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The effects of low-carbon transitions on labour productivity: analysing UK electricity, heat, and mobility with a techno-economic simulation model

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ABSTRACT

The low-carbon transition is generally portrayed as involving costs to the economy through lower productivity and generating benefits through avoided impacts of climate change. This mainstream economic narrative hinges on two critical assumptions that stem from an allocation perspective: that low-carbon technologies are more expensive than high-carbon ones, and that low-carbon investment displaces resources from their optimal allocation. However, evidence increasingly suggests that neither assumption may be true. Drawing on evolutionary and complexity economics and making different, empirically-supported, assumptions about innovation dynamics, structural change, and the endogenous creation of finance, this paper examines the impacts on UK labour productivity of a low-carbon transition in the power, transport and heat sectors using a coupled macro-econometric and technology model (E3ME-FTT). Using realistic assumptions, the model results show moderate but positive productivity increases in the transition that stem from technological learning-by-doing and productivity growth in specific sectors, which induces investments that ultimately lead to expanded economic capacity across the economy.

Key policy insights

- Low-carbon transitions in power, transport and heat can increase UK labour productivity growth economy-wide by reducing costs of key energy services
- Indirect induced economy-wide benefits of transitions on productivity are far larger than direct sector-based impacts of technological change
- The impacts of transitions on UK productivity depend on the ambition of decarbonization policies, the economic structure, the productive capacity, the import propensity, and whether other large economies also decarbonize
- Uncertainties arise around whether cost savings are passed on into lower prices and how resources saved are spent by households and businesses.

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1. Introduction

To transition to a 1.5°C stabilization pathway, annual greenhouse gas emissions must decrease by 45% by 2030 compared with the current trajectory (UNEP, 2022). The effects of climate change mitigation policy on

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economic growth have been debated for decades (Nordhaus, 1991, 1992). Conceptualizing climate mitigation as a pollution control problem (Aykut, 2016), it has often been assumed that mitigation policy would reduce levels of economic output, with stronger action leading to disproportionally higher costs as the cheaper options are picked off first. Based on standard growth theory (Solow, 1956), the basic logic is that either resources are diverted from productive investment, or there is a loss of productivity by diverting resources away from their optimal use (van Vuuren et al., 2020). In either case, labour productivity falls and economic growth is negatively affected.

Because productivity growth is a key driver of wealth creation (Krugman, 1992), there is understandable interest in how climate mitigation policy will affect productivity growth, which has been slowing in various countries (Coyle & Mei, 2023; van Ark & Venables, 2020). Neoclassical economics, and associated Integrated Assessment Models (IAM) (van Beek et al., 2020), historically, expected negative productivity effects based on two assumptions: that low-carbon technologies are expensive while fossil fuels are cheap, and that available resources for production are scarce. Climate policy is thus thought to force resources away from their most productive application, which reduces the overall efficiency of resource use and lowers productivity.

Recent empirical and conceptual developments have made both assumptions problematic. Low-carbon technology cost differentials have narrowed or are being reversed in key sectors, which thus empirically erodes the first argument. For example, the global average levelized cost of electricity decreased by 89% for solar-PV, 69% for onshore wind, and 59% for offshore wind between 2010 and 2022, making them the cheapest electricity-generation options in most parts of the world (IRENA, 2023). Likewise, the price of Li-ion battery packs fell by 89% between 2010 and 2020 (BNEF, 2021), which enabled electric vehicles to already reach cost parity with petrol and diesel cars on a total cost of ownership basis and will likely enable them to also reach sticker price parity in the coming years.

These real-world developments have, for the most part, been driven not by carbon pricing policies, which mainstream economists have advocated for decades, but by policies that increased *deployment* (e.g. feed-in-tariffs, adoption subsidies, investment grants, R&D subsidies), which, in turn, triggered increasing-returns-to-adoption mechanisms such as learning-by-doing, learning-by-using, scale economies, strategic complementarities across networks, and complementary innovations (Arthur, 1994; EEIST, 2021; 2022; Geels & Ayoub, 2023; Grubb et al., 2014; Lilliestam et al., 2021; Peñasco et al., 2021; Way et al., 2022).

The second argument is conceptually eroded by newer theories that conceptualize climate mitigation not as a pollution control problem but as 'system transitions' that include the creation of new resources, including not only new technologies, infrastructures, markets, and industries (Geels et al., 2017; Geels & Turnheim, 2022; IPCC, 2022; Mercure et al., 2016; RMI, 2022), but also new financial resources (Mercure et al., 2019; Pollitt & Mercure, 2018). Under these new theories, climate policy may be a driver of productivity improvements and economic growth rather than an impediment. Many of these are innovations that would have been beneficial to society and the economy irrespective of climate risks, but the required early investment and disruption confronts inertia in the system and prevents their uptake.

The IMF's, 2020 World Economic Outlook reflects this new understanding, suggesting that 'decarbonization policies focused on innovation policy (such as research subsidies) could trigger waves of technological change that would boost productivity and growth in the medium to long term' (IMF, 2020, p. 88). A recent UK Treasury report also concludes that:

> The transition to net zero will create new opportunities for economic growth and job creation across the country. The demand for low-carbon goods and services will encourage new industries to emerge, with the potential to boost investment levels and productivity growth. (HM Treasury, 2020, p. 3)

Despite the new emphasis on low-carbon system transitions, there are few studies that use new transition-oriented theories to assess potentially positive productivity effects of low-carbon transitions. Stern (2022, p. 1276) therefore calls for a change in economics, including a proper treatment of innovation and transition: 'The problems of rapid change, dislocation, increasing returns, system change, and rapid innovation that are of the essence here are very hard to capture in standard IAMs'. Stern (2022, p. 1284) further suggests that 'We are going to need to understand *innovation* in a much deeper and stronger way, because it is at the heart of the transition to net zero'. He suggests that 'We are going to need an array of different models, a

variety of perspectives, and a collection of different ways of understanding different parts of the problem. And then wisdom and good judgement in putting all these pieces together' (see also Stern, 2018; Stern, 2022).

Intriguingly, in standard macro-models, while growth is assumed driven by general R&D and innovation across the economy, low-carbon innovation receives an entirely different analytical treatment, and is assumed to be productivity-decreasing. This is critical given the pervasive nature of energy-related activities: any productivity gains in energy services have a potential to induce substantial productivity gains economy-wide. This study therefore aims to include the effect of low-carbon innovation on labour productivity, on which an important knowledge gap exists.

This paper aims to respond to Stern's calls to include innovation within macroeconomic analyses of low-carbon transitions, with a particular focus on their effects on labour productivity as the source of long-term economic growth, using the UK to 2035 as a case study. Section 2 uses a literature review to articulate conceptual backgrounds and mechanisms underpinning the established mainstream 'allocation economics' approach and the alternative evolutionary economics and complexity economics approach. It sets out the implications of theoretical assumptions for the question of productivity, with a focus on the role of innovation and endogenous finance. Section 3 operationalizes the conceptual discussion into a modelling approach that uses both an evolutionary model (FTT) to capture the dynamics of innovation technological transition, and a macro-economic model (E3ME) to assess economic effects with a focus on productivity. Section 4 then presents the modelling results and section 5 discusses the findings and concludes. A Supplementary Information document provides additional figures and tables and a detailed description of the economic model used.

2. Allocation economics and evolutionary/complexity economics applied to the low-carbon transition, productivity, innovation, finance, and policy

Following Mercure et al. (2019), we distinguish two main economic schools of thought and several specific economic theories with relevance for low-carbon transitions. The first is the 'unique equilibrium/supply-led' view, which understands the economic process as consisting of allocating existing scarce resources between competing demands. Rational actors ensure that resources are allocated optimally. Carbon pricing corrects for the externality of climate change. By 'getting the prices right', an optimal societal outcome, including the effects of climate change, may be found. Climate policy in *allocation economics* includes acute trade-offs because mitigation investments necessarily displace labour and capital resources away from optimal productive uses across the economy. The optimization assumption thus constrains economic climate models to only produce worse outcomes for any kind of climate policy. This perspective takes the costly and negative nature of climate action as a starting premise through theoretical constructs and models. Publications that show negative productivity impacts from mitigation policy typically follow this economic approach (e.g. Ajayi et al., 2021; Ajayi & Pollitt, 2024; van Vuuren et al., 2020).

The second, 'dynamic' economic view relates to various empirically-oriented approaches (of which evolutionary and complexity economics are particularly relevant for our paper) that understand economic development as consisting in the creation of new economic resources for productive use through innovation and creative destruction (Arthur, 2014; Arthur et al., 1997; Beinhocker, 2007; Dosi et al., 1988; Freeman & Perez, 1988; Mercure, 2022; Nelson, 1998; Pyka et al., 2018; Schumpeter, 1934). It focuses on processes of innovation, technological discontinuity, and sectoral transitions that drive both the transformation and the evolution of productivity. The Technology Innovation Systems (TIS) approach, for instance, explores how resources are created in innovation ecosystems through knowledge creation, knowledge diffusion, entrepreneurship, advocacy coalition creation, and market creation (Geels et al., 2017; Grubler & Wilson, 2012; Hekkert et al., 2007).

The two approaches provide different interpretations of productivity. In allocation economics, there is a fixed supply of resources, and the allocation of resources determines the level of productivity (Hsieh & Klenow, 2016), which results in a maximum amount an economy (or each worker) can produce. This, however, can be increased if the allocation can be improved, and not otherwise (Hallegatte et al., 2024). Given the underlying optimization assumptions, maximum output is assumed to be realized under the prevailing allocation, unless a market failure is removed enabling a better allocation. Under evolutionary thinking, productivity is an output of the socio-technical system, where the current state of technology and the amount of capacity determines what *could*

be produced, and the institutions, markets and business strategies shape what *is actually* demanded, normally less than productive capacity. Due to uncertainty over anticipated demand, businesses are known to maintain excess productive capacity as a resilience strategy towards demand shocks (Haluska et al., 2023; Rubbo, 2023). In other words, while productivity can be improved via better allocations of labour and capital (Hsieh & Klenow, 2016), demand normally also fluctuates below productive capacity and therefore spare capacity exists (Haluska et al., 2023).

Both approaches view innovation as essential driver of productivity growth. Allocation economics rightly emphasizes investments in R&D and general education as important enablers of the emergence of new ideas and technical improvements (Schot & Steinmueller, 2018). But evolutionary economics additionally emphasizes the importance of increasing-returns-to-adoption mechanisms that further improve technological performance and decrease cost. Arthur (1994), for example, distinguishes mechanisms such as learning-by-doing, learning-by-using, network externalities, complementary innovation, scale economies in production, and informational increasing returns, which lead to self-reinforcing dynamics in the deployment and diffusion phase. General R&D and education on their own are not considered sufficient in evolutionary frameworks to boost productivity as recorded in the statistics (Freeman & Louçã, 2001; Pyka et al., 2018).

The evolutionary/complexity approach also emphasizes that adopting new technologies induces creativity and innovation across the whole economy and generates new learning and experience along the way (Dosi et al., 1988; Lundvall, 1992; Mowery & Rosenberg, 1998; Rosenberg, 1982). It also allows for economies of scale in discovery and production, as businesses make and distribute products and services more efficiently, thereby dramatically lowering costs. This, in turn, makes deploying new technologies more attractive, generating a virtuous cycle of deployment-driven innovation, economies of scale, investment, and falling costs.

Dynamic interactions between innovation and diffusion can also provide an alternative explanation for the 'J-curve' relationship between technology development and productivity (Brynjolfsson et al., 2021). The J-curve suggests that productivity gains typically lag new inventions (i.e. product innovation) from R&D. In allocation economics, it simply originates from crowding-out of capital. In evolutionary economics, it takes time for the economy and labour market to adjust and fully absorb the new possibilities offered in order for higher productivity to be realized, due to diffusion dynamics that can follow different rates in different geographies or contexts.

The two approaches also have different views on finance, which is important because low-carbon transitions are capital-intensive processes as they replace indefinite expenditures on fuels, materials and labour with finite expenditures on upfront capital. Fossil fuels in electricity generation are replaced by technologies (wind turbines, solar-PV) with little or no variable input costs; and the burning of fossil fuels in gas boilers or car engines (which is relatively inefficient) is replaced by heat pumps and electric vehicles, which are more efficient in providing heating or mobility services but (presently) more expensive to buy upfront. Low-carbon transitions in general thus require substantial increases in investment and finance, but lead to lower operational expenditures later. How this finance is conceptualized and modelled not only affects production levels (Mercure et al., 2019; Pollitt & Mercure, 2018), but also impacts productivity rates.

Allocation economics employs the loanable funds theory, in which investment is equal to savings year on year. If savings remain a fixed proportion of GDP, green projects compete with brown ones for capital and 'crowding out' occurs (Hallegatte et al., 2024; Mercure et al., 2019; Pollitt & Mercure, 2018). This leads to an allocation of capital that is less productive than the counterfactual.

In contrast, evolutionary and complexity economics (e.g. Balint et al., 2017; Dosi et al., 2010, 2015; Mercure, 2022) can build on newer theories of finance that highlight the (partly) endogenous creation of money. The banking system, in particular, creates finance when it lends to projects that it deems profitable (Keen, 2014; McLeay et al., 2014; Mercure et al., 2019; Pollitt & Mercure, 2018; Werner, 2014). Crowding out only occurs when there are capacity constraints in the real economy, such as to the number of skilled workers, bottlenecks in the production of input materials and limits to the upstream productive capacity. This does not mean that there are no limits to borrowing, since banks typically limit credit to projects they deem risky. At most times, higher levels of economic activity can lead to higher utilization rates of labour and capital, subject to the

constraint of full employment. Money demand is thus endogenous and a function of output that can originate from the emergence of new ranges of bankable projects.

3. Modelling sectoral productivity change in a low-carbon transition

3.1. General description of the combined E3ME-FTT model

The Future Technology Transformations (FTT) framework (Mercure, 2012) has been designed to model the development of co-evolving low-carbon technology adoption and cost-reduction pathways under different policy conditions. The FTT-model is a system dynamics model that combines two important principles from evolutionary economics: learning-by-doing and technology diffusion dynamics. It is an evolutionary discrete choice model in which the menu of options seen by agents depends on the relative diffusion level of the various technologies (Mercure, 2015, 2018). This means that newer technologies that are seldom deployed are also seldom chosen, and conversely, established technologies are difficult to dislodge because they dominate the choice menu. However, rapid cost reductions can bring new technologies to the mainstream through the virtuous cycle where they attract more purchases, and purchases cause more cost reductions. This approach generates S-shaped diffusion curves as they are observed empirically. The model includes vintage technology effects (through aging and survival analysis) to reproduce fleet lifecycle dynamics.

The FTT family of models (power, road transport, heat, steel) are calibrated on bespoke datasets, with around 25 technologies per model. Some proxies are made where data are scarce or where countries share common markets. Cost data originate from manufacturer websites and the International Energy Agency (IEA), while fleet compositions and sizes are inferred from either the IEA (power) or national statistics (transport, heating, steel). The models are updated frequently and use data timeseries up to between 2019 and 2022, depending on the model. Projections are calibrated to match diffusion rates observed in the most recent years of data.

FTT has so far been applied to analyse low-carbon transitions in the electricity, personal mobility, household heating and steel sectors (Mercure, 2012; Mercure et al., 2014; Lam & Mercure, 2019; Knobloch et al., 2019, Vercoulen et al., 2023). The models include 5–7 technology-specific policy instruments in each sector (covering regulations, pricing instruments, mandates and public investment), in addition to economy-wide policies such as carbon taxes. In this paper we used the FTT-models for electricity, personal mobility, and household heating to simulate the low-carbon technological transitions in these sectors.

To estimate the productivity effects of these low-carbon technological transitions at sectoral and whole-economy levels, we use the highly disaggregated sectoral macroeconometric model E3ME that quantifies the demand for energy-related goods and services within a broader economic context, driven by the transformations occurring in low-carbon technology sectors modelled by FTT. For consistency with our evolutionary economics perspective, it is critical to use a demand-driven macro-modelling approach. This ensures three elements, *endogenous credit creation* (as discussed above), differentiating productive capital assets from investment capital,[1] and to respect the empirical observation of spare capacity in the employment of economic resources. As the economy is incentivized by policy to transform, new investment is induced to make that transformation happen (in e.g. energy-related technology, relative to the baseline), and this investment demand makes the economy increase and improve its utilization level of workers and of the productive capital stock more generally. Induced investment meanwhile creates new productive capacity across the economy that in the longer term accommodates the ensuing demand growth.

The demand-driven macro-econometric E3ME model (Cambridge Econometrics, 2022; Mercure, Pollitt, Edwards, et al., 2018b) embodies this approach (Pollitt & Mercure, 2018) using a detailed level of sectoral disaggregation that allows linkage to the FTT models. E3ME splits the global economy into 71 regions, with 70 sectors in each region. The model generates comprehensive CO2 emissions sources for all industrial and

[1]E3ME determines investment capital via an investment econometric equation that mimics investment behaviour by businesses in each sector. This is separate from the representation of productive capacity in both E3ME and FTT, on the basis of a 'perpetual inventory' vintage capital accounting method.

combustion origins. Further information about the model, assumptions, inputs, equations and identities, and model diagrams is provided in the Supplementary Information document, and the related report by Cambridge Econometrics, 2024.

3.2. Modelling productivity with E3ME-FTT

Productivity is generally defined as the amount of output from a system or process, divided by the amount of input, and can be measured in different units. Here, economic gross value-add per full-time worker (or worker-hour) defines labour productivity, while physical output per unit physical input defines physical productivity of machines and production systems (ONS, 2007).

Figure 1 shows the key relationships in the E3ME-FTT model that shape the results for productivity. Following the discussion above, the top grey box describes supply-side effects of technological change, the bottom left side shows demand-side effects (domestic and international), and the right-hand side explains the connection between supply-side *potential* production, and *actual* rates of production (and therefore productivity) determined by the demand-side. Supply and demand are linked through price changes, but prices adjust empirically rather than being constrained to matching supply and demand as in general equilibrium models.

Figure 1 also illustrates the specific mechanisms that we model to assess how transitions to low-carbon technologies (such as heat pumps, electric vehicles, solar-PV, onshore and offshore wind) affect productivity and other macroeconomic indicators. For the supply side (top half of Figure 1), we include the following effects:

- *The cost of new low-carbon technologies falls* as they are deployed more widely because of learning-by-doing, scale economies, complementary innovations leading to cheaper financing costs. The effects are domestic but also driven by other major economies (which depends on policies adopted elsewhere).
- *The cost of inputs to production falls*, within the affected sectors, especially fossil fuel inputs, raising the relative productivity of labour.
- *Electricity becomes cheaper* (because of cost reductions of renewable electricity technologies and reduced fossil fuel costs), which reduces costs in the wider economy and enables further productivity increases.

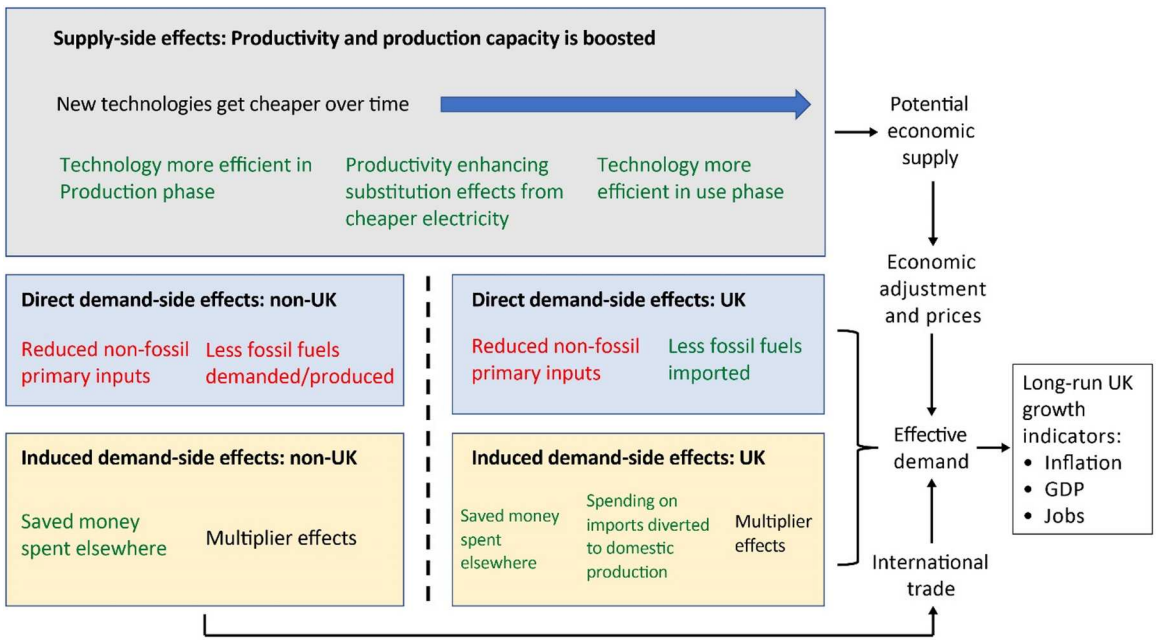

Figure 1. Summary of different productivity-shaping mechanisms in low-carbon transitions. Green/red indicates elements that increase/decreases economic activity.

The same occurs in other major economies.

For the demand side (bottom half of Figure 1), we included the following effects:

- *Consumer demand for fossil fuels declines*, because of the shift towards electricity-based technologies (such as heat pumps and electric vehicles). This, in turn, reduces fossil fuel imports, which increases money to be spend domestically: this boosts GDP if the spending is reallocated to domestically produced goods (including domestic electricity generation). However, it depresses output in fossil fuel and dependent sectors. This effect crosses borders.
- *Shifts to cheaper and more efficient technologies lead to consumer savings* for heating and mobility services which increase real consumer spending power. This saved money is spent elsewhere, creating additional demand for (primarily) consumer goods and services in other parts of the economy. This also occurs in other major economies, which indirectly impact the UK.
- *Increased spending power induce greater demand for consumer goods and services*, generating further multiplier effects with additional employment in these sectors, leading to higher aggregate wages across the economy and therefore higher real consumer spending in a virtuous cycle. This also induces investment in capacity expansion (relative to baseline) to supply this increased demand, which itself creates demand for capital goods and further employment down the line. This also occurs in other major economies.

Our critical assumption is that declines in energy service costs from low-carbon technological change are passed on to consumers as price reductions of energy services and lower costs of energy-using technologies across the economy. Therefore, we are implicitly assuming a market design and regulation that ensure that prices are reflective of costs, something that could require reform (electricity market reform and regulation of pricing at charge points). Prices reflecting costs is not guaranteed to happen, since due to lack of real competition, re-distributors (e.g. electric vehicle charge points, or the electricity grid) can in principle capture the input cost declines, from cost-cutting innovation, as profits.[2] Productivity impacts may become lower or even zero if cost reductions from innovation are captured as profits by third parties.

3.3. Measuring productivity in E3ME-FTT

In E3ME, productivity is an outcome, not an input to the model. In contrast to general equilibrium models where productivity is given to the model, E3ME allows for endogenous levels of employment and capacity utilization independently. It is important to distinguish the effects of the improvement of the capital stock through a transition, from the 'Keynesian boom' increase in capacity utilization that is induced by the higher productivity of the capital stock as it frees up purchasing power, itself different from the structural transformation occurring as patterns of spending change. The three are independent phenomena, but operate hand in hand in the model. We therefore explain our measurement strategy here.

We extract from E3ME-FTT productivity indices at four levels:

(1) Within individual sectors, we track physical productivity changes using production parameters. This is useful to understand what is happening at the micro-scale, for example estimating GWh of electricity generation or vehicle-km of transport service per unit of physical input. Learning-by-doing for capital costs was split to reflect the different learning rates for the cost of equipment versus the cost of installation (which are both aspects of capital expenditure) and the cost of operation (Steffen et al., 2020). To put all inputs on the same footing, we proxy them on the basis of their corresponding costs. For that, we use the levelized cost. We thus calculate the amount of energy service produced divided by the value of the inputs, i.e. MWh or vehicle-km per £ spent (with q indicating the type of technology, i is the economic sector, k is the region, G

[2]Notably, marginal cost pricing in the power grid is not, at the time of writing, reflective of declining offshore wind production costs, while public charging point prices for electric vehicles are not currently reflective of electricity grid prices.

is the generation of energy service of that sector, e.g. GWh, vehicle-km, by each technology, and *LC* is the unit levelized cost of using that technology, defined in the Supplementary Information):

$$R^1_{i,k} = \frac{\sum_q G_{i,k,q}}{\sum_q G_{i,k,q} LC_{i,k,q}} \quad , \tag{1}$$

The levelized cost is a unit metric that includes all relevant costs discounted according to when they are expected to occur over a project lifecycle (CAPEX and OPEX).

(1) A sector-level index for supply-side labour productivity changes, defined as sectoral gross value added (GVA) at factor costs in constant prices, divided by employment. Its interpretation is narrowly tied to this sector and does not represent what happens in the rest of the economy. These effects are moreover generally small with respect to the entire economy (for sector i, region k, sectoral GVA $Y_{i,k}$ and employment $E_{i,k}$):

$$R^2_{i,k} = \frac{Y_{i,k}}{E_{i,k}} \ . \tag{2}$$

(3) An economy-wide index of the induced labour productivity changes outside of the energy sector, due to lower energy-related costs that become available to all sectors, but excluding the effect of re-deployment of workers towards sectors of different productivity (i.e. keeping the structure of the economy constant). This measures the degree to which in many sectors, value-added increases by more than employment, indicating labour productivity increases. By keeping the structure of the economy constant in the calculation of the index, we separate the effects of induced productivity growth outside the energy sector, from structural transformation, in which spending and activity becomes re-allocated. To construct this index, we average sectoral productivity across the economy using weights $\gamma_{i,k}$ that reflect the sectoral distribution of employment in the baseline ($E^{Bas}_{i,k}$).

$$R^3_k = \sum_i \frac{Y_{i,k}}{E_{i,k}} \ \gamma_{i,k}, \quad \gamma_{i,k} = \frac{E^{Bas}_{i,k}}{\sum_j E^{Bas}_{i,k}} \tag{3}$$

(1) With induced productivity changes across the economy comes an inevitable structural transformation that induces further adjustments in productivity. As a fourth index, we calculate an economy-wide measure of induced labour productivity change outside of the energy sectors that includes structural change and re-allocation of workers and spending in the weighting factor. This is simply aggregated GVA divided by total employment.

$$R^4_k = \sum_i \frac{Y_{i,k}}{E_{i,k}} \ \gamma_{i,k}, \quad \gamma_{i,k} = \frac{E_{i,k}}{\sum_j E_{j,k}} \quad , \tag{4}$$

While the supply side effects of low-carbon technological change in power, transport and heat, due to rapid learning curves, generally increase *potential* productivity (both within sector and at the economy-wide level), the induced demand-side effects can both increase and decrease productivity, due to several mechanisms occurring at the same time. Demand-side effects can *reduce* economy-wide *actual* productivity if the additional spending, jobs and output is primarily re-allocated to consumer services which have lower productivity. Because these sectors historically have lower rates of productivity (e.g. hotels and catering services), additional economic activity in these sectors can partially cancel out gains in the *average* level of labour productivity across the economy, even though the aggregate economy is larger.

However, where the savings are re-allocated to new goods and services, notably as results from product innovation, the demand-side effects increase actual productivity. That's where spending is re-allocated to higher productivity sectors. Therefore, while the outcome on potential productivity goes only one way, the

outcome on actual productivity can have contributions that go in different directions. Hence we expect to see a difference between the third and fourth indices above.

3.4. Transitions scenarios following announced policies

The empirical analysis focuses on the UK as a medium-sized country that imports most of its energy, in the three chosen sectors (electricity, personal mobility, domestic heating). We model in FTT the effect of a set of policies recently announced by the UK government and assess differences against a baseline that estimates the current trajectory of technological change. We stress here that substantial technological change is already occurring in the baseline case, where UK greenhouse gas emissions decreased by 71% between 1990 and 2019, due to a relative shift from coal to gas and the diffusion of renewables, and automobility, where electric vehicles accounted for 17% of new car sales in 2022. These cost reductions were themselves induced by earlier policy efforts. We then create a more ambitious policy scenario to explore whether the impact of greater ambition can lead to more productivity benefits. Lastly, we explore whether climate action by other countries have an impact on UK productivity.

The baseline case is a business-as-usual case based on trends from European Commission and International Energy Agency (IEA) projections, and currently observed technological trajectories (e.g. exponentially rising capacity in solar energy), described in in detail in Cambridge Econometrics, 2024. For the UK and other countries, the baseline includes policies that have already been announced and implemented. Implementation of the 2022 *British Energy Security Strategy* (ESS), and the 2020 *Ten Point Plan for a Green Industrial Revolution* (TPP) are not included in the baseline. Those policies form the basis of the UK *additional* policy scenario. The *expanded* UK policy scenario further includes the phase-out of gas turbines for power generation from 2035, the phase-out of all new sales of fossil fuel boilers in residential housing from 2030, as well as the expansion of the Social Housing Decarbonization Fund by £1.75 bn. These two scenarios are combined with scenarios in which major economies decarbonize (EU, US, China, see Mercure et al., 2021). Supplementary Tables 1–2 summarize the four policy scenarios that we assess. Further information about policy measures in the scenarios is provided in the Supplementary Information.

4. Modelling results

4.1. Productivity impacts in key sectors

Figure 2 shows average costs weighted by technology shares of service generation in electricity (2A), transport (2B), heating (2C) and total energy spending (2D). The underlying technology transitions in power generation, household heating and transport are shown in detail in Supplementary Figure 1 for all technologies in all policy scenarios. It shows a gradual expansion of low-carbon technologies that occur at the rate of turnover of technologies according to their respective lifetimes (coal plants are long-lived, while diesel vehicles are short-lived relatively). Solar and wind come to dominate in electricity generation, and EVs and heat pumps diffuse widely in transport and heating over the simulation period. Resulting impacts on emissions are shown in Supplementary Figure 2.

The changing technology mix influences costs in these three sectors as the diffusing low-carbon technologies go down their learning curves, while the high-carbon technologies, with costs dominated by fuel costs, do not see comparable cost declines, although lower demand for fossil fuels reduces their costs too, which leads to moderate rebound effects.

Energy-related sectoral costs decline in all the scenarios in power, transport and heat due to learning-by-doing driven by capacity additions, and due to lower amounts of energy per unit service produced by EVs and heat pumps (effects on primary energy demand are shown in Supplementary Figure 2). Larger cost reductions occur in the Expanded UK policy scenario and when the rest of the world also takes mitigation action, whereas the baseline follows historical rates. The reduction in costs compared to the baseline narrows over time because the baseline catches up in renewable installation (i.e. the policies bring forward adoption). For heating, cost reductions originate from declining heat pump costs, lower final energy demand from heat pumps and lower electricity prices. The model

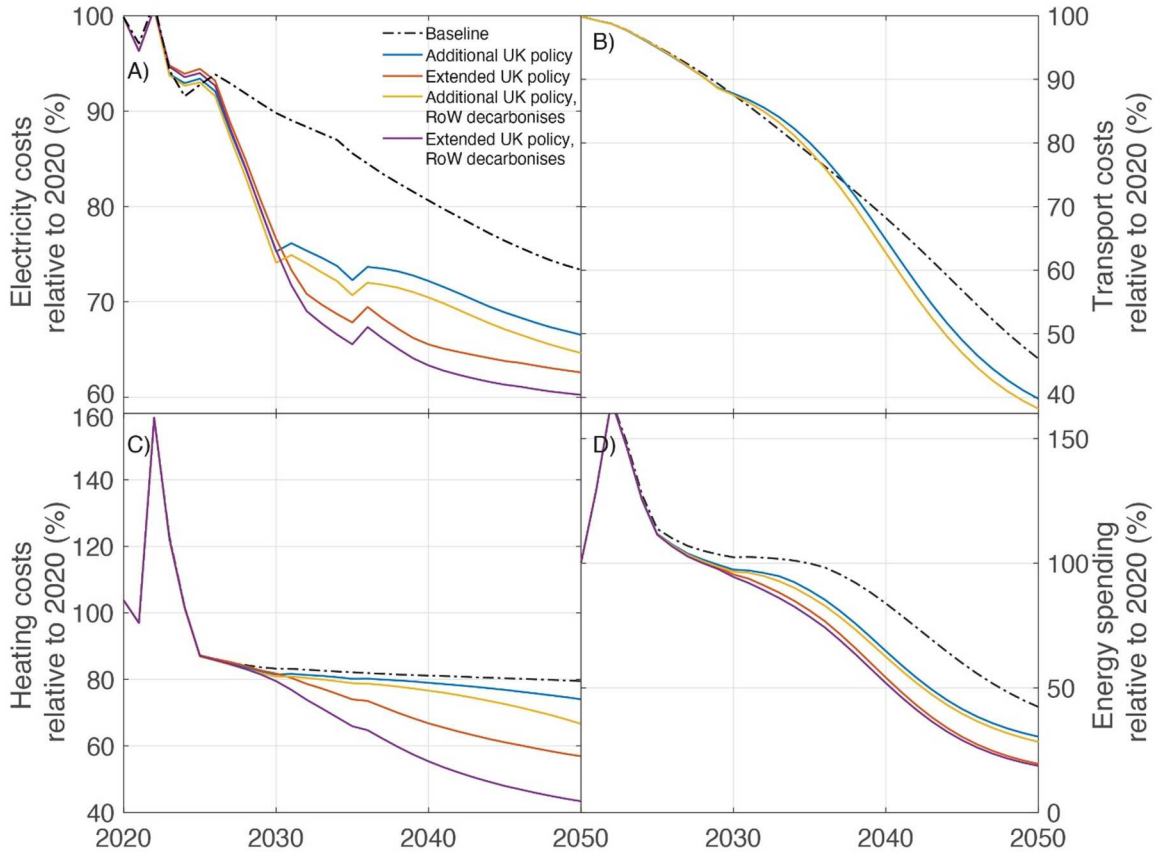

Figure 2 (Panels A to C) Evolving costs of energy end-use in electricity, transport and household heating relative to 2020 (use phase only, 100 indicates 2020), and (Panel D) total spend on energy. Sectoral costs (A–C) are averaged over all technologies, while in (D) expenditures are defined as the sum of deflated consumption times price for gas, electricity, petrol and other fuels. Note that spikes in 2021 are due to the energy crisis following the Ukraine war.

assumes that these cost reductions are reflected in the relevant prices and costs across the economy. Learning rates are provided in the Supplementary Information.

There are competing productivity-influencing mechanisms in the scenarios. Learning effects and scale economies decrease the cost of new technologies (both in installation costs and operations) as rates of uptake increase; this is driven by uptake anywhere in the world. In contrast, beyond a certain point, mounting electricity storage requirements limit productivity growth, as they increase non-linearly. The reductions in average electricity production costs, stemming in the model from the effects of learning against increasing resource costs (Figure 2A) show that the shift to renewables with falling costs dominates overall.

We show in Supplementary Figure 3 the corresponding evolution of physical productivity index 1 (as defined in section 3.3) in the three sectors and in the overall energy system, shown here as percent change from baseline. In the three sectors, the increase in productivity from a shift to renewables, electric vehicles (EVs) and heat pumps drives down cost dramatically against a slowly growing or stable output. Productivity growth is higher in power generation and slower to pick up in heat, and is faster the more ambitious the policies are. The reductions in productivity gains in the later years stem from the baseline catching up with the policy scenarios, and the fact that storage costs increase with the cumulative amount of renewables (Nijsse et al., 2023).

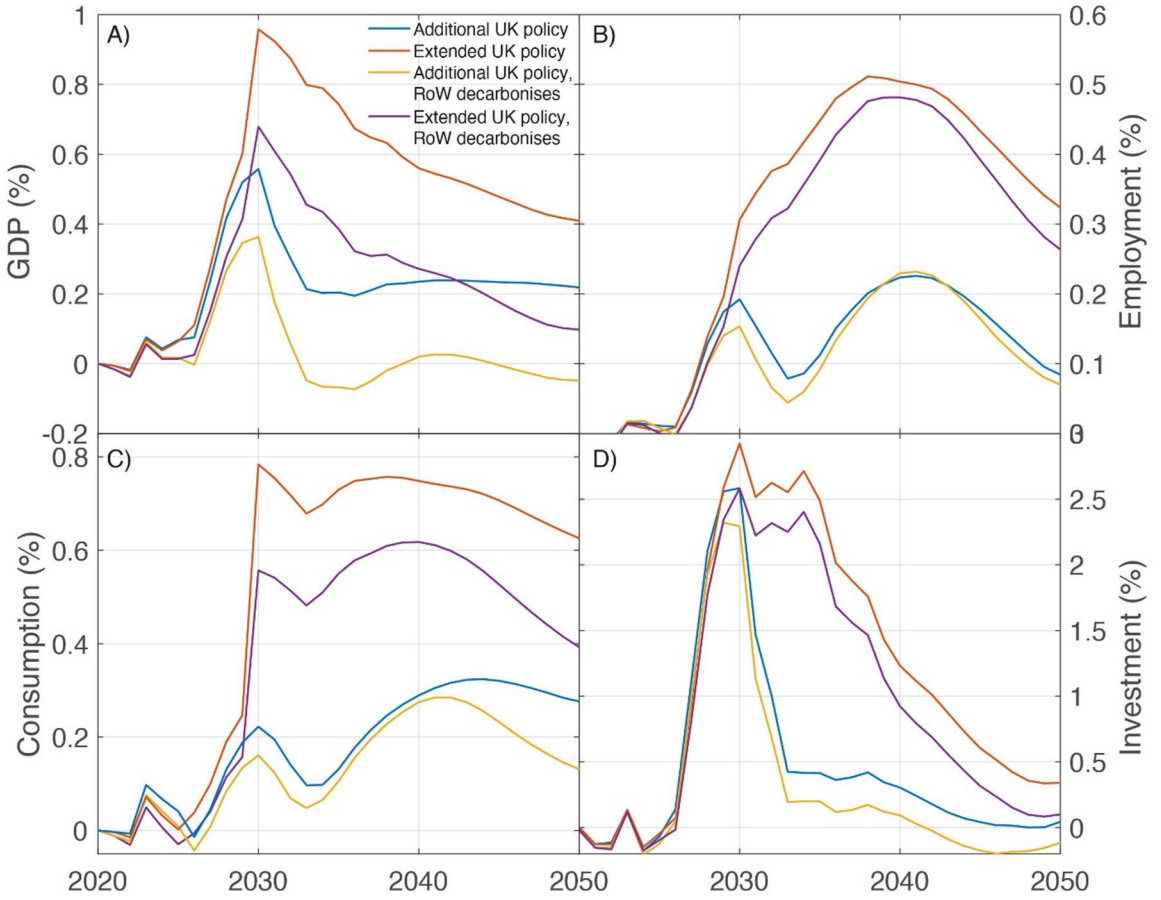

Figure 3. Changes relative to baseline in macro variables GDP, total employment, consumption and investment, as relative changes from the baseline.

4.2. Macro-level impacts of the policies on productivity

Figure 3 shows the macro-level impacts of the policies on GDP (3A), employment (3B), consumption (3C) and investment (3D). We stress that in a demand-driven model, investment is an endogenous quantity motivated by expected future output in each sector. These macro-results can be explained as follows. Climate policy in the UK, in the model, stimulates substantial private investment in new low-carbon technologies and related manufacturing, starting in 2025. This motivates activity in more manufacturing, construction, and services, in all of the scenarios, but with different magnitudes until around 2032/2040 (additional/extended UK policy scenarios). It also leads to losses of output, investment and employment in high-carbon technology output and manufacturing, inducing losses further downstream. Nonetheless, the gains are far larger than the losses, which is reflected in total employment, consumption and GDP up to beyond 2035. Decarbonization in other major economies also has important implications, which we discuss further below. The Extended UK policy scenarios motivate investment over a longer period than the Additional policy scenarios, which explains their more sustained effect on these macro-variables.

We turn to the main topic of this paper, labour productivity at the macro-level. Figure 4 shows labour productivity indices (2-4) (see section 3.3) in the four scenarios. In solid blue, we show Index 2, the supply-side effects of new technologies changing *the power sector's* own contribution to labour productivity, this specific sector's change in gross value-added (GVA) per worker against the baseline. We scale productivity (GVA per worker) in this graph by its share of sector employment to show the contribution of this sector's

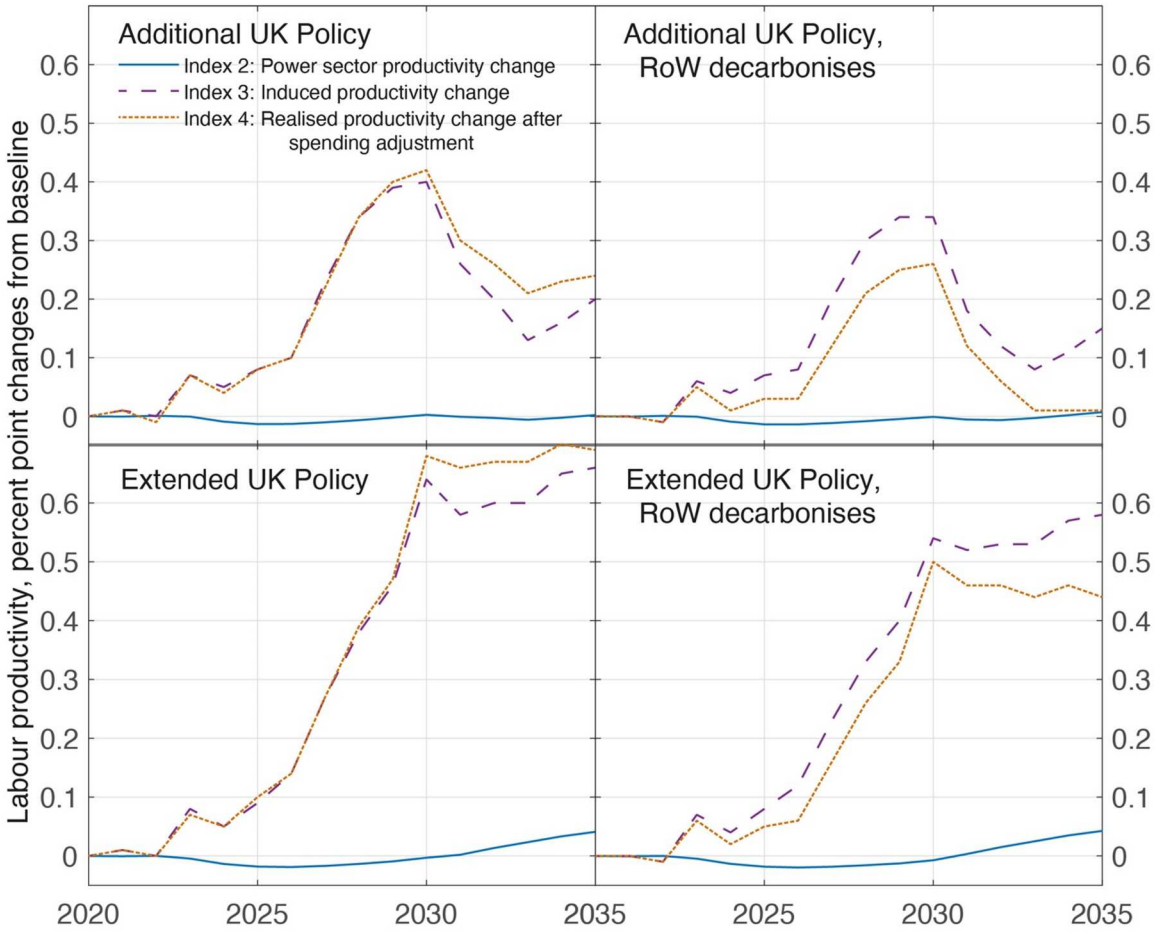

Figure 4. Labour productivity growth impacts in each scenario using three different indices (see section 3.3), expressed in percent point changes from baseline.

to economy-wide productivity. Since national accounts define transport and heat only when they occur as commercial activities, which vastly underestimates total heat and mobility,[3] we only show the power sector in these solid blue curves, which accounts by far for the largest share of investment in new technology.

Index 2 quantifies the contribution to productivity change from technology adoption excluding, for clarity, the economy-wide multiplier impact of the induced investment outside this sector needed to achieve this change (e.g. the construction and manufacturing needed), which are included in the next two indices. It does not include the economy-wide spending of energy cost savings from households either.

Index 2 follows a J-curve pattern due to renewables starting off as more employment-intensive than brown technologies, which declines over time due to learning-by-doing (e.g. learning to use less labour to operate and maintain the same wind turbines). The impacts are small relative to the economy, due to the relatively small size of the power sector, with roughly 0.4 percent of economy-wide employment. This indicates that direct sector impacts of technological change are much smaller than the indirect economy-wide private sector activity they induce.

[3]Transport and heating services are used across the economy, much of which is not recorded in national accounts as commercial transactions, and therefore national account values are vast understimates according to our definition. For example, households and other sectors purchase gas and electricity for heating rather than buying from a commercial heat provider, and use their own vehicles rather than buying a service from the road transport sector (e.g. taxis).

Figure 4 shows index 3 in dashed purple, the realized productivity changes outside of the energy sector induced by transitions in power, transport and heat. These are generated by private investment induced directly (within value chains) and indirectly (through increases in private consumption) by the policy change, as well as non-energy consumption increases due to energy cost savings, while keeping the allocation of employment constant. These productivity changes are primarily determined by changes in output induced in sectors other than where the technological change is occurring (e.g. construction, manufacturing), termed 'demand-side effects' in Figure 1.[4]

Figure 4 shows index 4 in dotted red, which additionally takes account of how the economy's structure also changes. This index matches what is recorded in aggregate UK productivity statistics, calculated as aggregate GVA divided by aggregate employment. It includes the net effect all of the productivity changes modelled in E3ME-FTT. The difference with index 3 is that as the economy transforms, the allocation of employment also changes, which dampens the economy-wide multiplier effect observed in index 3 as excess workers in sectors of increasing productivity get re-allocated to sectors of lower productivity in services, which receives the bulk of excess purchasing power freed up by declining energy costs and induced savings elsewhere.

Higher rates of capacity utilization in the sectors benefiting from increased spending, originating from savings on energy-related expenditures, mean that more output is produced requiring more employment as well. However, we observe a higher rise of GVA than employment, leading to a permanent increase in productivity that is not simply just the 'Keynesian boom' effect from induced investment. This is because the induced investment, kick-started by but mostly unrelated to energy, not only increases capacity utilization, but also improves the capital stock of sectors and creates scale effects, thus improving their labour productivity (capacity limits are discussed in Supplementary Information section 3).

We observe that the induced changes economy-wide are much larger, in absolute production, than the sector-specific ones. This suggests that the indirect economy-wide effects resulting from the policy are much larger than the direct effects from improving specific technologies, a reflection of the pervasive nature of the electricity, mobility and heat services.

However, these things are not independent; the indirect effect may not happen at all without the direct productivity effects that directly or indirectly motivate economy-wide investments. We note for instance that a tax reduction or an investment programme in fossil fuels of equal ambition does not induce the same multiplier effect in the model, since, although it induces investment in the relevant sectors, it does not reduce energy and operational costs economy-wide the way low-carbon technologies do (Figure 2), and therefore the inducement effect is smaller. This is a reflection of the general principle that we can improve productivity with new technologies more effectively than with old ones, because there is more opportunity for further innovation that has not already been done.

In the scenario modelled here, the labour productivity growth spillovers from investment last for as long as private investment in the transition can be motivated by the policy and the induced technological change. In the Expanded policy scenarios, the effects persist to 2035 following the assumptions adopted in the present exercise. In reality, much more investment is needed to achieve the overall climate goal, therefore the boost would likely be larger and last longer. It must be noted that these are investments made profitable by the policy, but that once costs fall below parity, investment can be expected to continue without policy support beyond the modelling horizon.

The differences between the UK-only and international decarbonization are also instructive. If major economies decarbonize, technology prices fall more than what UK action alone can induce. This boosts potential productivity, as recorded in Index 2. However, lower costs mean a lower investment multiplier, with the counter-intuitive result that the actual demand-driven productivity effects, seen in Indices 3 and 4, become smaller.

[4]We note that in declining sectors that reach zero employment, such as coal mining, a division by small numbers or zero occurs in the calculation of labour productivity, leading to spurious values. In those cases we assume baseline productivity, since increases are not expected to occur.

4.3. Trade impacts of the transition on productivity

Much of this story however is also influenced by whether changes are induced by the domestic transformation, or by transformations in other major economies. Notably, changes in the UK's oil and gas sector responds to signals from the global market more than the domestic market.

Supplementary Figure 4 explores balance of trade implications of the transition, which we use to further explain the productivity results of Figure 4. The baseline case shows that the UK suffers from a worsening balance of trade over time. For fossil fuel importing countries, the low-carbon transition offers, in principle, a significant opportunity to reduce trade deficits in replacing imported fossil energy by domestically produced renewables, equipment and durable goods such as cars. The UK, however, does not have a large capacity to produce low-carbon capital, equipment and durable goods, while it has a significant oil and gas sector that makes a key component of its current overall productivity. The oil and gas sector, however, is at high risk of becoming stranded due to climate policies abroad.

For that reason, in our model simulations, low-carbon transitions result in some relocation of domestic activity abroad having a negative impact on productivity. In the additional and extended policy scenarios, the UK reduces its domestic consumption of fossil fuels, and increases oil and gas exports to countries that are still ready to import fossil fuels. However, the UK imports substantial amounts of machinery and equipment needed to achieve decarbonization, due to its lack of domestic manufacturing capabilities. This largely offsets the gains in exports and reductions of imports. When major economies abroad decarbonize as well, the opportunity to export relatively costly oil and gas quickly diminishes, and the productivity decline induced by this is not replaced by anything. A policy question thus arises concerning how to revive or improve domestic technology manufacturing capabilities that could mitigate such a scenario.

5. Discussion and conclusions

Our model outputs illustrate with a broad brush some of the key economic risks and opportunities associated with low carbon policy in the UK. We find that while the policies analysed do not achieve the UK's climate goals, and that more stringent policies will have to be designed and adopted, their effects on productivity are nonetheless far-reaching. The transition to a low-carbon economy is not just a localized phenomenon, but a highly complex process that has many amplifying and dampening feedback mechanisms across sectors and countries. A detailed policy proposal that achieves targets is beyond the scope of this paper, but the implications for productivity are likely to be similar.

Our modelling analysis adds a new layer of sophistication over general equilibrium models that assume full employment, by allowing induced productivity changes to occur across the economy, in sectors unrelated to energy, via induced investment and spending. Our model shows that productivity can increase through several channels in the transition, and that changes resulting from the transition extend beyond the sectors and countries where technological change occurs. For the three analysed sectors, our model results show that (compared to the baseline) physical productivity increases most in the electricity sector (by about 40% in 2035), somewhat less in transport (about 20% in 2050), and least in heating (with results ranging from 10% increase in 2050 to 6% decrease in 2035). In each case, sector-specific productivity increases follow a J-curve pattern (initial decline, followed by improvements). This induces productivity growth across the entire economy of around 0.5% against baseline. We note that rebound and green paradox effects are fully accounted for in E3ME-FTT (see Supplementary Information), and find that climate policy and energy service cost declines do not lead to large rebound effects or a green paradox effect.

More importantly, we find that the indirect and induced effects of the transition are substantially larger, and positive, than the direct sector-based impacts. The primary productivity benefit of the transition may thus not be the direct contribution of energy-related sectors, but rather the activity generated across multiple sectors that would not have occurred without the sector-specific transitions and associated sectoral productivity increases. This is because of a broader economy-wide private investment wave, directly or indirectly linked to the sector transitions and public policy. It reflects findings in previous transitions, where the combination of product and process innovation drives further innovation across the economy (Freeman & Louçã,

2001; Freeman & Perez, 1988). Our analysis applies to the UK but is relevant to many other nations worldwide in which energy imports form a substantial component of expenditure; however, they may not apply to large fossil fuel producers where economic losses could exceed the gains.

Our findings of positive productivity effects deviate from the results of general equilibrium models, which usually find negative effects in energy transition scenarios. This difference is due to assumptions and conceptualizations about change processes, often applied by design, especially with regard to innovation and finance. Our model includes feedback loops not included in general equilibrium models, both positive and negative, that capture the complexity of low-carbon transitions including scale economies, learning effects, induced investment and structural change. Standard general equilibrium modelling tools are unable to accommodate the complexities and dynamism of transitions. The combined E3ME-FTT modelling framework, in contrast, focuses on the dynamics of resource creation (through innovation, diffusion, and structural change) as opposed to a static allocation of resources.

Our findings, however, hinge upon our critical assumption that input cost differences caused by learning-by-doing in the diffusion of low-carbon technologies, become reflected in energy service costs across the economy. This is not always the case currently, therefore to ensure this happens, market design and regulation will likely require reform. For example, under marginal cost pricing in the electricity grid, for as long as gas electricity continues to be used and set prices, solar or wind production cost reductions will continue to be captured as profits by producers, the grid operator or electricity distributors, rather than passed-on to consumers. Similarly with electric vehicles, public charging points currently set fixed prices at levels between 3 and 10 times current grid prices (65–95p/MWh), depending on the time of day and location, comparable to the cost per unit distance of using petrol. The difference is captured by operators as profits. Under current market designs, the productivity growth effects discussed in this paper are unlikely to fully materialize, while reform could enable them.

We also note that while our model suggests that productivity grows in the economy with the transition, other risks also emerge. This includes risks of stranded fossil fuel assets and their impacts on the solvency of their owners and the UK's financial sector as a whole. Structural transformation implies loss of employment in sunset industries, which may exacerbate existing or even create new regional inequalities across the UK.

It is important to acknowledge the limitations of this study and of our modelling method. While we capture process innovation (learning curves), our capacity to model product innovation (the emergence of new products) and the resulting shifts in consumer behaviour is limited because it is challenging to predict what form new goods and services may take. The split of spending on capital expenditures for specific low-carbon technologies between domestic and foreign recipients is not modelled in detail. Uncertainties over detailed short run capacity constraints also limits our ability to determine what exact level of investment could push up inflation and crowd out alternative domestic consumer or investment spending with a countervailing dampening effect. Our modelling suggests that although there is limited static spare capacity, as the UK like other developed economies struggles to counter entrenched inflation, there is plenty of potential dynamic spare capacity in the case where investment is redirected into productivity enhancing sectors. And lastly, this study does not explore the impacts on growth of other types of climate policies that could in principle be adopted, such as planning permission rules, limits to capacity expansion or limits to energy service use.

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