and academics with expertise in investment decisions. In total, 8 semi-structured and 9 structured interviews from December 2017 until December 2018 were performed (see Hafner et al., 2020 for details).

Insights

The qualitative investigation demonstrated that key green investment barriers include the ‘lack of a long-term climate change policy framework and lack of stable policies’ (see also Nemet et al., 2017), ‘the lack of appropriate projects or investment possibilities’, ‘constraints on decision making within investor companies’, ‘lack of knowledge/technical advice on green infrastructure investment’, the lack of suitable financial instruments’, ‘lack of liquidity in markets’ and ‘climate disclosure’. In addition, the qualitative study found that the identified key green investment barriers form a complex system of interrelated barriers which is characterised by path-dependency, lock-in, delays and non-linearity, deterring the green finance gap from closing (Hafner et al., 2020a). Given this, Hafner et al., (2020a) recommend the adoption of a systems perspective as analytical framework for the investigation of the green finance policy challenge and in particular for the identification of key leverage-points² for an effective, holistic and long-term policy intervention (subsequently referred to as system’s policy perspective or approach) to close the green finance gap.

2.2 The Green Investment Barrier Model (GIBM)

The Green Investment Barrier Model (GIBM) is a system dynamics energy-economy model built in Vensim⁷³. GIBM is calibrated to the UK. We choose to focus on a country scale since national governments are the main decision takers on energy and climate policies and, as explained previously, the UK is the first country that has adopted a net-zero carbon target for 2050 (CCC, 2019).

The initial model input data is from 2016 as the analytical input/output tables are only available until 2016. However, the input to the electricity sector is an exception as the most recent available data from 2019 has been used. The main data sources used to calibrate the initial conditions for the UK economy are from ONS and EUROSTAT, and policy reports for the electricity system (further details on the model building process and the calibration are stated in the appendix A; model validation tests are shown in the supplementary material in Hafner et al., 2021). The simulation horizon for this study is from 2016 to 2050, with time steps of 0.25 years. GIBM is smaller than a large-scale model but is larger than a stylised mathematical model⁴. Specifically, it includes more than 300 stock variables and around 3000 variables in total (see Hafner et al., 2021 for details).

GIBM’s economic model sectors are rooted in a post-Keynesian, ecological macroeconomic framework (Sawyer & Fontana, 2016; Hardt & O’Neill, 2017). Specific model equations generally build on non-equilibrium/simulation modelling approaches, including post-Keynesian economics, ecological economics or system dynamics (e.g. Sterman, 2000; Lavoie, 2014). Non-equilibrium (simulation)

² *Leverage-points* or ‘sensitive intervention points’ affect key feedback loops in the system; therefore, the system is sensitive to changes in those points.

³ If GIBM is reproduced with another Vensim version, there may be some differences due to different rounding approaches used in the software platform.

⁴ While the distinction between large-scale and small and stylised mathematical models is certainly not clear-cut, large-scale models involve a large number of variables and equations and cannot generally be solved analytical but are solved numerical. In contrast, stylized mathematical models contain relatively few equations, are more abstract than large-scale models and do not represent details.

models are underpinned by a similar analytical framework, influenced by a shared set of common presuppositions or metaphysical beliefs (Lavoie, 2014; Mercure et al., 2019). Non-equilibrium modelling approaches consider the economic environment as complex and dynamic, and are characterised by two-way linkages with other sectors (e.g. institutional setting, governance). In addition, they may consider the deep uncertainty (i.e. probabilities cannot be assessed), non-linearity and by path-dependency or lock-in that characterise the economy-environment relation. In this context, agents are subject to limited information and do not have perfect foresight. Therefore, agents are not outcome-maximizing but apply simple decision-rules to operate in the complex economic environment (e.g. Mercure et al. 2019).

GIBM includes key macroeconomic sectors, notably the production, consumption, labour market, interest- and exchange rate sector, and a government and an electricity supply sector. The production process at the macroeconomic level is represented with a demand led CES production function, implying that the production inputs, labour, capital, energy and intermediate inputs are not (necessarily always) fully utilised. The production sector also includes a sub-sector that simulates prices; the consumption sector models household consumption per product group; the labour market sector determines employment and simulates unemployment as the difference between labour demand (simulated in production sector) and the labour force. The labour market also simulates the wage level and includes a sub-sector that represents the UK working population endogenously; the exchange and interest rate sector simulates the exchange rate between the UK and its main trading partners, and the relevant interest rate for credits of UK firms; the government sector tracks state income and expenditures. Finally, the electricity supply sector includes representation of the UK electricity infrastructure, differentiated by 12 electricity production technologies, namely coal, gas, CCS gas, nuclear, onshore and offshore wind, solar, biomass, hydro, marine, other thermal and a category 'other renewables', and simulates electricity production in the UK (see Hafner et al., 2021 for details).

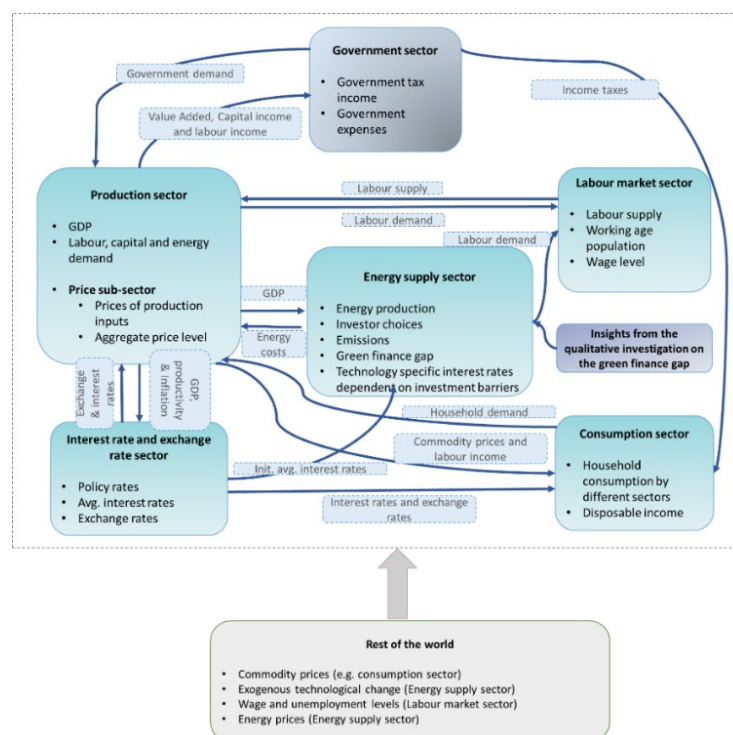
The version of GIBM presented in this study is extended in its structure when compared to GIBM presented in Hafner et al. (2021). Specifically, the extended structure enables the testing of a policy scenario that is designed to close the green finance gap and that is based on a systems approach (as recommended in Hafner et al., 2020a). That is, first, the extended GIBM model version represents technology-specific mark-ups on the interest rates for renewable electricity technologies that are dependent on the key green investment barriers identified in the qualitative investigation (Hafner et al., 2020a) and on the average interest rate simulated in GIBM. Second, compared to the earlier version of GIBM (Hafner et al., 2021), here, GIBM's electricity supply sector includes – when the respective scenario is chosen – a green finance gap, implying that there is not enough green investment for a low-carbon energy-transition in the power sector and that some of the desired renewable electricity production has to be covered with electricity imports instead (see appendix B). In other words, the representation of the green finance gap is introduced in a simplified way due to a lack of accurate numbers on this gap (Hafner et al., 2020a). In particular, when the green finance gap is introduced in the Green Investment Barrier Model only 90%⁵ of the required financing for the installation of

⁵ There are no exact numbers on this percentage available. So the 90% is our estimation based on the undertaken expert interviews (see Hafner et al., 2020a). When the finance gap is larger in reality, it will not change our conclusion, but rather increase the size of the achieved co-benefits due to the introduction of a systems policy scenario.

renewable electricity capacity in the base-run will be available and the other part of the planned renewable electricity capacity installations will be covered by electricity imports (or high-carbon electricity generated in the UK if chosen by the model user, please refer to appendix B for the equations of these parts of the model). That is, the difference between the desired and planned renewable capacity additions - occurring due to the green finance gap - are covered by electricity imports from abroad (or if chosen by the model user by high-carbon electricity from the UK). Importantly, following the approach of the E3ME model – which was used to assess the impacts of stranded assets on the economy (Mercure et al., 2018) - GIBM does not represent finance explicitly i.e. does not track financial flows. Similarly as E3ME it follows an endogenous money supply approach in the sense that it assumes full availability of finance through credit creation by banks, which means that *if* finance is available (e.g. by private investors that opt to invest in green assets or banks willing to provide credit) an increase in investments in one sector (e.g. energy) does not imply a decrease in investments in other sectors.

The features of (the extended) GIBM allow us to understand what the direct and indirect macroeconomic implications and electricity system costs of different low-carbon electricity-transitions are⁶. Figure 1 presents a stylised overview of the extended version of GIBM and table 2 gives an overview on the included model variables in GIBM.

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.



Source: adapted from Hafner et al. (2021)

⁶ However, we note that for the investigation of how climate policy risk might propagate through the financial system (e.g. Battiston et al., 2017) or on the impact of climate change on the banking system (see Lamperti et al., 2019) models that feature finance explicitly are required.

230 **Table 2: Overview on endogenously and exogenously key variables in the Green Investment Barrier Model**

	Endogenously represented	Exogenously represented / Exogenous inputs
Production sector and price sub-sector	<ul style="list-style-type: none"> • GDP • Production output • Aggregate Demand • Demand for production domestic inputs, notably energy, labour, capital and intermediate inputs • Intermediate inputs imports • Total factor productivity • Prices of production inputs and aggregate price level 	<ul style="list-style-type: none"> • Commodity prices of other countries • Parameters of substitution
Consumption sector	<ul style="list-style-type: none"> • Household consumption (on sectoral level and differentiated between domestic and abroad) • Propensity to consume 	<ul style="list-style-type: none"> • Commodity prices of other countries • Parameters of substitution (of income and prices)
Labour Market	<ul style="list-style-type: none"> • Wage-level • Employment • Unemployment • Labour supply / Labour force • Working age population • Pensioniers 	<ul style="list-style-type: none"> • Birth rate • Various elasticities
Government sector	<ul style="list-style-type: none"> • Government tax income • Government tax expenses • VAT income • Production tax income • Income tax income • Corporate tax income • Expenses for unemployed and pensioners • Depreciation of government infrastructure • Interest payments of the govt. for its debt 	<ul style="list-style-type: none"> • Various tax rates • Emission tax income (excl. emission tax income from energy supply emissions)
Interest and exchange rate sector	<ul style="list-style-type: none"> • Policy interest rate • Avg. interest rate • Exchange rate 	<ul style="list-style-type: none"> • Output gap • Investment barriers
Power supply sector	<ul style="list-style-type: none"> • Technology-specific interest rates for renewable power technologies (only influenced by the 'green finance gap' policy scenario) • Investment choices between eleven different energy production technologies • Cost decreases in energy technologies (on national level) • Energy infrastructure capacity, differentiated by eleven technologies • LCOE of energy technologies, differentiated by eleven different technologies • Energy storage and Grid- and transmission requirements and costs 	<ul style="list-style-type: none"> • Operational costs of energy supply technologies (per MW), differentiated by eleven different technologies • Energy storage and Grid- and transmission costs (per MW) • Cost decreases in energy technologies (on international level) • UK carbon price level and ETS price of carbon emissions • Learning rates • Energy imports • Changes in Exergy efficiency • Green investment barriers • Green finance gap

231

232 3. Results

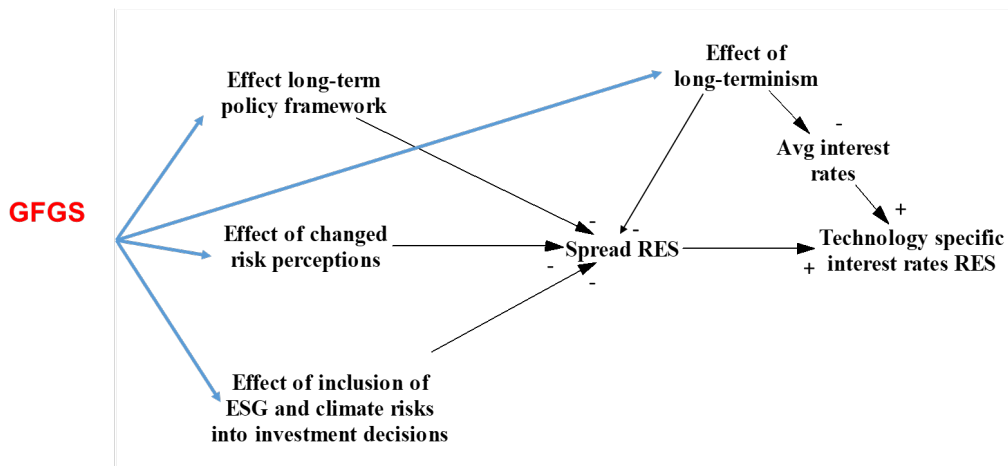
233 We simulate and compare the following two (policy) scenarios, building the current UK context:

- 234 • The **Low-carbon Electricity Transition policy Scenario (LETS)** influences variables in the
- 235 electricity sector of the model as it implies that only renewable electricity sources are chosen
- 236 for new installations. In addition, it also implies linear step-wise decrease of installed high-
- 237 carbon electricity capacity from 2020 onwards, leading to zero emissions by 2050 in the

electricity sector. The LETS is introduced by assumption and the related policies that would implement this scenario are not specified.

- The **closing the Green Finance Gap policy Scenario (GFGS)** assumes that key green investment barriers are tackled in a systemic and holistic way. Importantly, we note that while the details of the closing the green finance gap scenario are not specified in this study, we assume that it involves amendments in current regulations, investment advice, risk assessment requirements (e.g. ESG criteria and climate related risks disclosure), metrics reported and tools applied, drawing on empirical evidence stated in Hafner et al. (2020a). The closing the green finance gap scenario in GIBM, means that green investment flows to renewable electricity infrastructure are no longer restricted by the availability of finance as compared to the base-run that represents the current situation with a green finance gap. That is, in GIBM, without the introduction of an adequate policy approach/scenario available green finance is below the amount of finance required to finance a green electricity transition and unmet requests for finance to install renewable electricity capacity are covered by electricity imports from abroad. In addition, the tested scenario reduces the mark-up on interest rates of renewable electricity projects as well as the average interest rate as the scenario involves a reduction of risks particularly for low-carbon energy technologies (see figure below and see equation 3ff in the appendix). This is because the tested scenario is assumed to tackle the green investment barriers stated above, thus lowering the (perceived) risks of renewables and pressure for short-term profits on the average interest rate.

Figure 2: Impacts of closing the green finance gap policy scenario: It lowers (i) average interest rates, the interest rate spread (ark-up) on renewable electricity technology investment and (ii) closes the green finance gap (not visible on the figure).



In addition, the scenarios introduced above were tested in combination.

As indicated, we stress that we do not attempt here to specify particular policies (e.g. carbon prices) that would lead to the policy scenarios formulated. Instead, we impose them in the model by assumption so as to test the macroeconomic implications of closing the green finance gap within a low-carbon power transition. However, as in particular the closing the green finance gap policy scenario is based on the policy insights gained in Hafner et al. (2020a), we refer to them as ‘policy’ scenarios.

Importantly, although the UK has implemented a CFD (Contract for Difference) scheme, a stylised CFD scenario is not used as a base-run as the interest lies in understanding the additional costs of different policy scenarios compared with the base-run where carbon prices are accounted for, but where no major scheme is introduced⁷.

We present 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

We choose to define ‘unemployed’ in this study as sum of unemployed and inactive workers⁸. Electricity system costs are defined as the sum of the Levelized Cost of Electricity (LCOE) for new electricity infrastructure, the storage and interconnections costs of new installations in a particular year and electricity import costs due to the green finance gap (i.e. when there is not enough finance to cover the desired new instalments of renewable electricity infrastructure). The electricity imports not related to a lack of available green finance are not included in electricity system costs (and neither tracked in this version of GIBM) for simplicity and because they are assumed to be independent from the scenarios (and thus have no impact on the difference of electricity system costs between scenarios). We also indicate the results in accumulated terms / 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).

In the following, we explain the differences of the results between the tested policy scenarios and the base-run. A detailed explanation for the base-run simulation and the energy transition scenarios can be found in Hafner et al. (2021) (the medium scenario in Hafner et al. 2021 corresponds to the energy transition scenario in this paper). The key macroeconomic dynamics, induced by the introduced policy scenarios, are described in appendix C.

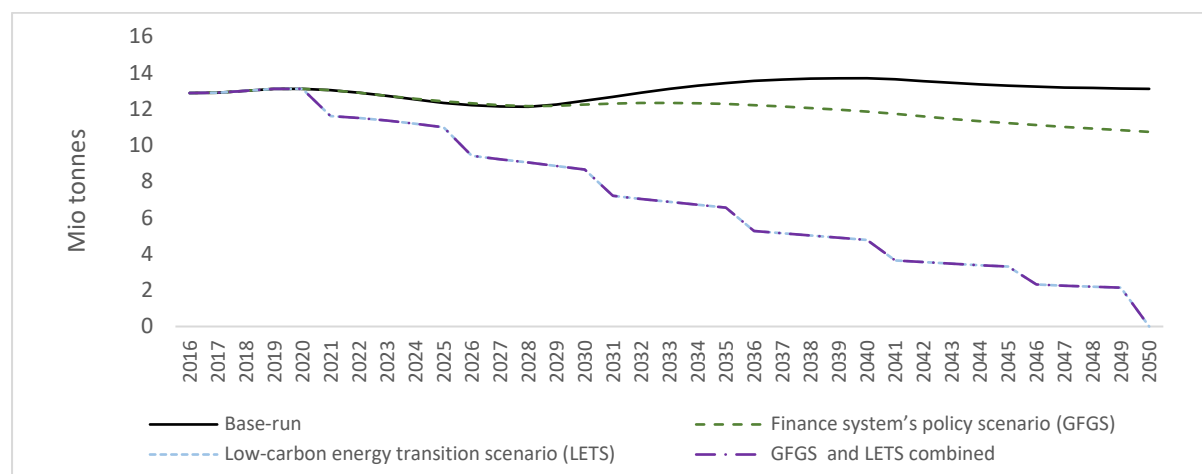
First, with regard to the results in terms of emissions. Figure 3 shows that only the LETS and a combination of both scenarios (i.e. LETS and the LETS in combination with a GFGS) combined reduce the electricity emissions to zero by 2050. When only a GFGS is introduced emissions decrease around 20% by 2050 compared to the base-run. The reduction of the emissions under the GFGS can be explained by the lower technology costs of renewable electricity technologies, which is due to their lower financing costs because of the lower technology specific mark-up because of the introduction the GFGS. We note also that in GIBM renewable electricity technologies are largely cost-efficient from 2025 onwards under the base-run and the market share of renewables increases therefore even in the base-run. Given this, a green electricity transition will likely implement itself (i.e. without any additional policies introduced), assuming that the required solutions to deal with the higher

⁷ We note that investment decisions by energy firms are influenced by a behavioural component (e.g. expertise or preferences) and therefore the base-run is not necessarily the most cost-efficient scenario in terms of energy system costs.

⁸ 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). Therefore, individuals who although would desire to work, may decide to stay outside the labour force due to discouragement and are therefore a part of the inactive labour force. In our study, we decided to consider these otherwise ‘hidden’ individuals in our policy evaluation.

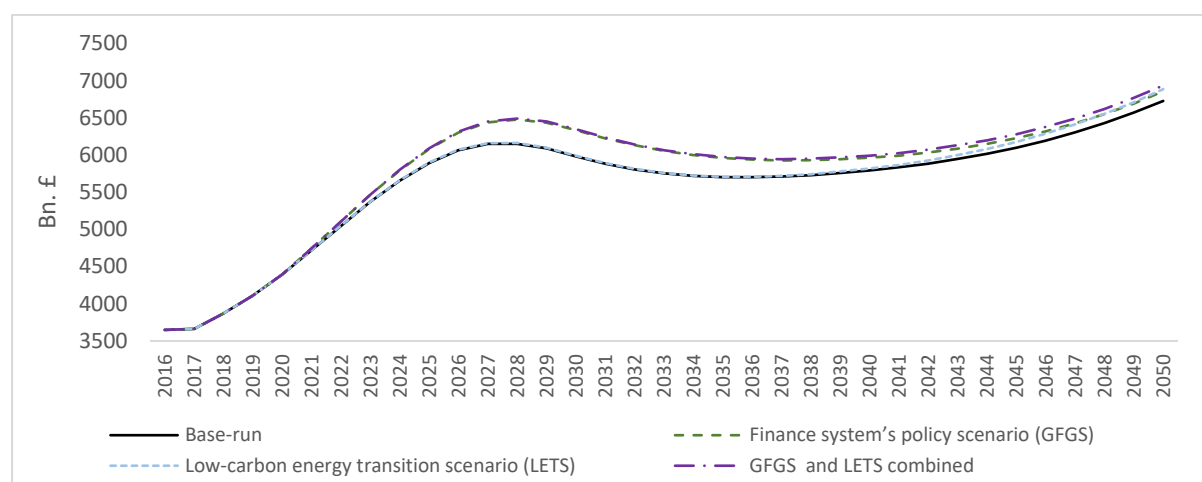
intermittency of renewable energy sources (RES) and sufficient green finance is available, however, it will not be fast enough to reach the net-zero carbon emissions target for the UK electricity supply sector (see figure below). Overall, the GFGS reduces the accumulated emissions by 7%, while both scenarios combined reduce accumulated emissions by around 45% - always compared to the accumulated emissions emitted under the base-run simulation (see Table 2). The reason for the similar trajectory of the two scenarios can be explained by the fact that the cost reduction of GFGS in the renewables does not incentivise more energy firms to invest in renewable energy than is already the case when the LETS is introduced in isolation.

Figure 3: Annual UK emissions emitted by the electricity supply sector



Second, the dynamics of GDP is driven by total factor productivity, changes in expected demand, and the macroeconomics induced by the introduced policy scenarios (see appendix C). Moreover, In 2050, GDP is 3.1% higher under both scenarios combined, 1.9% higher under GFGS and 2.3% higher under LETS – always compared to the base-run (see Figure 4). This means in aggregated terms by 2050, GDP is 3.5% higher under both scenarios combined, 3.1% higher under GFGS and 0.5% higher under LETS – always compared to the base-run (Table 2). GDP increases under the GFGS because of the lower average interest rates, leading in turn to an increase in capital investments and thus to an increase in GDP and it increases under the LETS in particular because of the aggregate demand stimulus due to increased investments and disposable income (due to increased employment).

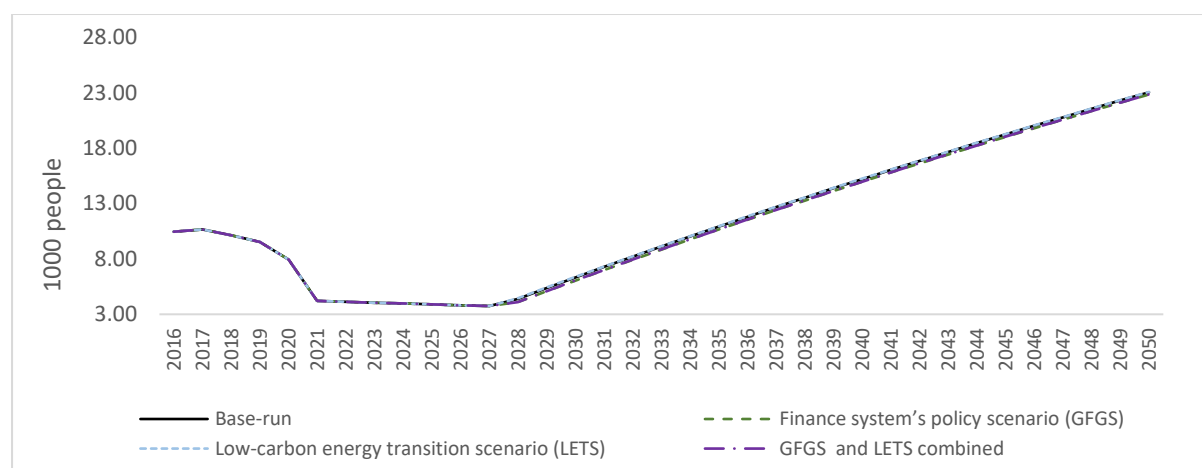
Figure 4: Annual GDP (in 2016 prices)



Third, the changes in unemployment are to a large extent negatively linked to the changes in GDP (see above), but include some inertia (Hafner et al., 2021). Moreover, Figure 5 shows that annual development of unemployment is similar for all policy scenarios and that differences are marginal.

However, in accumulated terms by 2050, differences are larger and more specifically, unemployment decreases 1.5% under GFGS compared to the base-run due to the higher GDP. Unemployment increases by 0.2%, despite the higher GDP under LETS, which is due to the path-dependency related to changes in the working-age population compared to the base-run. Under both scenarios combined unemployment decreases 1.4% relative to the base-run (Table 2).

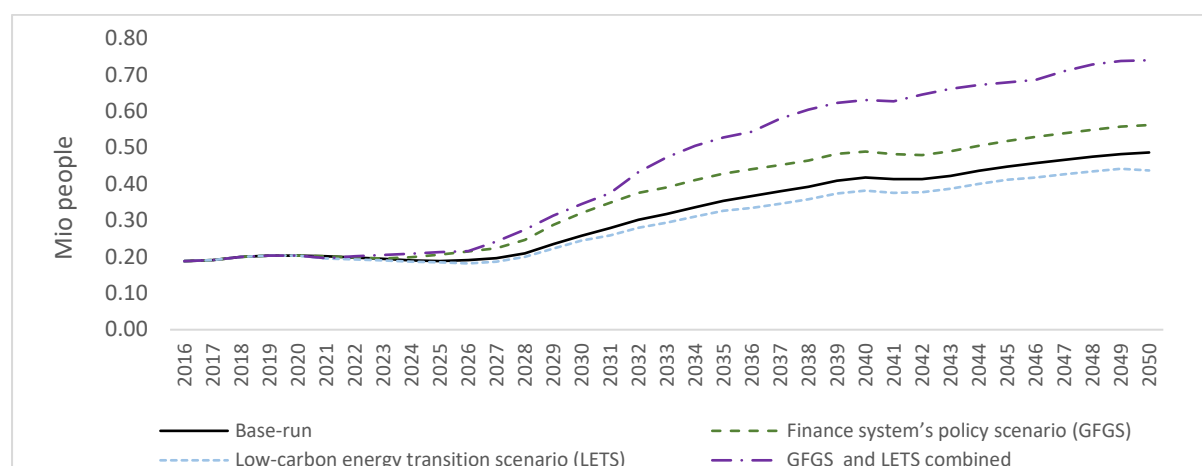
Figure 5: Annual unemployment



Fourth, annual direct employment in the power sector increases over time for all scenarios including the base-run. This is because the share of renewables in the energy mix leads to more direct employment (Wei et al., 2010) and this share increases in all scenarios and the base-run. Figure 6 shows that direct employment in 2050 is 52% higher under both scenarios combined and 15% higher under GFGS but 10% lower under LETS compared with the base-run in 2050. Direct employment under LETS is lower than under the base-run because of the occurrence of the 'green finance gap'. LETS implies that all new installed electricity infrastructure from 2020 onwards shall be renewable electricity-based – however, as there is a green finance gap, available finance does not cover required

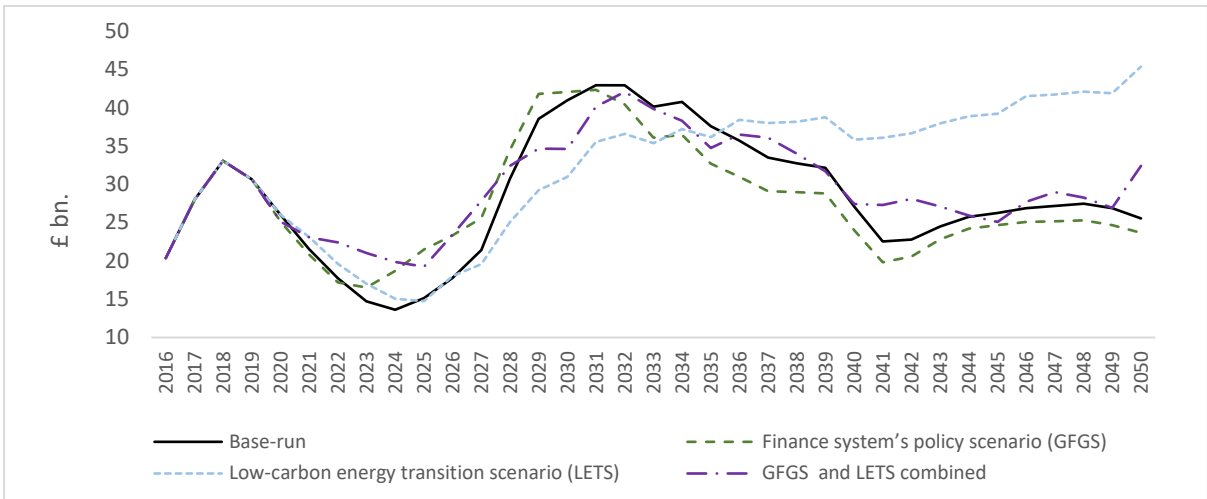
investments for these renewable electricity installations and therefore a certain amount of the UK electricity requirements are instead covered by electricity imports (see figure below). This in turn means that potentially additional direct employment for the installations of new renewable electricity infrastructure is not created in the UK but abroad. In accumulated terms 'Direct employment' increases 40% under both scenarios combined and 15% under GFGS but decreases 7% under LETS (Table 2).

Figure 6: Annual direct employment in the electricity sector



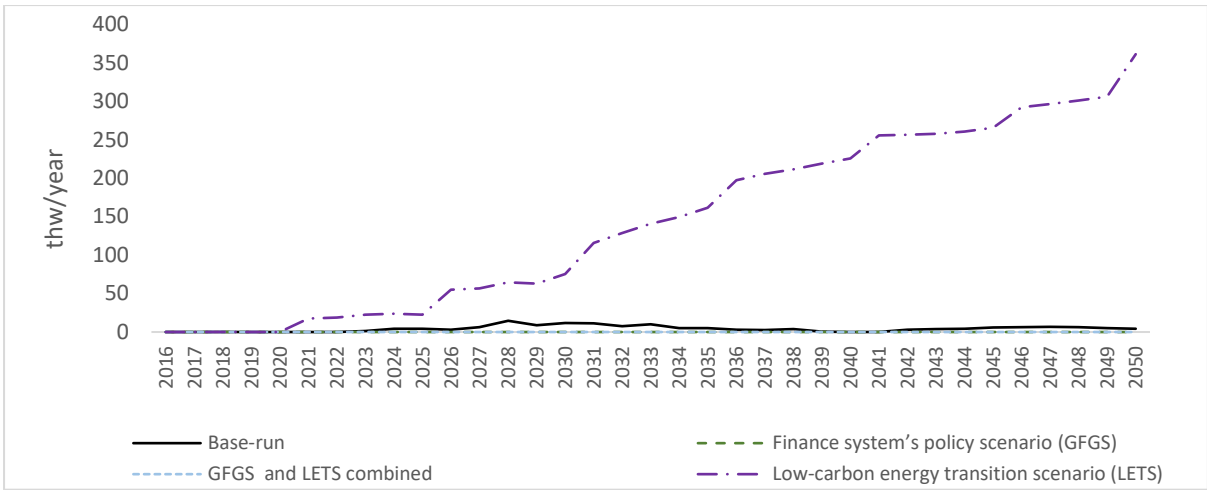
The annual electricity system costs are driven by the demand for power from transport and heating (exogenously given), changes in GDP (i.e. industry electricity demand), replacement of shut-down high-carbon infrastructure (in the case of the LETS) and the costs of the chosen power production technologies. Figure 7 illustrates that in 2050, annual electricity system costs are highest under the LETS (77% higher than under the base-run – because of electricity imports and the reinstallment of renewable electricity production capacity), under the GFGS they are 7.5% lower than the base-run (due to the lower interest rates and because the green finance gap is closed) and when a combined scenario is introduced they are around 25% higher compared to the base-run. Accumulated electricity system costs decrease 2.6% under GFGS but increase 12.4% under the LETS and 2.7% under both scenarios combined. Electricity system costs decrease under the GFGS because of the lower financing costs of renewable electricity infrastructure (Table 2).

Figure 7: Annual electricity system costs



As explained earlier, electricity imports include only those that are required due to the green finance gap. Therefore, they are zero as soon as the GFGS is introduced. Moreover, they are higher under the energy transition scenario compared to the base-run as this scenario assumes more installation of renewable energy infrastructure (Figure 8).

Figure 8: Annual UK electricity imports due to the green finance gap



Higher electricity system costs translate into higher electricity prices as electricity prices are given by the electricity system costs plus a constant mark-up (see figure below and refer to Hafner et al., 2021 for model equations).

Figure 9: Electricity prices

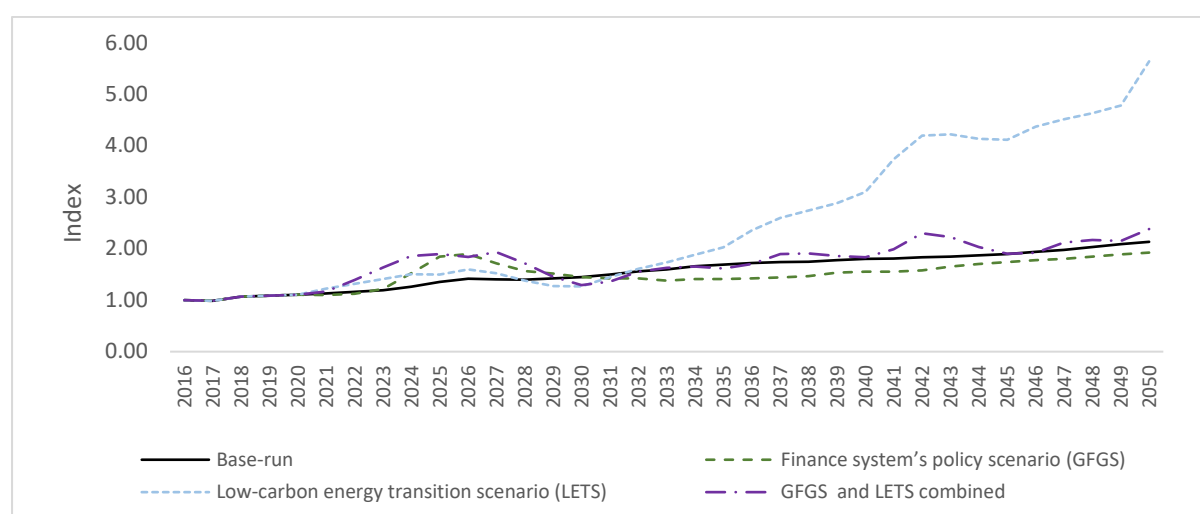


Table 3 shows the results of the simulated electricity policy scenarios in terms of the chosen policy indicators *as percentages against the base-run simulation results* of the same policy indicator (always in accumulated numbers, if not indicated differently).

Table 3: 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 2016 to 2050 in comparison to the base-run.

	Emissions (%)	GDP (%)	Unemployment (%)	Direct employment (%)	System costs (%)
Green Finance Gap (GFGS)	-7.09	3.05	-1.47	15.12	-2.58
Low-carbon electricity transition scenario (LETS)	-44.90	0.50	0.20	-6.90	12.44
GFGS and LETS combined	-44.90	3.46	-1.4053	40.15	3.66

We also undertook a variety of different sensitivity tests, including changes in key parameters of the electricity sector or the economic sector (e.g. prices, impact of interest rates on propensity to consume, reaction of the wage level to the average price level); however, they do not change our scenario implications and conclusions, and are reported in the appendix D.

4. Discussion

The simulation results presented in the previous section demonstrate that while there exists no clear win-win solution, the implementation of a policy scenario based on a long-term systems approach, designed to close the green finance gap, brings various co-benefits both introduced in isolation as well as in combination with a low-carbon electricity transition scenario:

- When the closing the green finance gap scenario (based on a systems approach (Hafner et al., 2020a)) is introduced in isolation it reduces the average market interest rates and leads to a lower spread on the interest rates of renewable electricity technologies. These effects lead further (i) to an increase in capital inputs and therefore to total factor productivity and

subsequently to (ii) an increase in GDP, (iii) a decrease in unemployment, (iv) to an increase in direct employment in the electricity sector due to lower financing costs of renewable electricity sources and (v) to lower electricity prices due to lower financing costs of renewables. The only disadvantage caused by this scenario are the higher emissions due to the increase in GDP, which requires higher electricity production.

- The tested closing the green finance gap scenario combined with a low-carbon electricity policy scenario leads to various co-benefits. In more detail, both scenarios combined lead to higher GDP and direct employment, and at the same time to lower unemployment and electricity system costs – and importantly to zero emissions in the electricity system by 2050.

Thereby, the advantages from closing the green finance gap based on a systems approach stem on one hand from its effect on lower interest rates and on the other hand because it closes the green finance gap, which subsequently avoids electricity imports from abroad (see appendix C for more details).

In the following, we aim to compare our results achieved by GIBM with studies that addressed comparable research questions in order to better understand whether the results of GIBM confirm or contradict these other results. Each of these studies uses a different modelling approach however they are all used to address similar policy questions within governments and therefore understanding the difference between the outputs of the models is important within a policy context. Bernardo & D'Alessandro (2015), Dunz et al. (2021) and Irena (2016) explicitly test policies or scenarios that upscale green finance into renewable electricity infrastructure. In addition, results from the HMRC 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. Table 4 below gives an overview of these models.

Table 4: Overview of selected models and GIBM

	GIBM	Bernardo & D'Alessandro, 2015 model	EIRIN	E3ME-FTT	HMRC model
Study	Current study	Bernardo & D'Alessandro (2015)	Dunz et al. (2019)	Irena (2016)	CCC (2010)
Time horizon	2020 to 2050	2010 to 2050	2018 to 2038	2010 to 2030	2020 - 2025
Geographical scope	UK	Italy	High income country	Global	UK
Modelling approach	System Dynamics	System dynamics	Stock-Flow Consistent behavioural model	Macroeconometric simulation model / bottom-up evolutionary technology model.	Computable General Equilibrium (CGE) model
Modelling type	Simulation model / Non-Equilibrium model	Simulation model / Non-Equilibrium model	Simulation model / Non-Equilibrium model	Simulation model / Non-Equilibrium model	Optimization / Equilibrium model ⁹

⁹ Utility optimisation algorithms (the social planner assumption).

Model sectors	Production, consumption, labour market, simplified interest & Exchange rate sector and power supply sector.	Production, consumption, energy and labour market sector.	Households-, Government-, Commercial banking- and a capital (green & high-carbon) and goods production sector.	Macroeconomic sectors desegregated by industry, Energy sector desegregated by power, transport, agriculture and heating.	Production (incl. top-energy sector), consumption and labour market sector.
----------------------	---	---	--	--	---

418

419 The table below compares the GIBM results with the previous studies. When no quantitative results
420 are reported, this means that there were no numbers indicated in the consulted study.

421 **Table 3: Comparison to results of other models: if not indicated differently, the numbers refer % change vs. Reference**
422 **case**

	GIBM	Bernardo & D'Alessandro, 2015 model	EIRIN	E3ME-FTT	HMRC model
Relevant scenarios or policies	Closing the green finance gap policy scenario in combination with a low-carbon electricity transition scenario	Roadmap scenario: investments in renewable energy sector, energy efficiency and direct reduction of carbon emissions.	Green Supporting Factor (GSF)	REmap Electrification scenario (RemapE): Increase in investments to expand the renewable energy sector. ¹⁰	Introduction of higher carbon prices
Reference case	No major policy scheme implemented; introduced & expected CO2 prices in the UK are considered.	No policies implemented	No policies implemented	Implemented and planned policies, leading to a warming of 2.6 Degree globally.	No policies implemented
Emissions from power system	-100 (power sector)	-75 (entire economy)	Zero emission target not reached, the GSF is not enough to scale-up green investments.	-15.7	- 50 (entire economy and relative to 1990)
Unemployed	-0.85	-38	No change	- 0.2	Constant
Real GDP	+3.1	-14	No change	+ 1.1	Decrease

¹⁰ This scenario also includes the electrification of heating and transport, requiring a greater deployment of renewables for power generation.

Electricity system costs	+26.8	Not indicated	Not indicated (no power sector)	Not indicated	Increase
Generated employment in the energy sector	+53	Increase, but not indicated by how much	Not indicated (no power sector)	+ 69(incl. indirect generated employment in the renewable energy sector).	Not indicated
Avg. Price level	+2.45	Not indicated	Decrease < 1	Decrease of electricity prices	Increase

423

424 The table above reveals that the simulation results of GIBM differ to some extent from the results
425 achieved in previous studies by other models applied to similar questions.

426 First, the study of Bernardo & D'Alessandro (2015) shows that an increase of low-carbon
427 investments to renewable energy infrastructure increases employment but slows down GDP-growth
428 and wages. The system dynamics model of Bernardo & D'Alessandro (2015) achieves the presented
429 results mainly due to the following mechanisms: an increase in low-carbon investment induces a
430 decrease in investment in the rest of the economy, which subsequently slows down productivity and
431 economic growth. This slowdown leads afterwards to a wage decrease and an increase in the labour
432 share in the economy, leading to an increase in overall employment and thus to a reduction in
433 unemployment. While an increase in investments into renewable energy infrastructure crowds out
434 investments in the rest of the economy in the study of Bernardo & D'Alessandro (2015), drawing on
435 the assumption of exogenous money supply, in GIBM an increase in investments in green power
436 infrastructure does not reduce investments in other parts in the economy as GIBM adopts an
437 endogenous money supply perspective. This is the key reason why the results in terms of GDP differ
438 between the two models. Moreover, while unemployment decreases in the former study due to
439 lower productivity and lower wages, unemployment in GIBM decreases due to the increase in GDP
440 and induced employment in the power sector due to low-carbon energy transition.

441

442 Second, Dunz et al. (2021) find that the introduction of a Green Supporting Factor (GSF)¹¹ although
443 scales-up green investments, GDP and employment is not enough to upscale the required green
444 investments for a low-carbon transition. This is in line with our finding that removing financial
445 barriers alone to close the green finance gap will not be sufficient to achieve the necessary scale of
446 investment (see also Hafner et al., 2020b). Dunz et al. (2021) find that the implementation of a GSF
447 does not change GDP and unemployment (by much), and decreases the average price level by less
448 than 1%, mainly due to the lower interest rates for green capital producer. In comparison the model
449 used in Dunz et al. (2021), GIBMs results show an increase in GDP, decrease in unemployment and a
450 decrease in the average price level. The stronger impacts in GIBM are mainly due to the stronger
451 overall impacts of the combined scenarios introduced in GIBM.

452

453 Third, based on the modelling results of E3ME, IRENA (2016) demonstrates that accelerating the
454 deployment of renewable energy will fuel economic growth and create new employment

¹¹ The introduction of the GSF would lower the risk weights applied to environmentally friendly (i.e. green) loans and investments, thereby reducing banks' capital requirements for these particular assets. This is supposed to encourage banks to finance environmentally friendly investments.

opportunities. Results achieved by E3ME and GIBM show both the same sign of direction (see also table 2 above), however, the drivers of achieved results are somewhat different. As it concerns the achieved results by E3ME, most of these positive impact on GDP are driven by the increased investment in renewable energy deployment, which subsequently triggers ripple effects throughout the economy via Keynesian-multiplier effects (similar to the ones explained for GIBM, see appendix B). In contrast, the results in GIBM are driven by the lower interest rates induced by the systems policy scenario, which subsequently increase capital inputs in the real economy, increasing total factor productivity, GDP, employment consumption, which is further reinforced by Keynesian multiplier-effects, see Appendix C). Similarly, to the study of Bernardo & D'Alessandro (2015), IRENA (2016) does not analyse how the investments required for a low-carbon energy transition can be scaled-up, instead, the availability of green finance is introduced by assumption.

Fourth, we compare the achieved results of GIBM with the HM Revenue & Customs (HMRC) model results. This model has initially been developed for HMRC to assess the GDP effects of tax policy changes. We have chosen to include it here as the HMRC model has been very relevant in UK government decision making on climate policy and in particular regarding the adoption of the fourth carbon budget (see Ackerman, 2014). 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. 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; Hafner et al., 2020b). The different modelling paradigm may explain the differences in the direction of the results between HMRC and the other simulation models (see Mercure 2019a;b).

5. Conclusions and policy implications

The system dynamics Green Investment Barrier Model (GIBM) presented in this study is a descriptive simulation model as opposed to the more common equilibrium (optimization) models. Its speciality lies in the integration of a green finance gap in the context of a UK electricity transition, which allows the investigation of a policy scenario that scales-up the required finance for renewable electricity production capacity. That is, extending earlier studies (e.g. Irena, 2016) that test the impacts of renewable energy deployment, GIBM includes a green finance gap, rather than assuming the availability of sufficient financial resources as a necessary precondition for the tested renewable energy policy scenario and therefore allows to explore the macroeconomic impacts of a policy scenario designed to scale-up green finance. This policy scenario is assumed to tackle key green investment barriers (short- termism, unstable policy strategy and information disclosure) in a holistic way i.e. based on a systems perspective, drawing on insights from Hafner et al. (2020a) and can be tested in combination with a low-carbon energy scenario that allows only the installation of renewable energy infrastructure.

Our results show that the introduction of a policy scenario which aims to close the green finance gap alongside policies in the electricity sector brings co-benefits in terms of higher GDP, lower unemployment and electricity system costs. However, focussing on closing the green finance gap alone would not be enough to reach net-zero emissions of low-carbon electricity production by 2050

– policies in the electricity sector itself need to complement it. Given this, we recommend the implementation of a low-carbon energy transition scenario in combination with policies aiming to close the green finance gap that are based on a systems approach. These findings are in line with findings of other models in the current literature on the economic implications of energy transitions. For example, Dunz et al. (2021) find that the introduction of a green supporting factor by itself would not be sufficient to trigger a low-carbon transition.

Our results, discussion and recommendations are robust under the sensitivity analysis performed. Accordingly, when key parameter values are changed, the above-stated policy insights and recommendations still hold (i.e. they are robust to these amended parameter values), although the magnitude of the indicated benefits/dis-benefits changes by some percentage. Our sensitivity tests involved changes in key parameters in the electricity production system (e.g. learning rates, CO2 price, investment costs of different electricity production technologies) and the economic sectors (e.g. parameter of substitution, changes in the link between interest rates and propensity to consume and changes in the reaction of the wave level to the consumer price index).

We underline that our study assumes that storage or demand-side management technologies are available to deal with the higher intermittency of a renewable electricity system. Further, the results indicated above rely on the links between a scenario aimed to close the green finance gap and its impact on the interest rates as well as indicated relationship between lower interest rates and higher capital usage in the economic production. Therefore, future research should validate that these links also hold under future circumstances. We also recommend that future research investigates in more detail the complexity of the green finance gap to further specify the needed finance system policy.

6. Data availability

The initial data and the simulation outcomes of the model that support the findings of this study are available at: <https://doi.org/10.25411/aru.14432591>.

7. Code availability

The Green Investment Barrier model was developed in Vensim 7 DSS¹². The code for the model can be viewed at: <https://doi.org/10.25411/aru.14432591>.

8. 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.

¹² 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.

- Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., & Visentin, G. (2017). A climate stress-test of the financial system. *Nature Climate Change*, 7(4), 283-288.
- Bernardo, G., & D'Alessandro, S. (2016). Systems-dynamic analysis of employment and inequality impacts of low-carbon investments. *Environmental Innovation and Societal Transitions*, 21, 123-144.
- Cambridge Econometrics (CE) (2019). E3ME. Technical Manual, Version 6.1. March 2019. Available: <https://www.e3me.com/wp-content/uploads/2019/09/E3ME-Technical-Manual-v6.1-onlineSML.pdf/> (Accessed 01.12.2019).
- Committee on Climate Change (CCC) (2019). Net Zero – The UK's contribution to stopping global warming. Available at: <https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/> (Accessed 14.05.2019)
- D'Alessandro, S., Cieplinski, A., Distefano, T., & Dittmer, K. (2020). Feasible alternatives to green growth. *Nature Sustainability*, 3(4), 329-335.
- Dunz, N., Naqvi, A., & Monasterolo, I. (2021). Climate sentiments, transition risk, and financial stability in a stock-flow consistent model. *Journal of Financial Stability*, 54, 100872.
- Del Granado, P. C., Van Nieuwkoop, R. H., Kardakos, E. G., & Schaffner, C. (2018). Modelling the energy transition: A nexus of energy system and economic models. *Energy strategy reviews*, 20, 229-235.
- Ekins, P., Anandarajah, G., & Strachan, N. (2011). Towards a low-carbon economy: scenarios and policies for the UK. *Climate Policy*, 11(2), 865-882.
- Fontana, G., & Sawyer, M. (2016). Towards post-Keynesian ecological macroeconomics. *Ecological Economics*, 121, 186-195.
- Hafner, S., Jones, A., & Anger-Kraavi, A. (2021). Economic impacts of achieving a net-zero emissions target in the energy sector. *Journal of Cleaner Production*, 127610.
- Hafner, S., Jones, A., Anger-Kraavi, A., & Pohl, J. (2020a). Closing the green finance gap—A systems perspective. *Environmental Innovation and Societal Transitions*, 34, 26-60.
- Hafner, S., Anger-Kraavi, A., Monasterolo, I., & Jones, A. (2020b). Emergence of New Economics Energy Transition Models: A Review. *Ecological Economics*, 177, 106779.
- Hafner, S., James, O., & Jones, A. (2019). A scoping review of barriers to investment in climate change solutions. *Sustainability*, 11(11), 3201.
- Hardt, L., & O'Neill, D. W. (2017). Ecological Macroeconomic Models: Assessing Current Developments. *Ecological Economics*, 134, 198-211.

- HM Treasury & Department for Business, Energy & Industrial Strategy (2019). Green finance strategy. Available at: <https://www.gov.uk/government/publications/green-finance-strategy> (Accessed 14.08.2020).
- Janamanchi, B., & Burns, J. R. (2013). Control theory concepts applied to retail supply chain: a system dynamics modeling environment study. *Modelling and Simulation in Engineering*, 2013.
- Lamperti, F., Bosetti, V., Roventini, A., & Tavoni, M. (2019). The public costs of climate-induced financial instability. *Nature Climate Change*, 9(11), 829-833.
- Lavoie, M. (2014). *Post-Keynesian economics: new foundations*. Edward Elgar Publishing.
- Mercure, J. F., Knobloch, F., Pollitt, H., Paroussos, L., Scrieciu, S. S., & Lewney, R. (2019). Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use. *Climate Policy*, 19(8), 1019-1037.
- Mercure, J. F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., ... & Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change*, 8(7), 588-593.
- Monasterolo, I., & Raberto, M. (2019). The impact of phasing out fossil fuel subsidies on the low-carbon transition. *Energy Policy*, 124, 355-370.
- Nemet, G. F., Jakob, M., Steckel, J. C., & Edenhofer, O. (2017). Addressing policy credibility problems for low-carbon investment. *Global Environmental Change*, 42, 47-57.
- Ponta, L., Raberto, M., Teglio, A., & Cincotti, S. (2018). An agent-based stock-flow consistent model of the sustainable transition in the energy sector. *Ecological economics*, 145, 274-300.
- Sterman, J. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill, Boston.
- Vandyck, T., Keramidas, K., Saveyn, B., Kitous, A., & Vrontisi, Z. (2016). A global stocktake of the Paris pledges: implications for energy systems and economy. *Global Environmental Change*, 41, 46-63.
- Vivid Economics (2012). *Energy and the economy the 2030 outlook for UK businesses*. A London School of Economics Report Commissioned by RWE Power. Available at: www.vivideconomics.com/publications/energy-and-the-economy-the-2030-outlook-for-uk-businesses (Accessed 04.05.2019).

529

530

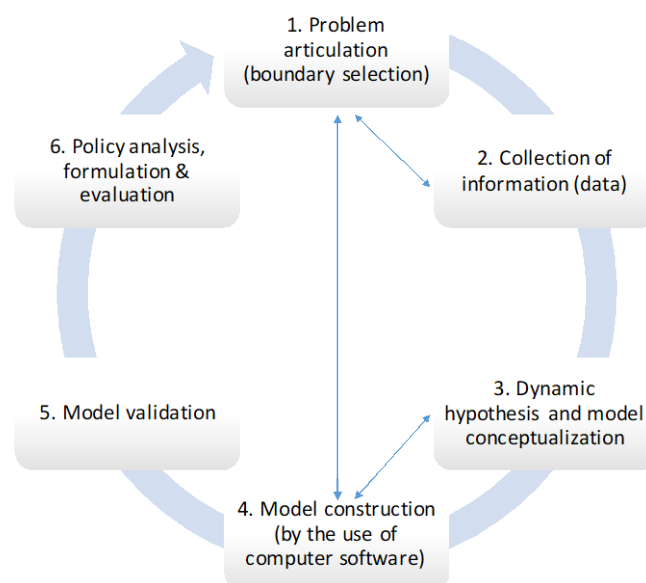
Appendix

Appendix A – model building process and calibration strategy in system dynamics

1.1.1. Modelling process

The following sections describe the different steps to build a systems dynamics (SD) simulation model. While this is generally outlined in chronological order, in reality it is to some extent an iterative process among problem articulation, hypothesis generation, model formulation, testing, and policy analysis (see Figure A1). For example, the testing of the model might reveal the necessity to reformulate the research problem and extend the system boundary. This would bring the modeller from step 4 back to step 1 (see Figure A1). Alternatively, the formulation of the dynamic hypothesis (step 2) might reveal that the modeller must re-adjust the model boundaries to include the main feedback loops endogenously (step 1). Moreover, the ‘translation’ of the conceptual model into formal equations (step 4) may reveal inconsistencies in the mental map, bringing the modeller back to the model conceptualisation (step 3). The collection of information is present in almost every step of the modelling process. The following description is based on Sterman (2000) and Forrester (1994).

Figure A1: SD Modelling as an iterative process



Source: Own elaboration based on Sterman (2000, p. 87ff) and Forrester (1994, p.4)

1. Problem description, model purpose and model boundary

The initial identification of a problem followed by the definition of a research/model purpose and the determination of the model boundary is crucial for the success of an SD application (Sterman, 2000).

In SD, the modelling process starts by defining a problem or – in SD terms – the research or policy **problem**, which is described as ‘undesirable behaviour’ that needs to be corrected (Forrester, 1992; Sterman, 2000). SD modellers describe their problem quantitatively through a ‘reference mode’,

which shows the development of the problem¹³ over time (e.g. graphically by data points) and thus represents the past behaviour of the selected variable over a certain time horizon (Sterman, 2000). Moreover, the problem description also includes the specification of the time horizon of the simulation. Thereby, SD emphasises the importance of choosing a time horizon that is sufficiently long to avoid the risk of neglecting important dynamics (e.g. due to the time delays between cause and effects relationships), which could influence the choice of policies and hence ultimately affect the (future) state of the real system (Sterman, 2000, p. 94).

The formulation of the (research) problem determines the purpose of a model, namely 1) to understand the causes of the problematic behaviour (problem) and 2) to provide information about the 'leverage points' for efficient policy implementation. According to SD, every model needs a clear purpose (Sterman, 2000).

Based on this, the selection of the model boundary is determined by the research problem and the model purpose, which provides criteria that should be included or excluded from a model (Sterman, 2000, p.85ff). As explained before, the model should include the main mechanisms required to understand or explain the research problem – and not more than this. That is, a modeller should seek to build a model that represents the system relevant for its purpose, but not enlarge the model if not required for its purpose.

2. Information collection

The initial problem formulation is followed by a more extensive information collection period. This involves reading about the problem, consulting experts from the field and collecting data (e.g. statistics) (Forrester, 1980; 1992). This process enables the modeller to better understand the problem context and either formulate an initial dynamic hypothesis (see point 3) or re-state the initial research question (see point 1). However, as explained in the introductory part of this section, the information collection happens during the entire modelling building process (e.g. Sterman, 2000). This information collection should also include to define sources for appropriate values of parameters (e.g. from econometric studies or other models).

3. Dynamic hypothesis and model conceptualisation

After an initial phase of information collection, SD practitioners formulate a dynamic hypothesis, namely a theory that explains why the reference mode (= research problem) emerged. Thereby, it is important that this theory includes an explanation about the structure and feedback effects (dynamics) that causes the reference modes, which is why it is called a *dynamic* hypothesis. Subsequently, the SD model constructed (see point 4, model validation) is used to test the dynamic hypothesis formulated.

Subsequently – or during the formulation of a dynamic hypothesis – SD modellers formulate a conceptual model (e.g. by applying a CLD or SFD, see section 3.2.6). Conceptual maps are a visual representation of the underlying structure (namely the linkages between the variables of the relevant system) of the research problem and dynamic hypothesis (e.g. Sterman, 2000; Randers, 1980).

¹³ As will be seen later on, system dynamics defines a problem always in stock variables and not as flows. For example, the accumulation of greenhouse gas emissions over time is the problem, and the annual emissions over time simply determine this accumulation, but are not the actual problem.

4. Model construction and visualisation

Through the application of computer software (e.g. Vensim, iThink), the actual model-building process involves ‘translating’ the conceptional model into mathematical differential equations. Thereby, SD software represents the model mathematically through equations and visually through stocks (levels), flows (rates) and variables (these concepts are explained in the next section in more detail).

5. Model validation

In SD, model validation involves both quantitative and qualitative model tests that validate both the model structure and the simulated behaviour (see e.g. Barlas, 1961, 1989 or Senge & Forrester, 1980 for an overview of such tests). For example, they involve testing the model under extreme conditions and verifying whether the simulated behaviour is reasonable, or consulting experts on the topic in order to test the model structure. These tests will be shown in the next appendix section.

6. Policy analysis, formulation and evaluation

Based on the understanding of the underlying structure of the system through model analysis, SD modellers identify ‘leverage points’ for policy interventions. As explained before, those ‘leverage points’ for policy intervention strengthen/weaken desirable/undesirable dynamics and therefore improve the overall state of the system. Moreover, in SD policy design and recommendations include – in contrast to traditional policy analysis – creating entirely new strategies, structures and decision rules. Accordingly, they extend beyond changing certain parameter values (e.g. tax rates) (Stermann, 2000). After the initial formulation of different policy strategies, those strategies are implemented in the simulation models and tested and evaluated through simulation. If necessary, new strategies are formulated, implemented, tested and evaluated again. Based on those findings, final policy recommendations are formulated.

2. Vensim calibration tool for (fine-tuned) model calibration

The simulation software used for GIBM (i.e. Vensim) enables using an optimisation tool. That is, Powell’s ‘hill climbing’ algorithm is built into Vensim and can be used to perform the parametric optimisation. Thereby, optimisation can be used in two ways, namely model calibration and policy optimisation. Model calibration is relevant in this case and here the Vensim optimisation tool adjusts model parameters (constants) so that the simulated model behaviour best fits time series data. In more detail, the model user first specifies which model variables should be matched to data series. Subsequently, the model user specifies the model parameters that should be adjusted and within which range they should be varied. This range is generally selected according to information found in current research literature (Janamanchi, & Burns, 2013).

Powell’s ‘hill climbing’ algorithm is an iterative algorithm that starts with an arbitrary solution to a problem and it subsequently attempts to find a better solution (i.e. reduce the distance between the simulated variable value and time series data) by making an incremental change to the solution. If the change produces a better solution, another incremental change is made in the same direction, which repeats until no further improvements can be found. Put differently, the Vensim optimisation tool compares the model behaviour of the pre-selected model variables with time series data and aims to optimise the pay-off by minimising the distance between the data and the generated model values

for these variables and changing the selected parameter values within the specified range. A limitation of this mathematical optimisation technique is that while it finds optimal solutions for convex problems, for other problems it might find only local optima that are not necessarily the best possible solution (the global optimum) out of all possible solutions (the search space). The Vensim optimisation tool is part of the so-called Full-Information Maximum Likelihood via Optimal Filtering (FIMLOF) process (see Peterson, 1975; 1980 for information on the mathematics of this technique).

Methodologically, it is important to underline that in SD, model calibration – as introduced above – should only be applied *once a model is structurally complete and simulates properly*. Model calibration should not be used when the model structure is not yet clear and to force a model to match empirical data. However, it can be used to fine-tune the model and adjust parameter values within plausible ranges.

In line with the above, the Vensim optimisation tool has been applied for parameter optimisation of GIBM as follows. First, values or the range of possible values for most elasticities or other exogenous parameters have been taken from the research literature, which is indicated in the model documentation (see supplementary material of Hafner et al., 2021). Subsequently, these values have been optimised within a plausible range to adjust the simulated model behaviour to the past data. This second step is adequate as the indications in the research literature frequently refer to other countries than the UK and while these countries are comparable to the UK, these parameter values may nevertheless vary to some extent. In addition, the adjustment is also justified as sometimes the time horizon considered differs from the one considered in this model exercise (Stermann, 2000). Indeed, research studies on empirical relationships in the past were used, as there are by definition no empirical estimations on relationships from now on onwards.

Appendix B - Representation of the green finance gap and interest rates in the Green Investment Barrier Model (GIBM)

Equation for planned renewable energy capacity additions:

(1) *Planned renewable energy capacity additions = IF THEN ELSE (Activate green finance constraint=1, min (RES market share new installations[Renewable energy] * Total additional generation required twh*MW into TWh coefficient RES[Renewable energy], Annual financial RES constraint[Renewable energy]), RES market share new installations [Renewable energy] * Total additional generation required twh * MW into TWh coefficient RES[Renewable energy])*

The green finance gap is formalised by the following equation:

(2) *Planned renewable energy capacity additions = IF THEN ELSE (Activate green finance constraint=1, min (RES marketshare new installations[Renewable energy] * Total additional generation required twh*MW into TWh coefficient RES[Renewable energy], Annual financial RES constraint[Renewable energy]), RES marketshare new installations [Renewable energy] * Total additional generation required twh * MW into TWh coefficient RES[Renewable energy])*

The difference between the desired and planned renewable capacity additions are covered by energy imports from abroad.

Furthermore, the indicated market or average interest rates are given by the following equation:

$$(3) \text{ Indicated market interest rate} = \text{Init market interest rate} * \text{Effect of key policy rate} * \text{Effect of profit-share on interest rates} * \text{Effect of the exchange rate on interest rates} * \text{Effect of productivity on interest rates},$$

Where the initial market rate is given by data in 2016 (see Hafner et al.) and the effects are given by the following equations:

$$(4) \text{ Effect of key policy rate} = \text{Relative key policy rate}^{\text{Elasticity key policy rate on market interest rate}}$$

$$(5) \text{ Effect of profit-share on interest rates} = \text{Relative profit share}^{\text{Elasticity of profit on interest rates}}$$

$$(6) \text{ Effect of the exchange rate on interest rates} = \text{Relative exchange rate}^{\text{Elasticity of exchange rates on interest rates}}$$

$$(7) \text{ Effect of productivity on market interest rates} = \text{Relative TFP}^{\text{Elasticity of productivity on market interest rates}}$$

The following table provides an overview of the chosen elasticity and other parameter values of constants (e.g. adjustment times) in interest rate sector.

Table A1: Overview of the parameter values in the interest rate sector

Parameter name	Values indicated in the literature	Range used for optimisation	Applied value
AT of market interest rate	No specific values based on empirical analysis found	0.25 - 5	3.13013
Elasticity key policy rate on market interest rate	No specific values based on empirical analysis found	0 - 1	1
Elasticity of exchange rates on interest rates	No specific values based on empirical analysis found	(-1) - 0	-0.039
Elasticity of productivity on interest rates	No specific values based on empirical analysis found	0.1 – 1.2	1.2

Appendix C - Key macroeconomic dynamics of GIBM

1. Key dynamics induced by the introduction of the low-carbon energy transition scenario

The tested low-carbon energy scenarios require a different amount of capital investments into energy infrastructure than under the base-run simulation due to the differences in applied electricity production technologies and the amount of electricity produced. Capital investments are a component of aggregate demand and therefore differences in the amount of capital investments change the amount of aggregate demand. Furthermore, the installation of renewable electricity infrastructure generally requires more labour inputs than high-carbon infrastructure (Wei, 2010) and therefore the tested low-carbon energy scenario leads to a higher amount of direct employment in the electricity sector and consequently of aggregate employment as compared to the base-run. Finally, the electricity system costs, including operational and capital costs and investments into grid and storage infrastructure, vary between the tested low-carbon energy scenario and the base-run. Electricity system costs in turn influence subsequently domestic electricity prices, which then impact the average price level.

Given the above, the following three variables in the macroeconomy are influenced *directly* by the tested low-carbon energy scenario:

(1) Capital investments (i.e. electricity capacity and grid) investments

- Directly influence aggregate demand

(2) Direct employment

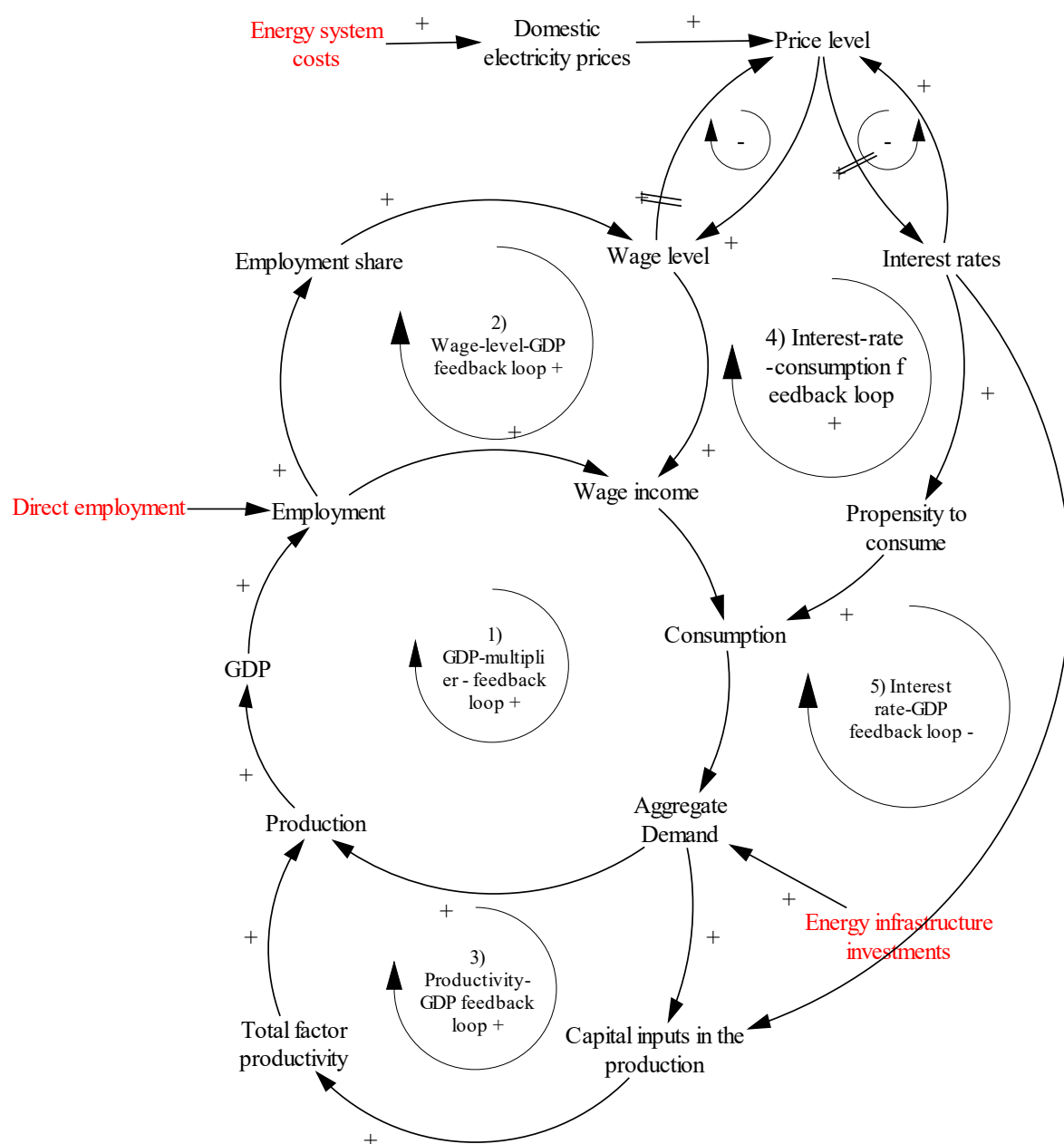
- Directly influence desired employment

(3) Electricity system costs

- Directly influence domestic electricity prices

In the following, it is described how these directly triggered macroeconomic variables induce various macroeconomic dynamics in GIBM, whereby Figure A2 presents a visual overview thereof, using a Causal-Loop-Diagram (CLD) that is often applied in system dynamics (e.g. Sterman, 2000). Regarding figure 1, the signs close to the arrows indicate whether the following variables change in the same (+) or opposite direction (-). For example, a plus sign between variable x and y means that if x decreased, y would also decrease. By contrast, a minus sign between variables implies that if variable x decreased, y would increase. Two lines on the arrow between two variables indicate that the impact happens with a delay. A positive sign in the loop description situated in the middle of a feedback loop indicates that it is a reinforcing loop (i.e. the initial impact is reinforced via this loop) and a negative sign indicates that it is a balancing loop (i.e. the initial impact is weakened/balanced via the loop).

Finally, it is noted that for simplification the macroeconomic dynamics triggered by the tested low-carbon energy scenario are explained in the following based on the assumption that the direct impacts (1) to (3) are positive/increase subsequent to the scenario introduction; in the opposite case these dynamics would naturally occur in the opposite direction, applying the same logic.



Note: variables in red are impacted directly by the introduced policy scenarios.

With regard to the first direct impact of a low-carbon transition scenario, the figure above shows that higher capital investments into electricity capacity or grid and storage infrastructure lead to higher aggregate demand, production, GDP and therefore employment, which in turn implies higher disposable income, consumption, aggregate demand, etc., leading to reinforcing multiplier effects named 1) *GDP multiplier feedback loop +*. Subsequently, this *GDP multiplier feedback loop +* triggers a number of further – mostly reinforcing – feedback loops, including the following. First, increases in GDP lead to higher employment: as production increases, more labour inputs are required to produce it. An increase in employment in turn leads to a higher wage level, which leads to higher consumption, thus increasing GDP and adding to the previously described feedback loop. This feedback loop is labelled as 2) *Employment feedback loop +*. Moreover, the increase in investments has a positive

impact on the total factor productivity, which is determined by the invested R&D capital (assumed to always be one-third of total capital). In particular, the increase in aggregate demand caused by the increase in capital investment leads to an increased use of all production inputs – including capital – thus leading to an increased productivity level. An increase in productivity leads first to an increased production given the used production inputs, and subsequently to higher GDP, employment, disposable income and aggregate demand. As the production inputs required to produce the desired amount are only lowered after a delay, the productivity dynamics further reinforce the previously-introduced multiplier effects (this feedback loop is named as 3) *Productivity feedback loop*).

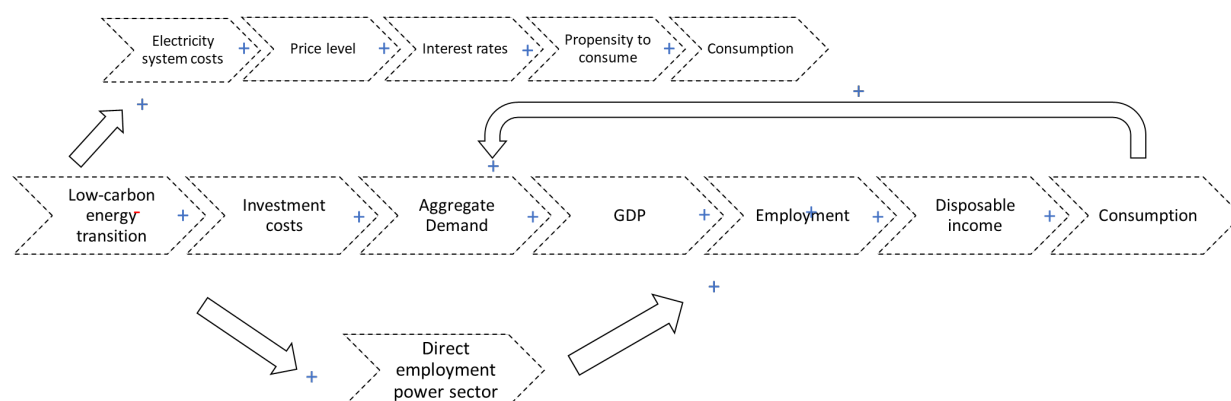
Regarding the second direct impact via the low-carbon scenario, the installation of RES infrastructure generally requires more labour inputs than high-carbon infrastructure (see Wei, 2010) and therefore the installation of renewable electricity infrastructure creates more additional direct employment in the electricity sector as compared to the building-up of high-carbon electricity capacity. The higher labour inputs in the electricity sector add to overall employment levels, and thus strengthen the feedback loops described before. Thereby, it is important to note that the labour costs for the RES infrastructure installations are already included in the LCOE of RES and therefore no additional labour costs need to be considered.

Finally, regarding the third direct impact due to the implementation of a low-carbon scenario, higher electricity system costs lead to higher domestic electricity prices, a higher price level and therefore higher interest rates and wage levels (see figure above). Higher interest rates lead to a higher propensity to consume, which leads to higher consumption and higher GDP, forming the reinforcing loop termed 4) *interest rate consumption feedback loop* +. On the other hand, higher interest rates lead to less capital inputs and thus to less productivity increases than otherwise, thus forming a balancing loop labelled as 5) *Interest rate capital input feedback loop*.

Besides these main mechanisms, some smaller reinforcing loops are relevant here. In particular, an increase in the wage level leads to an increased price level, which subsequently leads to a higher wage level with a delay, which causes a higher price level, thus forming a reinforcing feedback loop. The same holds true for the market interest rates and the price levels. These additional loops reinforce the previously described reinforcing feedback loops further (see Figure A3).

The impacts of the low-carbon energy transition scenario are summarised as well in the figure below. Here, the minus and plus signs refer to the impacts of the policy on the variable. So, for example, if sign of an arrow before the next variable is positive (negative), it means that the impact of the policy on this particular variable is positive (negative) as well.

Figure A3: Overview on key impacts of a low-carbon energy transition policy scenario



2. Key dynamics induced by the closing the green finance gap scenario (GFGS)

In the following, key macroeconomic mechanisms triggered by the implementation of a systems policy are introduced. Figure A4 displays these dynamics.

The introduction of a systems policy lowers (i) average interest rates and (ii) interest rate spreads for renewable electricity technology investment, and (iii) if applicable closes the green finance gap. Thus, the implementation of a systems policy leads to the following direct impacts (see also figure below):

(1) Lower average market interest rates

- This leads to higher capital investments in the production process

(2) Lower interest rates spread for renewable electricity capital investments

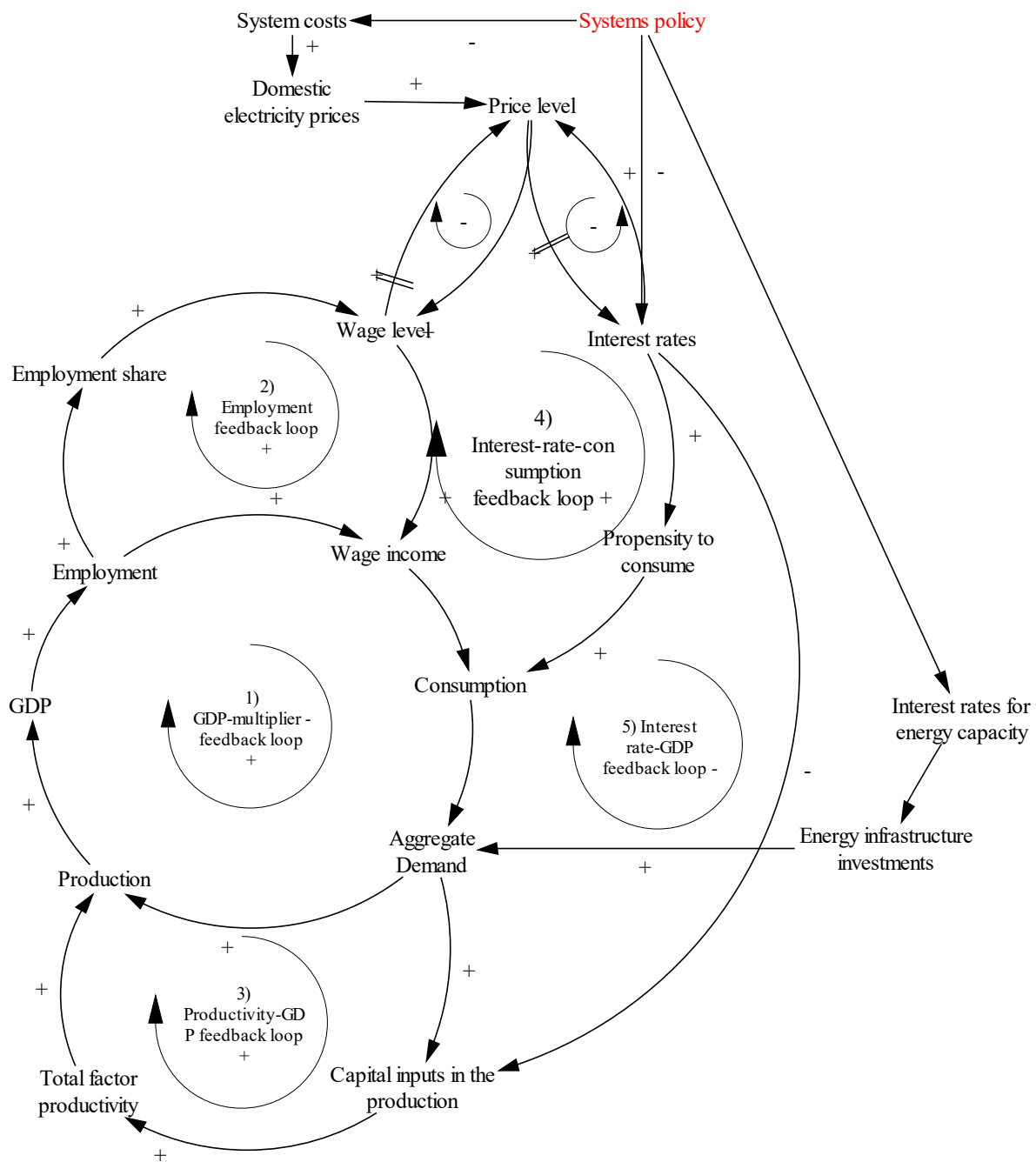
- This leads to lower electricity system costs and electricity price level

(3) Availability of sufficient green finance

- This leads to higher shares of renewable electricity installations, leading to the key macroeconomic dynamics introduced in the previous section.

The macroeconomic dynamics induced by the above-introduced direct impacts are summarized in the following. A decrease in the average market interest rates and decrease in electricity prices triggers the same macroeconomics dynamics as introduced before (see feedback loops 1) to 4) in Figure A4). Second, the availability of green finance leads to a higher share of renewables in the UK electricity system and thus to the same macroeconomic dynamics as introduced in the first section for the ow-carbon energy scenario.

793 **Figure A4: Economic feedback loops triggered by the introduction of a systems policy**



794

795 As shown in the results section in the main part of this article, when a finance systems policy is added
 796 to the tested low-carbon energy scenario it has no impact on accumulated emissions but decreases
 797 emissions when added to the base-run. Moreover, introducing a finance systems policy on top of the
 798 low-carbon energy scenario or base-run leads to an increase in electricity system costs, GDP and a
 799 decrease in unemployment. This explained in more detail in the following.

800 First, when a finance system policy is introduced emissions remain at the same level in case of a low-
 801 carbon energy transition as any new installations in these scenarios are always carbon-neutral, and
 802 thus emissions will not further increase when electricity production is increased. Under the base-run
 803 plus finance systems policy, emissions decrease because of the higher share of low-carbon electricity

sources in the electricity production. This is because renewable electricity technologies become more cost-efficient due to the lower mark-up on the interest rates for renewable electricity technologies.

Second, the introduction of a finance systems policy leads to a higher GDP. This mainly is due to the lower average interest rate, leading to higher capital inputs in the macroeconomy, and therefore to higher productivity while at the same time also triggering the reinforcing feedback loop (i.e. 1 to 3). However, these positive effects caused by these multiple reinforcing feedback loops are counteracted by the impact of the lower prices and reinforcing feedback loops working towards the opposite direction to some extent (see Figure A5). In addition, lower average interest rates also lead to a lower propensity to consume, which then lowers consumption, aggregate demand and therefore GDP. Nonetheless, overall, the reinforcing feedback loop induced due to higher capital inputs and higher productivity overweighs the reinforcing mechanisms working towards the opposite direction. This is why, overall, there is a positive impact due to a finance system's policy on GDP.

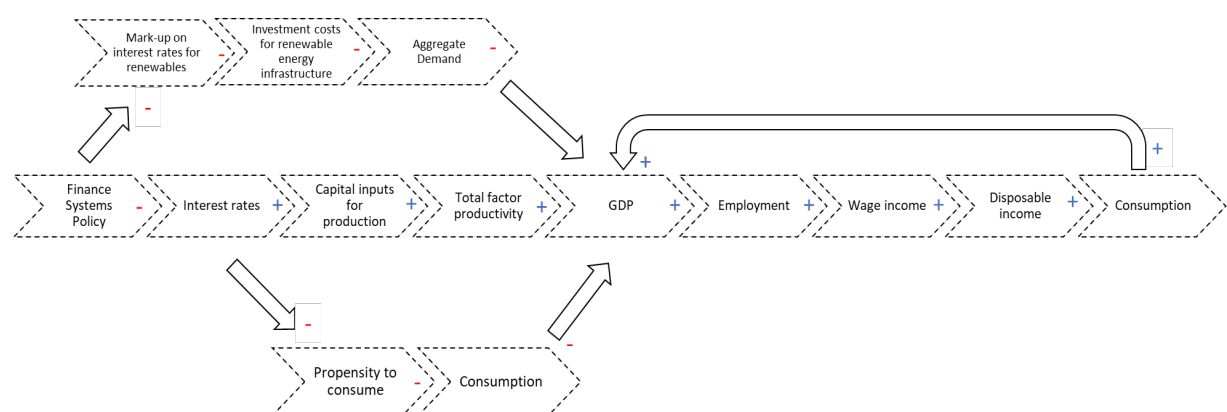
Importantly, it needs to be underlined that the overall impact of lower interest rates of a systems policy is positive on GDP because the impact of the finance systems policy on the average interest rate is permanent. By contrast, the impact of lower prices on interest rates is a one-off impact that is subsequently counteracted by the various reinforcing feedback loops driving the system in the opposite direction.

Third, the impact of a systems policy on unemployment when added to any policy is negative, i.e. it leads to decrease in unemployment compared with the situation without a systems policy. This is due to the higher GDP caused by the introduction of a systems policy, which subsequently leads to higher employment level and lower unemployment levels.

Finally, the electricity system costs increase when a finance systems policy is introduced. This is because of the caused increase in GDP and the therefore higher required electricity production. However, the electricity system costs per unit of produced electricity decrease (due to the lower financing costs of electricity capacity).

The impacts of the finance systems policy are summarised as well in the figure below. Here, the minus and plus signs refer to the impacts of the policy on the variable. So, for example, if sign of an arrow before the next variable is positive (negative), it means that the impact of the policy on this particular variable is positive (negative) as well.

Figure A5: Overview on key impacts of a finance systems policy



Appendix D - Sensitivity testing

1. Parameter changes in the electricity sector

In this appendix section, the results of two extreme scenarios involving changes in parameter values in the electricity supply sector are presented. The table below provides an overview of the amended variable values for each of the two tested extreme scenarios. Scenario 0 is the default case and related results are reported in the result section of the main body of this article.

Table A2: Overview of parameter values for the different scenarios

	Scenario 0	Scenario high (SH)	Scenario low (SL)
Learning rates (concern the <i>regional</i> part of the RES construction cost)	Biomass: 0.074 Hydro: -0.02 Onshore wind: -0.105 Offshore wind: -0.136 Solar: -0.269 Other thermal: -0.074 Other renewable: - 0.06	1.25 times base-run learning rates	0.75 times base-run learning rates
Cost reduction potential for Opex (lowest possible value of Opex) (£/MW)	Coal: 179015 Gas: 500008	Coal: 232719 Gas: 64010	Coal: 131272 Gas: 31755
Construction costs international lowest value (£/MW)	Biomass: 664080 Hydro: no cost reduction potential Marine: 3083000 Onshore wind: 571710 Offshore wind: 1058200 Solar: 337330 Other thermal: 3223500 Other renewable: 3545850	Biomass: 557040 Hydro: no cost reduction potential Marine: 1481000 Onshore wind: 339150 Offshore wind: 857450 Solar: 275720 Other thermal: 1362000 Other renewable: 1498200	Biomass: 690960 Hydro: no cost reduction potential Marine: 4652000 Onshore wind: 639030 Offshore wind: 1304050 Solar: 426390 Other thermal: 3453500 Other renewable: 3798850
Discount rates	0.075	0.07	0.08
Emission tax-rate (highest value in 2050) (£/tonne)	42	220	38

Note: The ‘scenario – high’ represents the case that all cost components ‘are to the benefit’ of the capacity accumulation of renewables (e.g. high learning rates, high carbon taxes), and the ‘scenario – low’ assumes that all variables are to the dis-benefit of renewables (e.g. low learning rates, low carbon taxes).

Similar as in the result section, we present the simulation results of our sensitivity tests for the following key policy indicators (in accumulated terms):

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

1.1. Scenario high

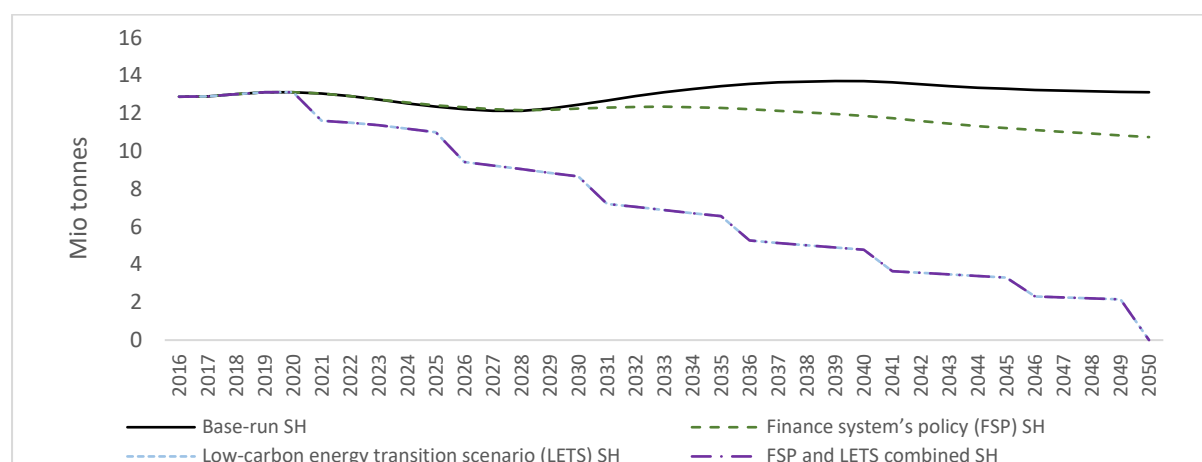
The table below shows the results of the simulated energy policy scenarios of scenario high in terms of the chosen policy indicators *as percentages against the base-run simulation results* of the same policy indicator under scenario high (always referring to accumulated numbers).

Table A3: 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 2016 to 2050 in comparison to the base-run.

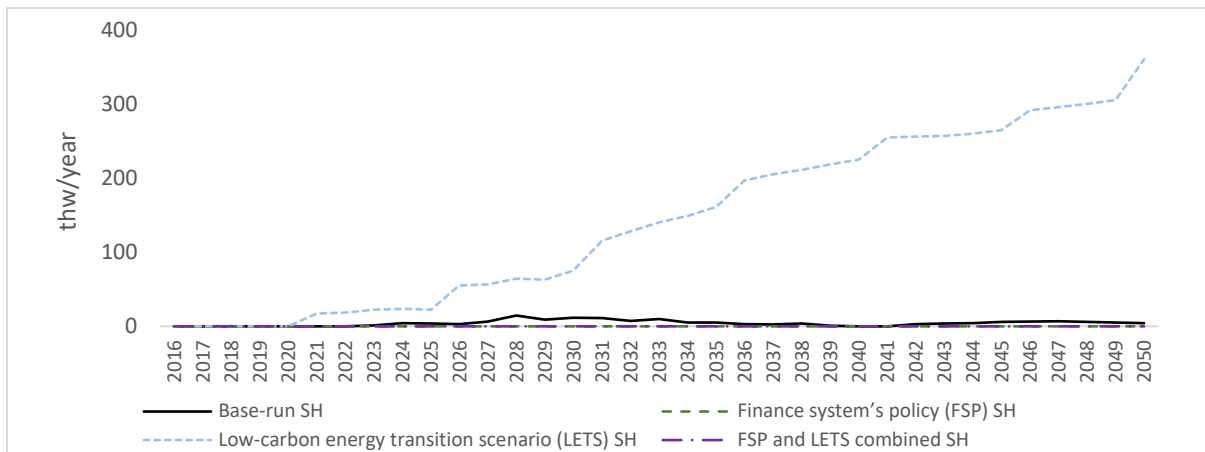
	Emissions (%)	GDP (%)	Unemployment (%)	Direct employment (%)	System costs (%)
Green Finance Gap (GFGS)	-5.94	2.93	-1.46	23.55	-5.44
Low-carbon energy transition scenario (LETS)	-41.58	0.50	0.23	-5.41	12.48
GFGS and LETS combined	-41.58	3.38	-1.39	45.53	-0.12

Importantly, in aggregated terms, the different policies rank the same as under scenario 0. Moreover, the results do differ by more than by 5% and therefore the results are not described here in more detail. The figures below show the development from 2016 to 2050 of the considered key indicators under scenario high. Moreover, the figures below shows the development from 2016 to 2050 of the considered key indicators under scenario high.

Figure A6: Annual emissions from the electricity sector

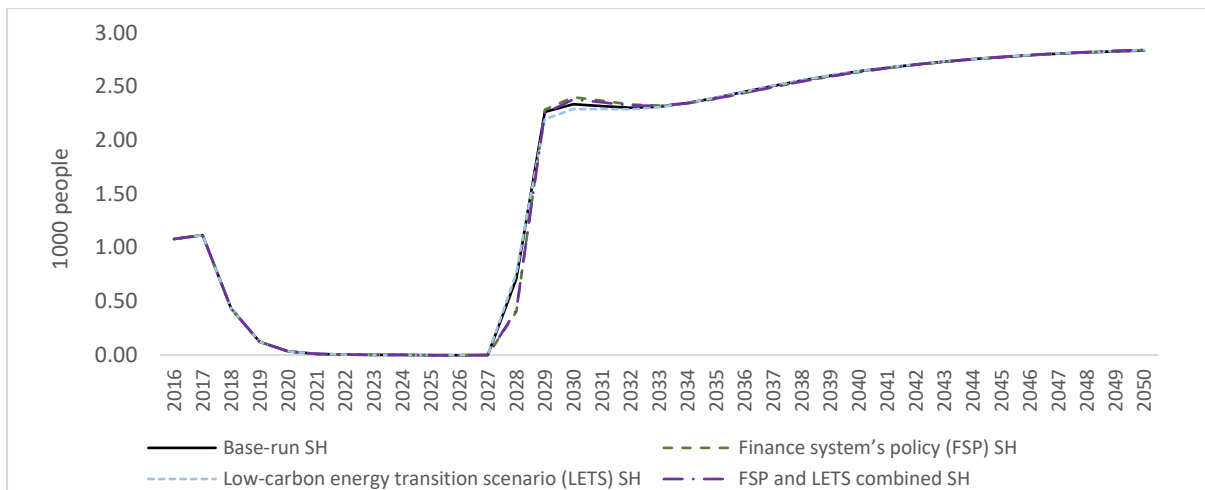


869 **Figure A7: Electricity imports due to the green finance gap**



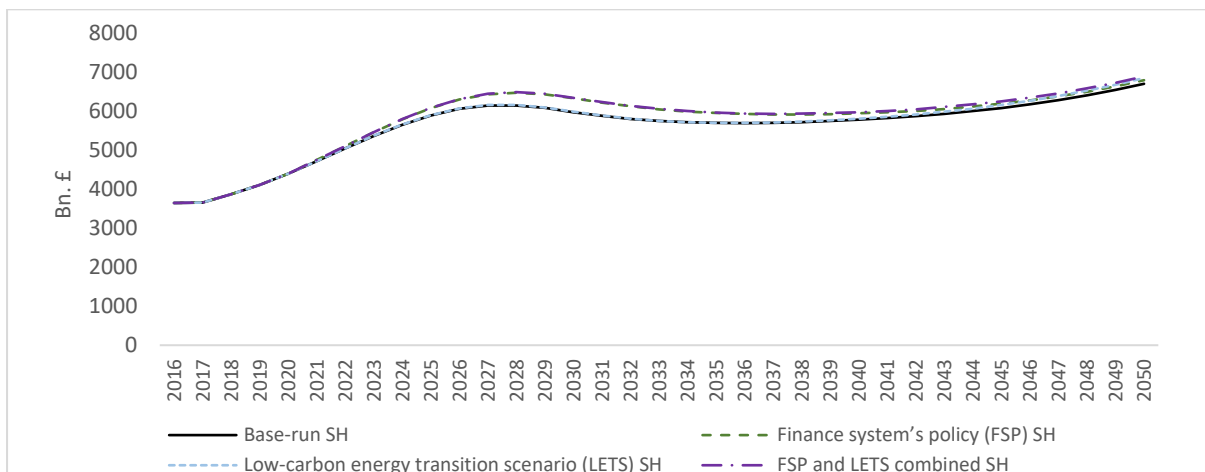
870

871 **Figure A8: Annual unemployment**



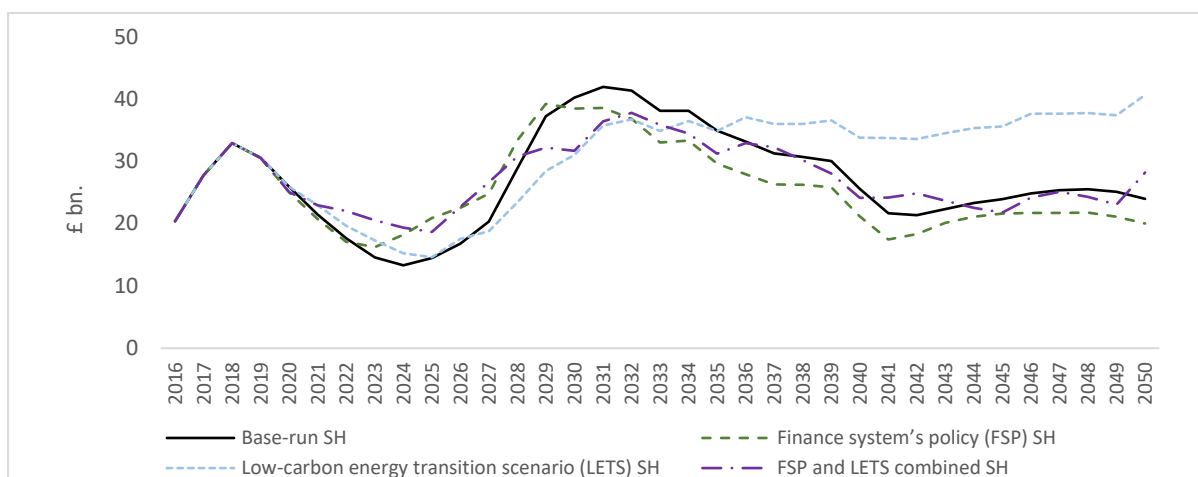
872

873 **Figure A9: Annual GDP (in 2016 prices)**



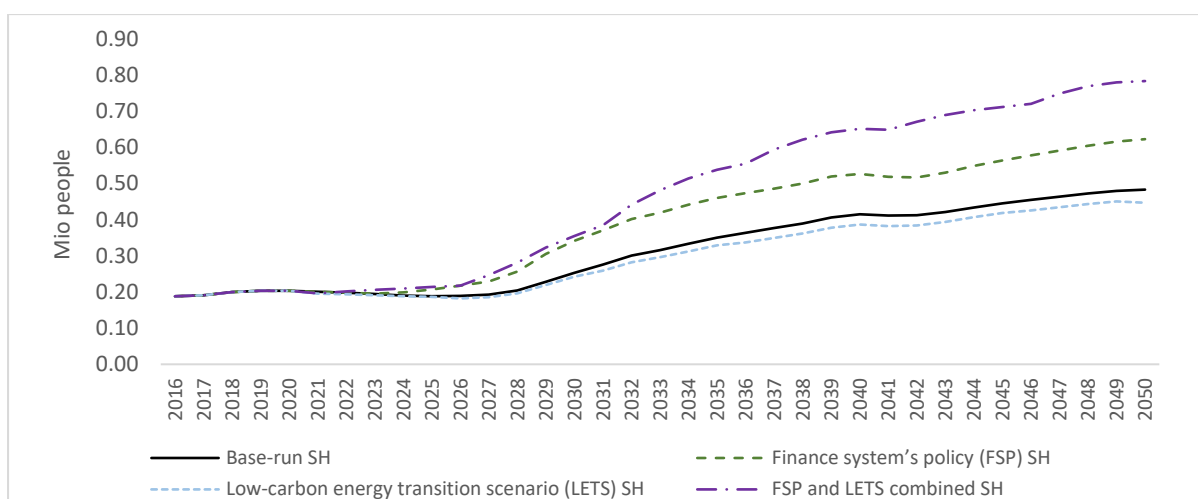
874

875 **Figure A10: Annual electricity system costs**



876

877 **Figure A11: Annual direct employment**



878

1.2. Scenario low

The table belows the results of the simulated electricity policy scenarios of scenario low in terms of the chosen policy indicators *as percentages against the base-run simulation results* under scenario low of the same policy indicator (always referring to accumulated numbers).

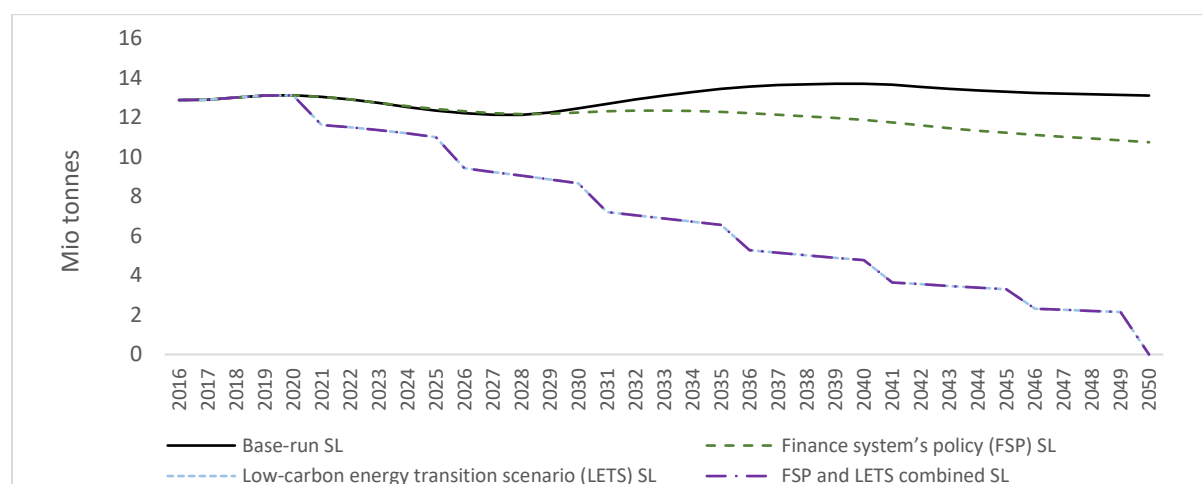
Table A4: Overview on policy outcomes of the tested scenarios - red colour highlights the worst achieved results and the blue colour the best achieved one of all tested low-carbon policy scenarios, impacts on accumulated variables from 2016 to 2050 in comparison to the base-run.

	Emissions (%)	GDP (%)	Unemployment (%)	Direct employment (%)	System costs (%)
Green finance gap (GFGS)	-4.41	3.14	-1.51	14.91	-0.34
Low-carbon energy transition scenario (LETS)	-49.24	0.56	0.19	0.12	17.06
GFGS and LETS combined	-49.24	3.63	-1.44	50.51	9.42

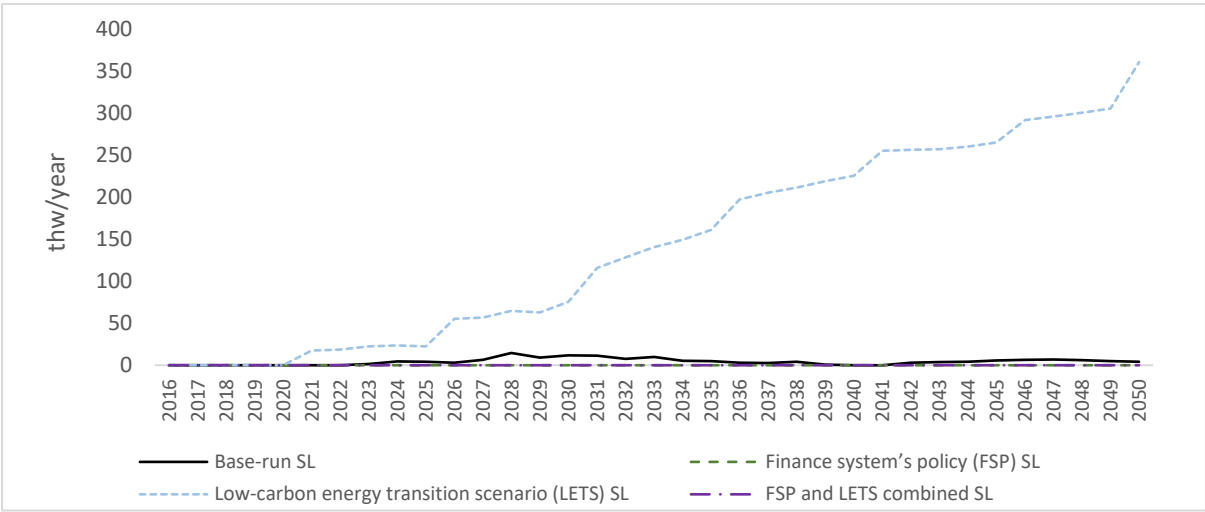
Importantly, in aggregated terms, the different policies rank the same as under scenario 0. Moreover, the results do differ by more than by 10% and therefore the results are not described here in more detail. The figures below show the development from 2016 to 2050 of the considered key indicators under scenario low.

The figures below shows the development from 2016 to 2050 of the considered key indicators under scenario low.

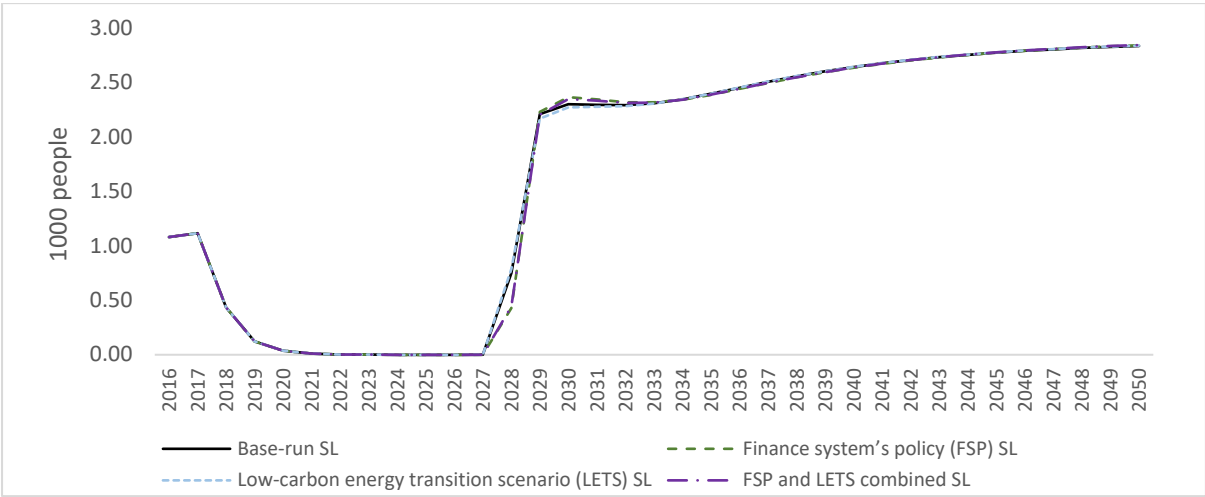
Figure A12: Annual emissions from the electricity sector



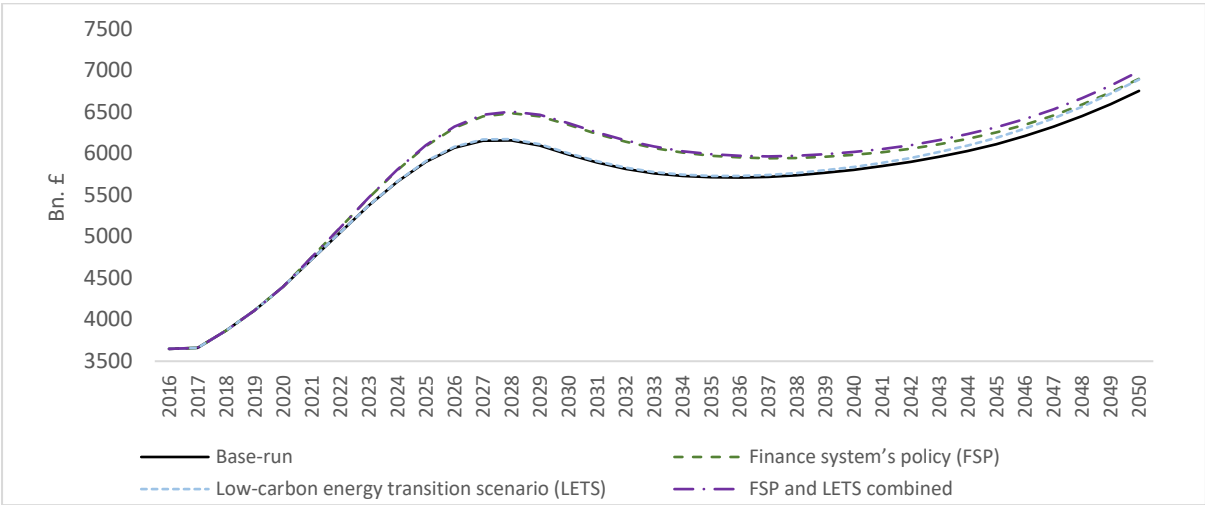
895 **Figure A13: Annual electricity imports due to the green finance gap**



896
897 **Figure A14: Annual unemployment**



898
899 **Figure A15: Annual GDP (in 2016 prices)**



900

Figure A16: Annual electricity costs

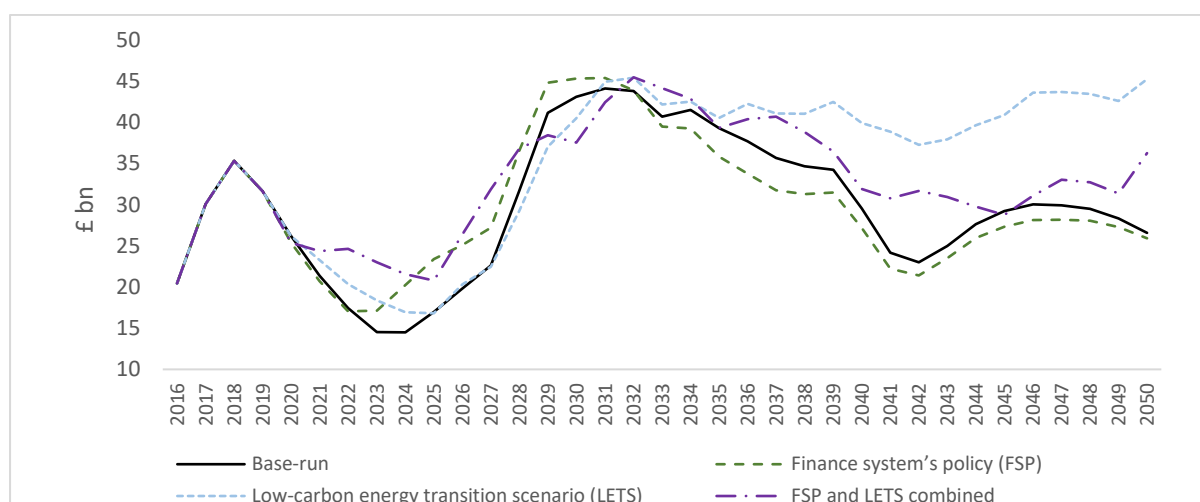
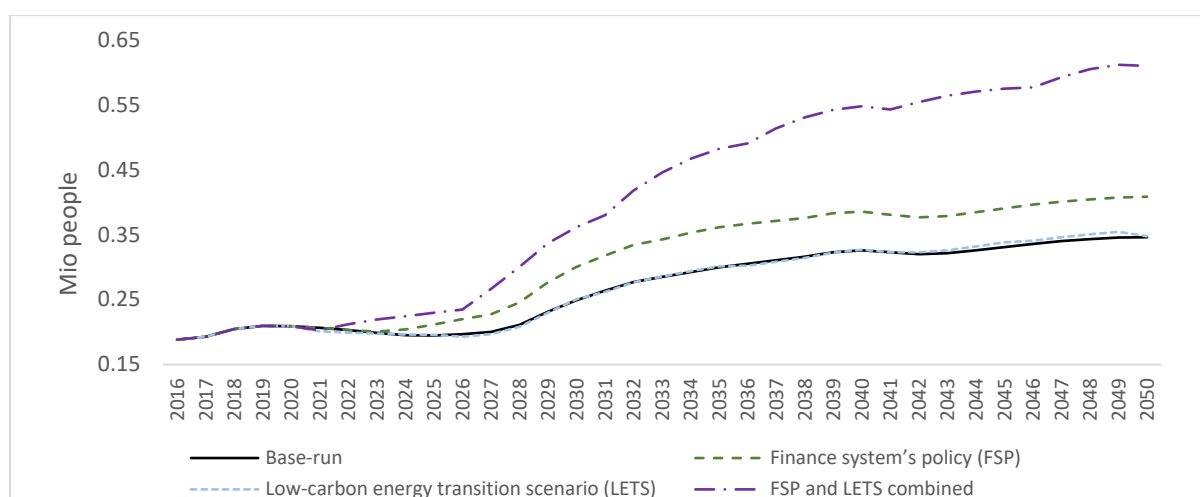


Figure A17: Annual direct employment



2. Parameter changes in the economy

The following sensitivity tests involves changes in key economics parameters. The table below gives an overview on the tested parameter changes.

Table A5: Overview on sensitivity tests concerning the economy in GIBM

Scenarios	Description
No link between interest rates and propensity to consume (PC)	Under scenario 0, the propensity to consume increases when interest rates increase as savers need now to save less to reach their saving targets. Under scenario PC, this link is taken out of the model. This means that the saving rate is independent of the interest rates. This scenario is relevant as the link between the interest rates and the propensity to consume has changed in the current context of zero interest rates.
Doubling of the import prices for electricity (IP)	This scenario assumes a doubling of import prices of electricity compared to scenario 0.

No adjustment in salaries when the average price level (consumer price index) increases and Doubling of the import prices for electricity (IPNW)

This scenario no longer assumes that the wage level changes proportional to changes of the average price level. That is, the wage level is independent of the wage level. In addition, this scenario assumes a doubling of import prices of electricity compared to scenario 0.

2.1. No link between interest rates and propensity to consume

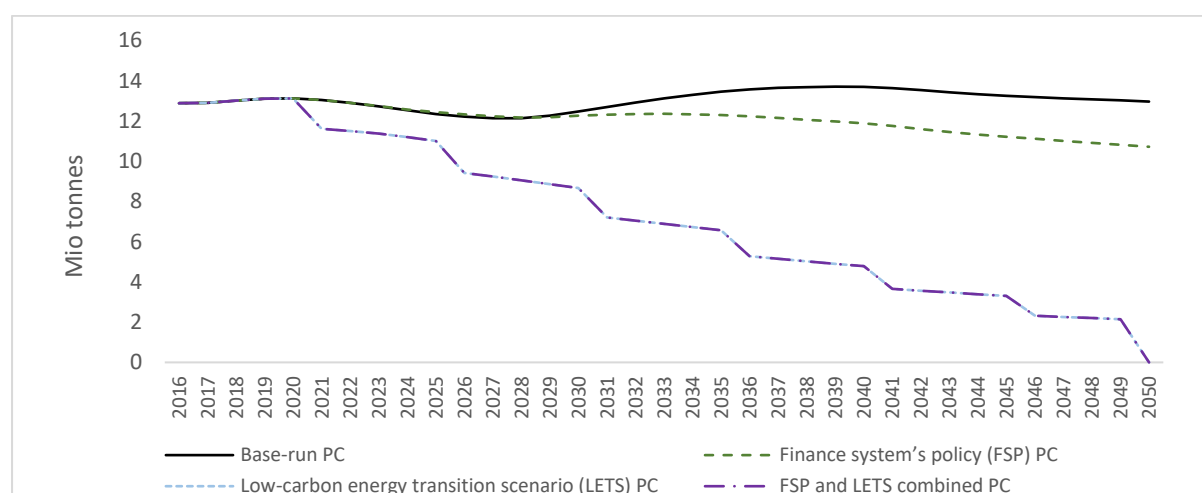
This section presents the results of the simulated policy scenarios under the scenario 'no link between the interest rates and the propensity to consume' ('PC'). The results in the table below are shown in terms of the chosen policy indicators *as percentages against the base-run simulation results* under scenario PS of the same policy indicator (always referring to accumulated numbers).

Table A6: 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 2016 to 2050 in comparison to the base-run.

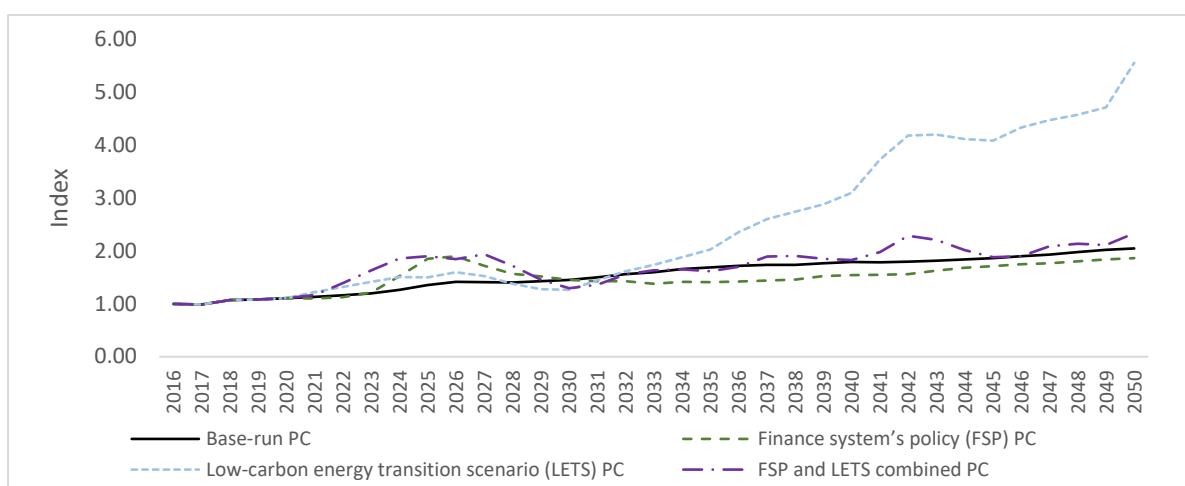
	Emissions (%)	GDP (%)	Unemployment (%)	Direct employment (%)	System costs (%)
Finance system's policy (FSP) PC	-7.01	3.14	-1.48	15.07	-2.30
Low-carbon energy transition scenario (LETS) PC	-44.86	0.49	0.20	-6.81	12.92
FSP and LETS combined PC	-44.86	3.54	-1.41	40.19	4.10

Importantly, in aggregated terms, the different policies rank the same as under scenario 0. Moreover, the results do differ by more than by 1% and therefore the results are not described here in more detail. The figures below show the development from 2016 to 2050 of the considered key indicators under scenario PC.

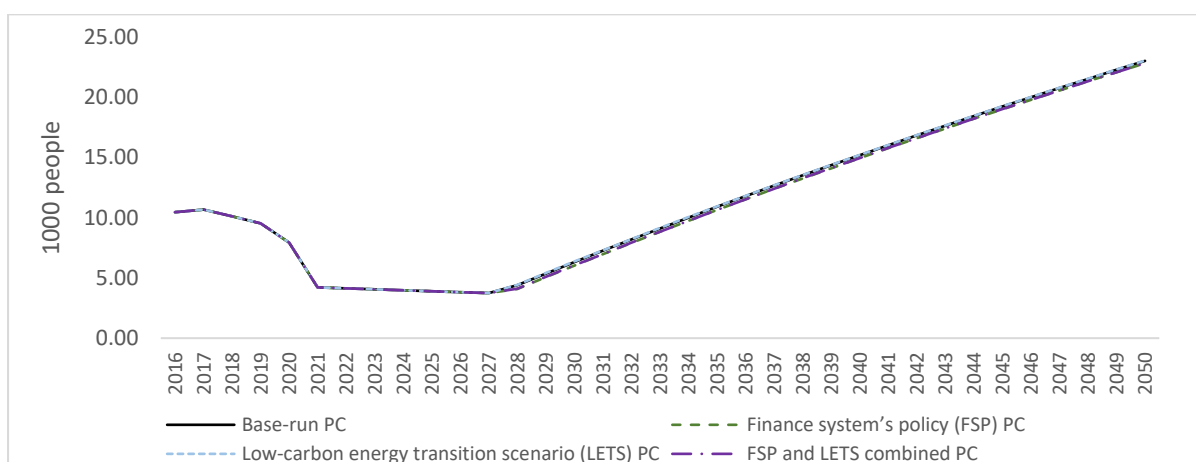
Figure A18: Annual emissions from the electricity sector



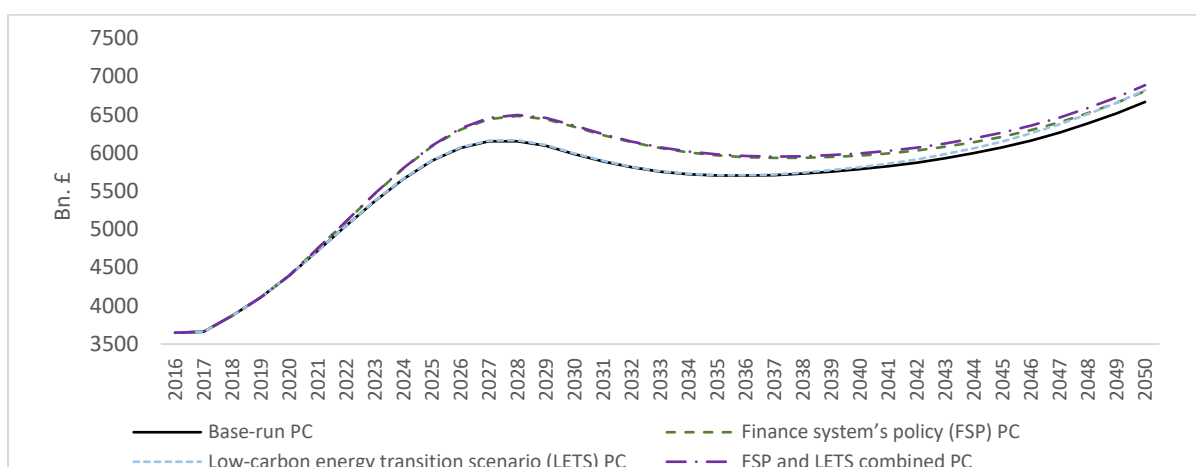
928 **Figure A19: Domestic electricity price**



929
930
931
932 **Figure A20: Annual unemployment**



933
934
935
936 **Figure A21: Annual GDP (in 2016 prices)**



937
938
939

Figure A22: Annual electricity system costs (in 2016 prices)

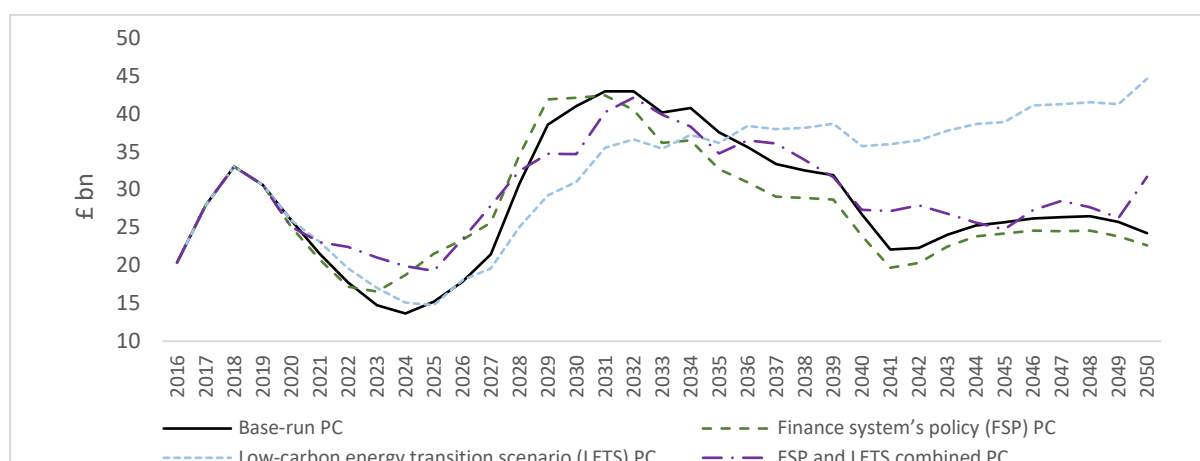
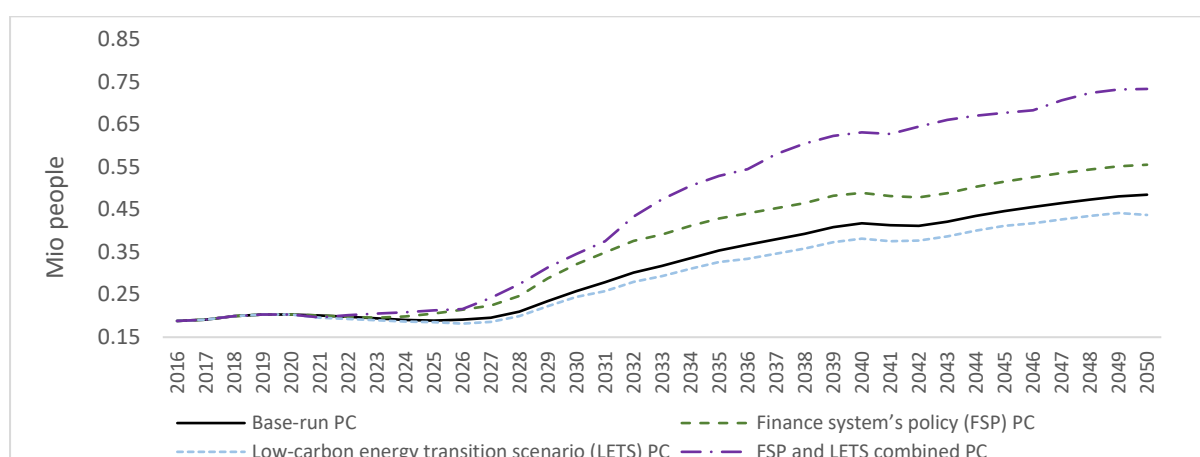


Figure A23: Annual direct employment in the power sector



2.2. High import prices

The table below shows the results of the tested policy scenarios under a scenario that doubles the prices for electricity imports and is called the high import scenario ('IP').

The table below shows the results in terms of the chosen policy indicators *as percentages against the base-run simulation results* under scenario IP of the same policy indicator and in aggregated terms (i.e. summing up the values during the simulation period).

Table A7: 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 2016 to 2050 in comparison to the base-run.

	Emissions (%)	GDP (%)	Unemployment (%)	Direct employment (%)	System costs (%)
Finance system's policy (FSP)	-7.14	3.02	-1.50	15.11	-3.81
Low-carbon energy transition scenario (LETs)	-44.93	1.00	0.32	-6.92	52.74

FSP and LETS combined	-44.93	3.43	-1.43	40.14	2.35
-----------------------	--------	------	-------	-------	------

Importantly, in aggregated terms, the different policies rank the same as under scenario 0. Moreover, the results do not differ by more than 1% at most, and therefore the results are not described here in more detail. The figures below shows the development from 2016 to 2050 of the considered key indicators under scenario IP.

Figure A24: Annual emissions emitted by the electricity sector

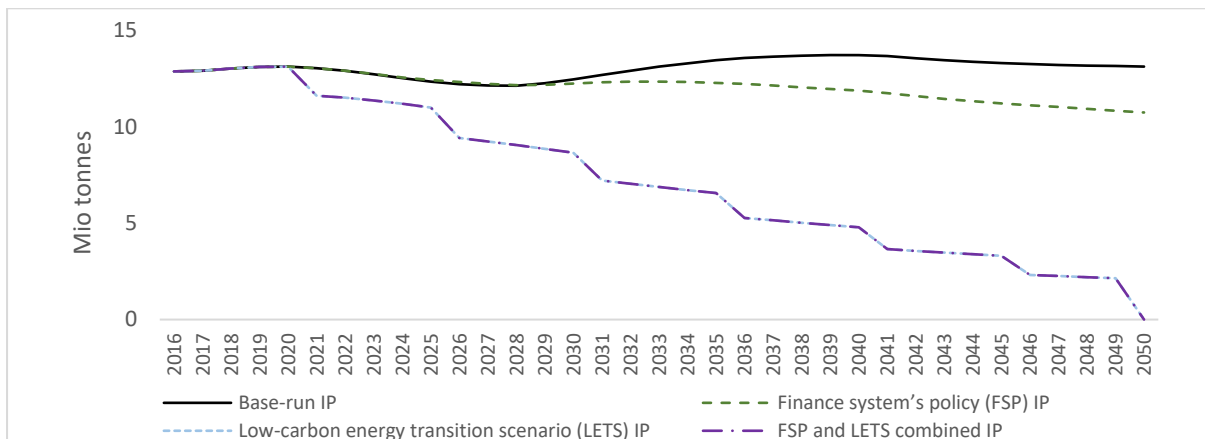
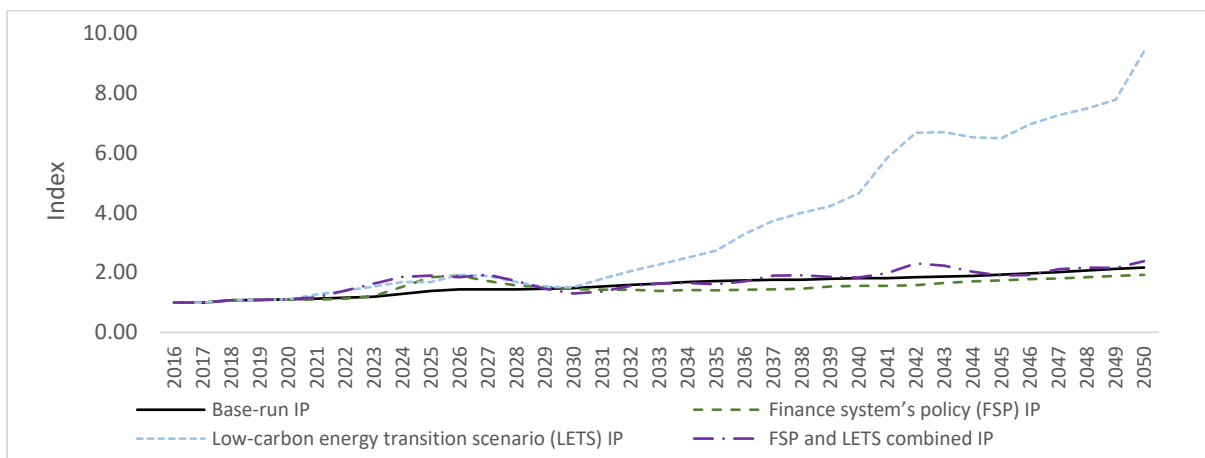
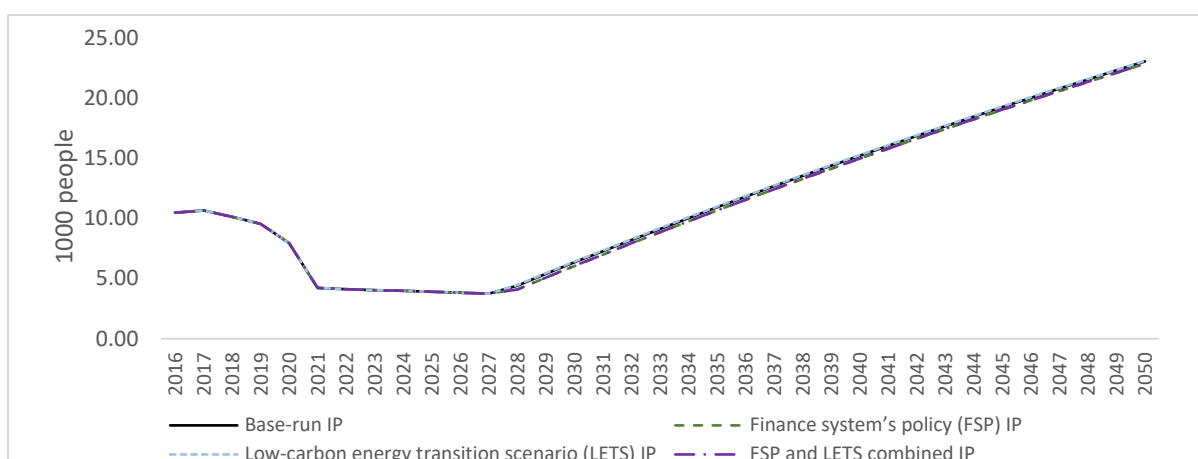


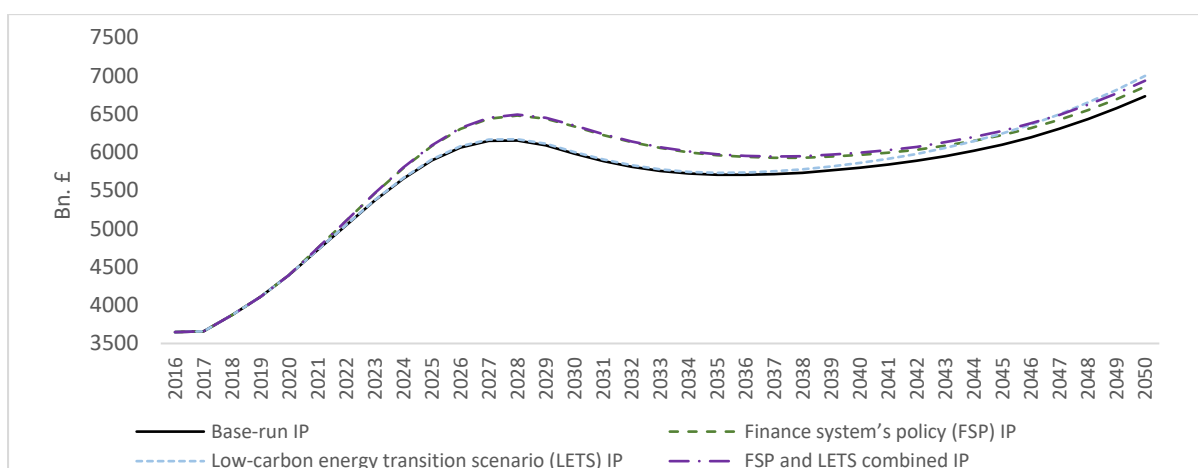
Figure A25: Domestic electricity price



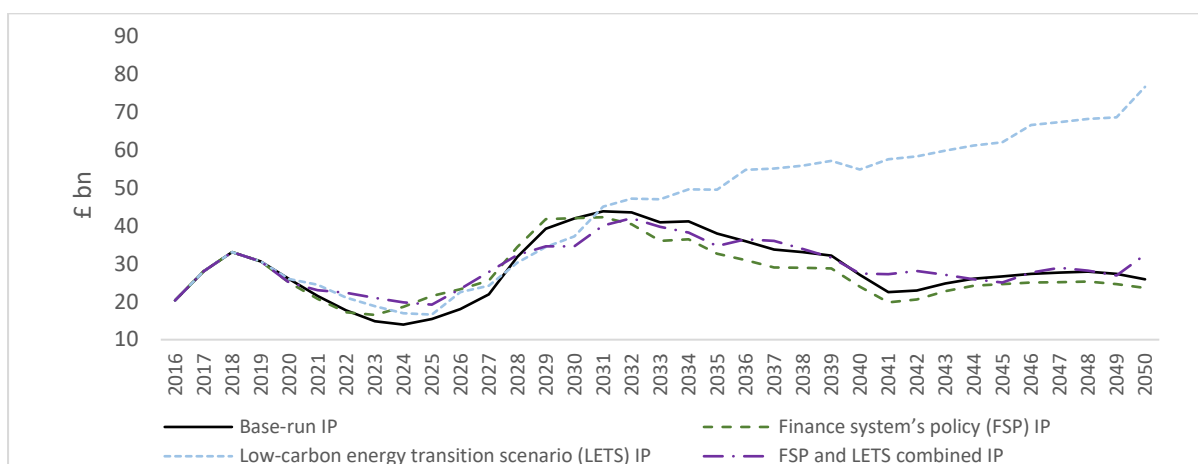
968 **Figure A26: Annual unemployment**



969
970
971 **Figure A27: Annual GDP (in 2016 prices)**

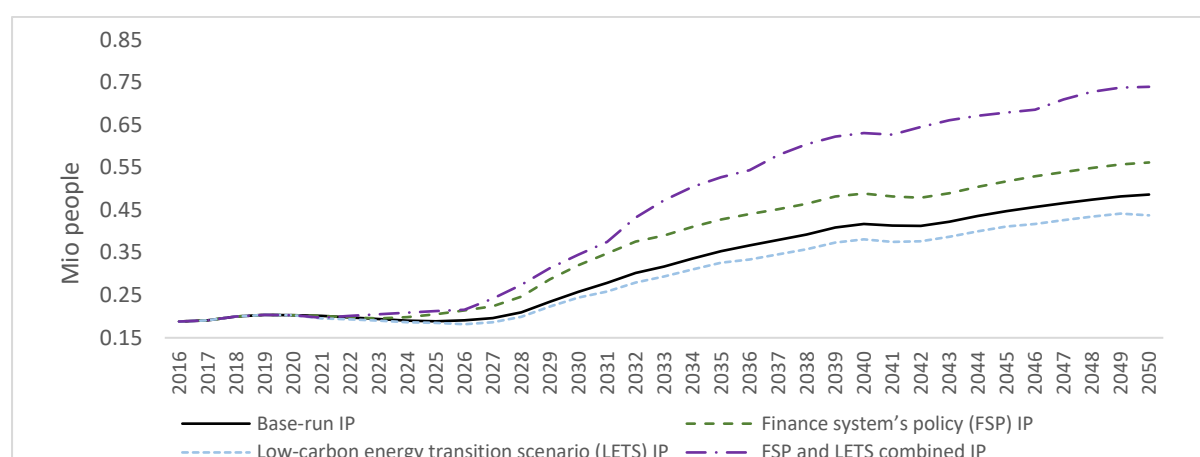


972
973
974 **Figure A28: Annual electricity system costs (in 2016 prices)**



975
976
977

FigureA29: Annual direct employment in the electricity sector



2.3. No changes in salaries and increase in import costs

The table below shows the results of the tested policy scenarios under a scenario that doubles the prices for electricity imports and in which wages do not increase when the average price level increases. The scenario is called the high import prices and no wage increase scenario ('IPNW').

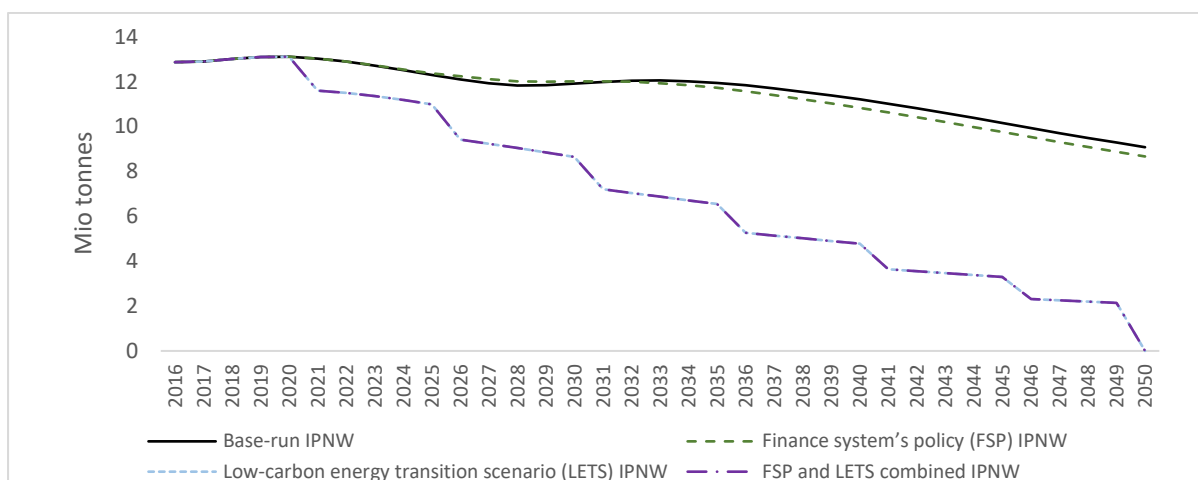
The table below shows the results in terms of the chosen policy indicators *as percentages against the base-run simulation results* under scenario IPNW of the same policy indicator and in aggregated terms (i.e. summing up the values during the simulation period).

Table A8: 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 2016 to 2050 in comparison to the base-run.

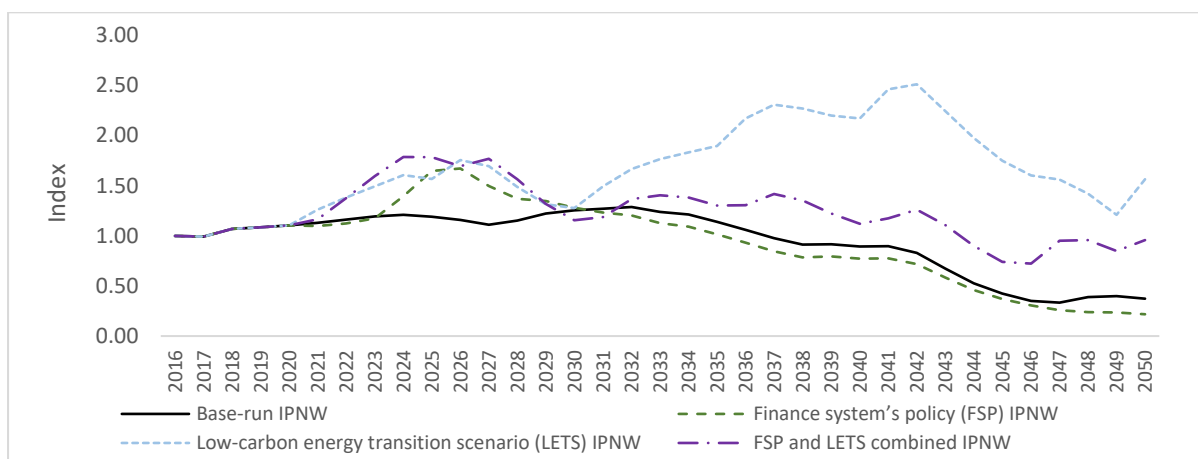
	Emissions (%)	GDP (%)	Unemployment (%)	Direct employment (%)	System costs (%)
Finance system's policy (FSP)	-1.28	3.58	-1.76	9.90	1.68
Low-carbon energy transition scenario (LETs)	-38.30	0.09	0.05	21.03	40.45
FSP and LETs combined	-38.30	3.66	-1.76	38.45	18.91

Importantly, in aggregated terms, the different policies compare the same as under scenario 0 – an exception thereof is however the direct employment indicator which reaches under scenario IPNW in the GFGS the worst impact, but under scenario 0 in the LETs. However, this does not alter our key policy conclusions (see section 5 in the main body of this article) and therefore the results are not described here in more detail. The figures below show the development from 2016 to 2050 of the considered key indicators under scenario IPNW.

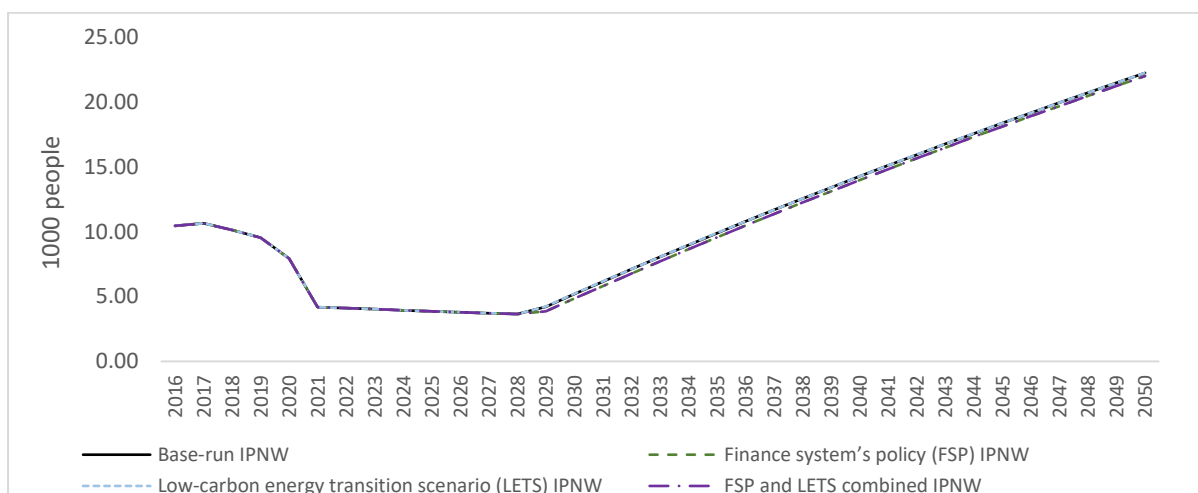
998 **FigureA30: Annual emissions emitted by the electricity sector**



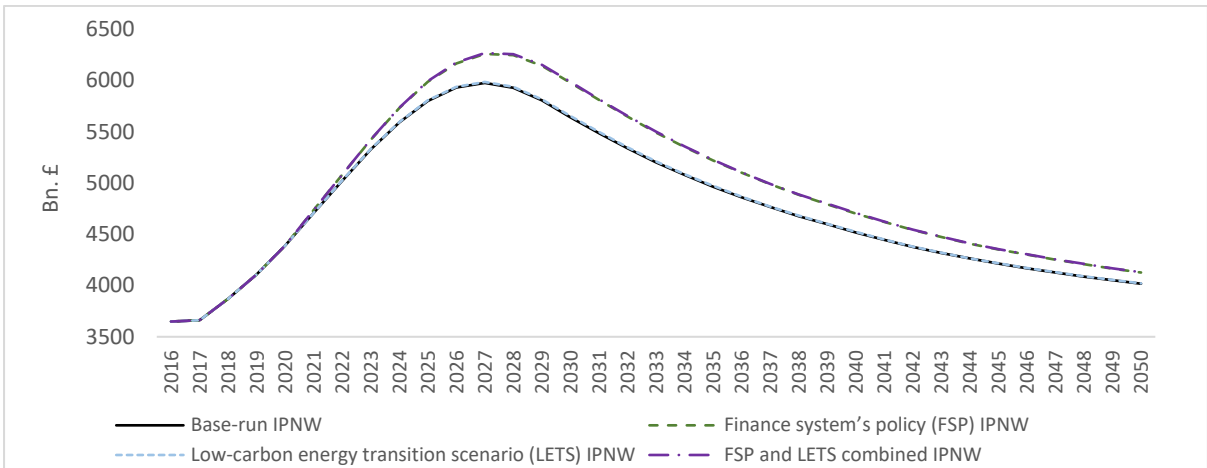
999
1000
1001
1002 **FigureA31: Domestic electricity price**



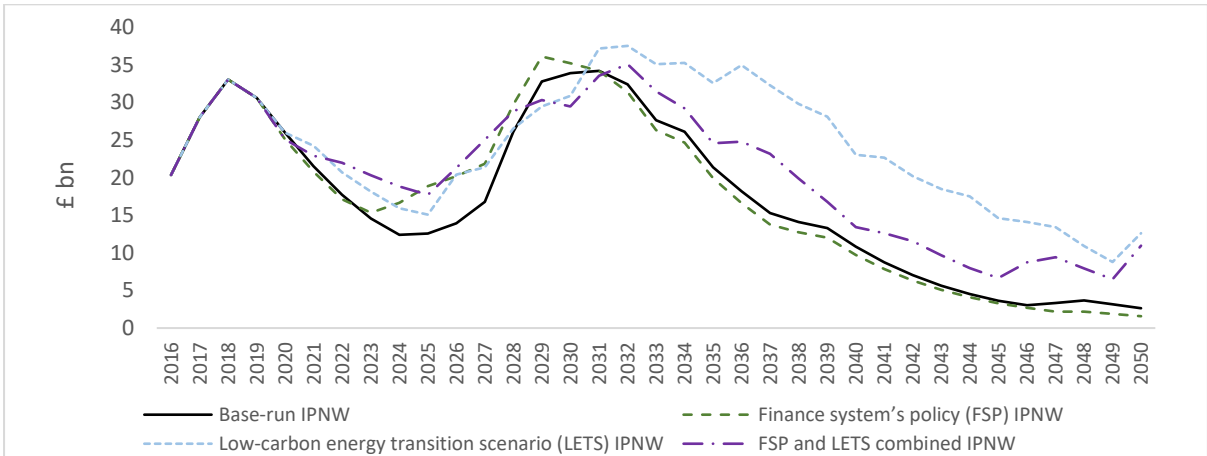
1003
1004
1005
1006 **FigureA32: Annual unemployment**



1010 **FigureA33: Annual GDP (in 2016 prices)**



1011 **FigureA34: Annual electricity system costs (in 2016 prices)**



1012 **FigureA35: Annual direct employment in the power sector**

