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Can network spending to support the shift to electric vehicles deliver wider economy gains? The role of domestic supply chain, price, and real wage effects

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ABSTRACT

The transition of societies to a low carbon future presents several important political economy challenges. For example, can the deployment of low carbon solutions deliver economic prosperity and support policy makers in developing decarbonisation policy pathways around which societal and political consensus can build and be sustained? Taking the example of decarbonising private transport in the UK, we use a computable general equilibrium model – informed by energy systems analysis – to consider the potential wider economy impacts, over different timeframes, of electricity network upgrade costs to enable the EV rollout required by 2050. We demonstrate opportunities for both transitory and sustained gains in GDP, employment, and earnings across the UK economy. The key source of sustained expansion is the strength of domestic supply chains supporting the UK electricity sector. However, the transition pathway is sensitive to how network upgrade costs and trajectories respond to the speed of consumer behaviour adjustments, and to the price impacts of constrained wider economy expansion, with notable implications for the price of electricity. The key outcome of concern for UK policymakers is how a lasting constraint on total labour supply means that the EV rollout is associated with lasting impacts on electricity and other consumer prices.

1. Introduction

The transition of societies and economies to low/net-zero carbon futures presents a challenge for policy makers charged with meeting dual aims of sustaining and improving economic performance and prosperity while simultaneously delivering deep reductions in greenhouse gas emissions. Commitments to mid-century net-zero targets, like that of the UK Government (BEIS, 2019) requires systematic changes in how we live our lives and do business. This translates to a significant political economy challenge. One central issue is how enabling (e.g., through large scale electricity network upgrade spending) and realising emissions reducing activities (e.g., rollout and uptake of electric vehicles) impacts the composition and level of economic activity, including jobs and income generation therein, as economies move forward through the transition process. This issue is recognised in the Paris Agreement (UNFCCC, 2015, p.4) particularly in terms of addressing the national priorities for a 'Just Transition'. National policy concern tends to lie in sustaining gross domestic product (GDP) and employment growth as emissions fall, and how this translates to changes in labour productivity, average wages, earnings, and the composition of economic activity.

A timely example of policy focus in this context is the challenge of decarbonising private transportation through electrification, and the increasingly common commitment to transitioning from conventional to low emission electric vehicles, EVs (Abrell, 2010; Dai et al., 2016; Fujimori et al., 2014; Li et al., 2017). In contrast to other areas of climate mitigation policy (e.g., see Babatunde et al., 2017), the existing literature to date is lacking in terms of understanding the potential economy-wide impacts and implications of enabling and/or realising EV rollouts/uptake in different political economy contexts, particularly where this involves displacing current modes of personal and/or commercial transportation. However, such research focus is necessary to inform a wider public policy focus on the broader set of common societal and political concerns around considering and understanding wider economy or economic wellbeing consequences. This is central to building consensus around proposed decarbonisation actions, thereby facilitating the low carbon transition in different national contexts (Turner et al., 2020).

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Here in the context of the applied example of a systemic shift in how personal transport must be delivered in the UK, with a relatively rapid shift from conventional petrol/diesel fuelled to electric vehicles recommended by the UK Committee on Climate Change (CCC, 2019) in that statutory body's advice informing the UK's 'net zero' territorial emissions generation commitments (UK Legislation, 2019). In previous analyses (Alabi et al., 2020; Turner et al., 2018) we have begun to investigate the wider economic impacts of transitioning from conventional to electric private transportation in the UK context. We have identified a particular source of potential expansion in the fact that fuelling vehicles using electricity involves exploiting stronger UK supply chain 'multiplier' relationships than is currently the case with relatively import-intensive petrol and diesel (Turner et al., 2018).

Our initial applied computable general equilibrium (CGE) analysis (Alabi et al., 2020), considered the impacts of projected near-term spending in the order of £2.7billion to upgrade the UK electricity network in support of a limited 20% EV rollout by 2030 in terms of how expansion trajectories may be constrained by even short-term price pressures.

Here we turn our attention to longer-term scenarios, where there is a need to consider how the wider infrastructure upgrade (and larger associated costs), greater EV penetration, and the differences in consumer behaviour in terms of when charging takes place impacts on the potential outcomes. We also focus on the importance of labour market conditions. Such focus is crucial for any nation, given the central role of the supply and cost of labour in governing how the wider economy responds to any decarbonisation (or other) policy action. However, it is increasingly important for the UK, where a key outcome of Brexit is to reinforce and tighten the national labour supply constraint, and a desire to raise real wage rates and associated incomes (HM Treasury, 2021) challenged by the potential implications for producer costs and consumer prices (Bank of England, 2021). Generally, this paper addresses a key gap in the literature regarding how the wider economy impacts of enabling and realising EV rollouts are affected both by wider economy conditions, with specific focus on labour markets, and by conditions directly associated with enabling and realising such a transformative shift.

Our central focus is to consider the nature and distribution of the net gains that might be anticipated, in what timeframes, to better understand the impacts and consequences of constraints more fully as well as the opportunities for sustained economic expansion. We develop our multi-sector economy-wide CGE framework for the UK to focus on the extended and substantial cost of network upgrades required to enable almost full (99%) EV penetration in the private fleet by 2050 in the UK. Particular attention is devoted to the impacts of differential speeds of consumer responses to 'smart charging' capability on the level of network upgrade cost required and the subsequent adjustment of the economy.

Our overarching objective is to develop an evidence base that can inform both the wider research community, UK policy makers and regulators on the challenge of developing low carbon policy strategies, here with focus on the decarbonisation of personal transport. In the UK context in particular, a key concern is likely to lie in determining how and where benefits/gains may emerge to offset the large-scale cost of network upgrades, distributed over an extended timescale, to enable what has become a central net zero action in supporting a full EV rollout and uptake by the middle of this century. The specific research questions we address are: 1) How does the electricity network upgrade, cost recovery and the EV rollout combine to impact the wider economy under different charging response scenarios? 2) What is the nature, evolution, and extent of the potential impacts on key economic wellbeing indicators? 3) What sectors of the economy gain the most and which lose out? In addressing these questions, we show that crucial challenge lies in understanding how low/net zero actions are funded and who ultimately pays/bears the burden of cost recovery if outcomes are to be sustainable.

2. Materials and method

We begin by explaining the scenario simulation strategy and modelling approach we use to address our research questions in the UK context. The objective of our simulation strategy is to analyse different approaches to electricity network investment to enable the expected EV rollout in the UK, with attention to how different 'smart charging' adoption rates may impact both the required network upgrade costs and resulting outcomes for the wider economy and sectors. We use UKENVI, a multi-sector, economy wide, dynamic CGE model for the UK as the core tool for our analysis. We inform the CGE by drawing information on network upgrade costs and timing, as well as EV energy efficiency in the provision of transportation services, from the outputs of UK TIMES (UKTM) energy system model.[1]

2.1. Simulation strategy and modelling approach

Our approach involves two main steps. First, we formulate EV penetration and smart charging scenarios, informed by relevant literature and 'sense checking' with informed stakeholders in one of the three UK electricity network-operating companies (Scottish Power Energy Networks). We base our simulations in the assumption of the UK reaching 99% EV penetration with 75% of smart (off-peak) charging by 2050, as set out in National Grid's Future Energy Scenarios (FES) 2019 (National Grid, 2019), informed by the method set out in Calvillo and Turner (2020). Note that peak time is defined here as between 17 h and 20 h, which is when people are at home and electricity demand is highest. We consider smart charging as taking place outside those peak hours while 'non-smart' or 'dumb' charging occurs within. 'Dumb' charging increases the maximum electricity demand putting extra pressure to the network.

We develop three illustrative energy system scenarios considering different smart charging adoption rates, i.e., how quickly EV users adopt smart charging. We simulate three energy system scenarios in UKTM to determine the magnitude, timing, and upgrade cost requirements of the necessary network upgrades to enable the EV rollout:

1. 'Mixed charge slow', involving slower adoption of smart charging where 15% of all EVs doing smart charging by 2030, 30% by 2040, then increasing rapidly to 75% by 2050.
2. 'Mixed charge central', involving steady adoption of smart charging with 20% smart charging by 2030, 60% by 2040 and 75% by 2050.
3. 'Mixed charge fast', involving faster adoption of smart charging with 45% smart charging by 2030, 70% by 2040 and 75% by 2050.

A key element we seek to explore through these scenarios is how differences in consumer behaviour can affect the timing, size, and overall economy-wide impacts of the necessary network upgrade to enable the EV rollout. Different consumer behaviors are reflected in their choices regarding the time in which they charge their EVs and how this evolves over time as we move towards a point where 75% of charging takes place in off-peak times. This advances the shorter-term focus of Alabi et al. (2020), here considering 99% EV penetration (rather than 20%) and extending focus from the basic question of how spreading network upgrade activity over a condensed or extended time impacts outcomes.

Table 1 shows the breakdown of the estimated network upgrade cost for the three scenarios to enable the EVs rollout and uptake in the UK private transport fleet between 2020 and 2050, up to 99% penetration (in 2050). This information is drawn from analyses using the UK TIMES (UKTM) energy system model and reflecting the network upgrade cost necessary in each decade to enable a certain level of EV penetration by

[1] Fuller details of the energy system specification are described and discussed in supplementary material 3.

Table 1
Breakdown of network upgrade cost (in £billion) per decade and total, relative to a 'No EV rollout/uptake' scenario, to enable 99% EV penetration in the UK by 2050.

Scenario	2021–2030	2031–2040	2041–2050	Total upgrade cost
Mixed charge_slow	9.10	6.12	1.63	16.85
Mixed charge_central	7.86	1.22	1.60	10.69
Mixed charge_fast	4.41	3.36	2.08	9.84

the end of each decade (see Fig. S1 in Supplementary material 3 for the evolution of the EV penetration). The speed of adoption for each scenario is compared with a 'No EV rollout/uptake' scenario. The transmission and distribution network reinforcement cost per unit that inform the network cost breakdown for the three scenarios (Table 1) is explained in Supplementary material 3 Table S3, while the full projection of the EV penetration and the EV charging scenarios are illustrated in Supplementary Figs. S1 and S2. All three scenarios apply only to private car and van transportation. Other modes of transportation such as buses and heavy good vehicles are not included. The UKTM output also informs on associated efficiency gains in delivering miles travelled (due to technology progress) of about 30% by 2050, relative to 2010 levels (see Supplementary material 3 Table S2 and S3 for more detail on car demand projections and the EV technical parameters respectively).

Our second step involves using the information from the UKTM analyses to reset the three scenarios above for economy-wide simulations in our UKENVI CGE modelling framework, with a focus on examining the wider economy impacts of the pattern and spread of the network upgrade activity and cost recovery programme required to enable the rollout of EVs (see Fig. 2 in Section 4.1). Note that (in the absence of fuller information) we assume the upgrade in each decade is spread evenly over two 5-year planning periods (consistent with the UK energy regulator's 'price control' periods within which network operator investment plans must be developed and deployed). The upgrade costs are recovered over a 45-year timeframe (i.e., the cost recovery is spread over the full average lifetime of the assets), with the repayments beginning at the start of each planning period (with the total costs fully recovered by 2090). A further key assumption, applying to all three scenarios and informed by informal stakeholder engagement, is that one-third of network upgrade cost in each timeframe is made within the UK, where this is focussed on construction rather than equipment requirements. The remaining component of the of the network upgrade cost (i.e., two-thirds) of other necessary materials, equipment and services is assumed to constitute imported goods and services required to upgrade the UK network. As we use a national CGE model, we do not model external production of goods and services, but we do model the spending on them. Further details are given in Section 4.1.

2.2. *The UKENVI CGE model*

UKENVI is currently calibrated on a 2010 UK Social Accounting Matrix (SAM) – the most recently available at the time the research was conducted, and which we treat as reflecting the real economy in the effective policy year 2020 - that includes all sectors of the UK economy aggregated to 30 industries/commodities. Supplementary material 1Table A1 details the sectoral breakdown of UKENVI mapped to specific Standard Industrial Classification (SIC) 2007 codes. UKENVI has previously been used to consider the economy-wide impacts of a range of energy economics, energy policy topics and net zero actions (e.g., Allan et al., 2007; Lecca et al., 2014; Turner, 2009; Turner et al., 2019). Here, we draw on the variant developed to consider transport specifications and fuel use, developed, and extended in Figus et al. (2017, 2018), with further adjustments to permit the adoption of EVs in private transportation developed in Alabi et al. (2020). Here, we present the key assumptions, parameters and elements of the model required for computing and simulating the scenarios set out above, before explaining our CGE scenario simulation strategy.

2.2.1. *Household consumption*

We assume that private consumers (households) are myopic and in each time period make consumption decisions based on the following general form:

$$C_t = Y_t - S_t - HTAX_t - CTAX_t \tag{1}$$

where C represents the total consumption, Y is the income, S are the savings where we assume a fixed marginal propensity to save, $CTAX$ is the direct tax on consumption, and $HTAX$ is the income tax, all for period t.

Of the different components of household consumption specification, the key one for this paper is the private transportation decision. Households can meet their private transportation needs by using either electric (ET) or conventional transportation (NET) vehicles. We assume a Leontief demand function for both private transportation options, meaning that the shares of the two are fixed rather than determined from changes in relative prices.

$$NET_t = \beta_t^{NET} T_t$$

$$ET_t = a_t^{ET} T_t \tag{2}$$

In (2), T is the total private transportation with a_t^{ET} and β_t^{NET} being the shares of electric and non-electric transportation. As we do not consider any other options, $a_t^{ET} + \beta_t^{NET} = 1$. In the base year, the conventional vehicles are the dominant option of meeting households' private transportation needs, with β_t^{NET} starting at a value of 98% in the base year. Consequently, electric vehicles' (EVs) initial share (i.e., the initial value of a_t^{ET}) is calibrated at 2% in the base year, which is representative of the current share of EVs in the private transportation market. However, over time, a_t^{ET} is exogenously determined in order to simulate the increased penetration of EVs, until they reach a 99% penetration in 2050.

Of the other goods and services consumed by households, the other key one for this work is electricity, which is used to heat and light, and run appliances within their properties, as well as for transportation. The demand for electricity is determined as follows:

$$ELET_{h,t} = \delta_h^{ele^{\rho eg}} \left(\frac{PET_t}{Pele_t}\right)^{\rho^{et}} ET_{h,t} \tag{3}$$

$$ELE_{h,t} = \delta_h^{\rho^C} \left(\frac{CPI}{Pele_t}\right)^{\rho^C} C_t \tag{4}$$

In both (3) and (4) P_{ele} refers to the price of electricity. Eq. (3) is the demand function for electric transportation with ET being the electric private transportation, as in (2), PET is the price of electric transport, δ_h^{ele} is a share parameter and ρ^{et} is the elasticity of substitution between electric vehicles and electricity.[2] Eq. (4) is the demand function for household electricity demand. In (4), C reflects the total household demand, CPI is the consumer price index and ρ^c is the elasticity of substitution between the consumption of residential energy and other goods and services.

2.2.2. *Industry production function*

We model $i = 1, \ldots, N = 31$ industries, including separately identified

[2] The elasticity of substitution is set at 0.5, indicating that fuel and vehicles are complementary goods, but allow the consumer some flexibility in their choice of what combination of fuel and vehicles delivers the desired private transportation services, rather than imposing a fixed proportion of fuel and vehicles.

energy industries and a new EV manufacturing sector. In the knowledge that it is existing manufacturers switching to EVs, where most of supply chain will be retained but with the main differences in terms of services inputs (e.g., financial, insurance and other professional services) for operating and running the industry, a useful starting point in identifying an 'EVs Manufacturing' industry is to disaggregate the existing UK 'Motor Vehicles Manufacturing' industry/conventional vehicle sector identified in the national accounts. This means that we assume that the new EVs sector shares the same input structure (including labour intensity) as the existing conventional vehicle sector, an assumption driven by a current lack of data in the appropriate (input-output) format on how EV production may differ. Crucially, we note that the nature and/or extent of the impacts modelled below may differ if this assumption is relaxed, providing a key focus for future research. At present, the basic development is to breakout these vehicles manufacturing sectors to enable substitution between non-electric and new EV vehicles (as they roll out) in the household consumption choice for private transportation as discussed in Section 2.2.1.

The full list of the sectors in our model is available in Supplementary material 1 Table A1. Production X in each industry is determined through a nested constant elasticity of substitution (CES) production function, structured as shown in Fig. 1.

We assume a KLEM production function where capital and labour (KL) combine to form the value-added (Y) nest and energy (E) and non-energy (Material, M) intermediates combine to form the intermediates nest (INT). The default value of the elasticity of substitution between the value-added and intermediate nests is set at 0.3 (see Turner, 2009). For simplicity (and in the absence of better information), we also use the same elasticity between capital and labour, as well as energy and non-energy intermediates. Note that to fully inform this elasticity parameters econometric estimates are required of all the production structures. At this stage, in the absence of this inform and in the interest of transparency we are making a judgment call that there is substitutability, and it is relatively inelastic which allows us to capture direct and indirect effects. We assume no endogenous change in the production technology so as to isolate impacts driven by the EV rollout and the necessary network upgrade.

Focussing on the use of specific sectors' outputs as intermediate goods for other sectors, the most important one for this paper is the output of the electricity generation sector. The output price of this sector is affected, apart from changes in the cost of labour and capital, by the demand for electricity for transportation (see above) and also by the cost of the network upgrade (see Section 2.2.3). The electricity used as an intermediate input by each sector j is defined as follows:

$$INTele_{j,t} = \left(A^{E\rho_j^E} \left(\delta_j^{INTele}\right) \bullet \frac{PE_t}{Pele_t} \right)^{\frac{1}{1-\rho_j^E}} \bullet INTEN_{j,t} \tag{5}$$

In (5), ρ_j^E is the elasticity parameter between electricity and non-electricity energy goods in production, PE is the price of the composite energy good, P_{ele} is the price of electricity and INTEN is the total energy demand by sector j.

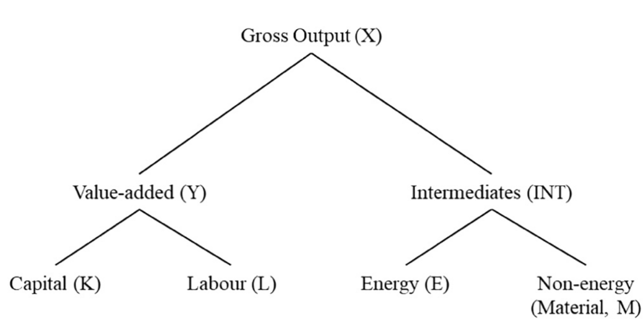

Fig. 1. Production function in UKENVI.

2.2.3. The network upgrade repayment

All UK users of electricity (i.e. both households and both public and private production sectors) need to cover the full network upgrade cost through energy bills, with this cost recovery spread over a 45-year period that broadly maps to the lifetime of the new assets created. Here, Eqs. (3), (4) and (5) show that there is a common endogenous price P_{ele} for all the electricity users. In order to cover the network upgrade costs, we need P_{ele} to include a mark-up on the price in a perfectly competitive market, i.e. the marginal cost of electricity production and supply.

$$P_{ele_t} = P_{elemc_t} \bullet (1+\theta_t) \tag{6}$$

In (6), θ is the mark-up so the difference between the two prices is the marginal profit rate of the electricity firms.

$$mp_t = P_{ele_t} - P_{elemc_t} \tag{7}$$

Multiplying the marginal profit rate to the total revenue of electricity sales gives us the total profit (NTW).

$$\overline{NTW_t} = mp_t \left(\sum_h ELE_{h,t} + \sum_w INTele_{\delta,t} \right) \tag{8}$$

We exogenously determine the total profit to be equal to the annual repayments of the network upgrade. Introducing a non-zero value to NTW, leads to an appropriate increase of θ to get the marginal profit required in order to cover the network upgrade repayments. It is important to highlight that the annual repayments are not fixed here, and they fluctuate as more parts of the network upgrade programme are implemented. This means that the mark-up to electricity price also has to adjust for changes in the size of the annual repayment.

2.2.4. Investment

We assume that capital in all production sectors is determined through a process of forward-looking investment. We follow Hayashi's (1982) treatment of an optimal path of investment in each industry, derived from maximising the V_t value of firms subject to a capital accumulation function K_t*:

$$MaxV_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r} \right)^t [\pi_t - I_t(1+g(x_t))] \tag{9}$$

Subject to $K_t^* = I_t - \delta K_t$. In (9) π_t is the firm's profit, I_t is the private investment, r is a discount factor and $g(x_t)$ is the adjustment cost function, where $x_t = {}^{I_t}/_{K_t}$, and δ is depreciation rate. The solution of this intertemporal problem produces the adjusted Tobin's q time path of investment along with the law of motion of the shadow price of capital λ_t. We assume that the economy has reached its new equilibrium when the desired capital stock is equal to the actual capital stock. At this point net investment is zero, with gross investment only covering the depreciation of the existing capital stock.

2.2.5. Labour market

Sectoral labour demand is determined as follows:

$$L_{j,t} = \left(A^{Y\rho_j^Y} \bullet \delta_j^l \bullet \frac{PY_{j,t}}{w_t} \right)^{\frac{1}{1-\rho_j^Y}} \bullet Y_{j,t} \tag{10}$$

In (10) the nominal wage w_t effects the level of labour demand in all sectors. PY refers to the price of value added. We assume that the national labour supply is fixed (i.e., there is no flow migration or other market response to labour shortages beyond adjustment in the pool of unemployed labour). For our default or central case, we assume that wages are determined by a bargained real wage function, in which the real wage is directly related to workers bargaining power and negatively related to the rate of unemployment. We employ the bargaining function and approach as in Blanchflower and Oswald (2009):

$$ln\left[\frac{w_t}{cpi_t}\right] = \omega - \varepsilon ln(u_t) \tag{11}$$

where w_t is the nominal wage, cpi_t is the consumer price index, ω is a parameter calibrated to the steady state and u_t is the UK unemployment rate, which is assumed to start from a base value of 6%.[3] This pool of unemployed labour ensures that any additional labour demand can be met by the domestic labour force, which we assume remains constant given our fixed labour supply assumption. ε is the elasticity of wages related to the level of unemployment rate and in our model takes the value of 0.113 (Layard et al., 1991). We examine the impacts of this real wage determination assumption, particularly in the presence of the national labour supply constraint, by conducting sensitivity analyses where we imposed a fixed real wage closure. This involves holding the real wage fixed/constant so that the nominal wage is adjusting to offset any changes in the economy-wide prices, reflected by the CPI.

2.2.6. Government and trade

The government budget (*GB*) is given by government revenue (*GY*) minus government expenditure (*GEXP*):

$$GB_t = GY_t - GEXP_t \tag{12}$$

Here we assume that total *GEXP* is fixed so the government spends the same nominal amount on goods and services over the different periods. On the other hand, *GY* changes over time as the activity in the UK economy changes due to the EV rollout. The budget is not constrained to balance with the implication that government can accumulate savings or deficit, depending on the relative changes between revenue and expenditure. In the base year, GB_t is negative, indicating a fiscal deficit that we assume to be passive. Crucially, this treatment of the Government budget allows us to track the impacts on public budgets driven by the EV rollout and the network upgrade, an approach motivated by a current lack of information on how current vehicle/fuel taxation may be reset in the EV context (where UK policy decision makers may use CGE model outputs to inform fiscal modelling).

We do not impose a trade balance, similarly, to track the full potential impacts on variables of policy concern in enabling and realising the EV rollout, here with a particular focus on competitiveness. We assume that all producers and consumers use a combination of domestically produced and imported goods and services, where imports from two exogenous regions - rest of the EU (REU) and rest of the world (ROW) – substitute for domestic goods under the Armington assumption of imperfect substitution (Armington, 1969). Production sectors can also sell output domestically or export to the two exogenous external regions via a constant elasticity of transformation (CET) function. We assume that the nominal price of goods and services in the external regions is fixed, meaning that the demand for UK exports and imports is sensitive to changes in relative prices between (endogenous) UK and (exogenous) REU and ROW prices (Armington, 1969). We set a default value of export price elasticity of 2 (see Turner, 2009) but subject this to sensitivity analyses in Section 4.4.

3. Building on the emerging theory and literature on economic and socioeconomic impacts of the decarbonisation of transport

There is a growing number of economy-wide impact studies, generally also using CGE methods, to consider the economic and socioeconomic impacts of regional, national, and global decarbonisation pathways in transportation, where the aim is to quantify the contribution of the whole of transportation to emission reduction in relation to other sectors in the economy. In some cases, this includes consideration of how low carbon emission vehicles (e.g., battery-electric vehicles, plug-in hybrid-electric and hydrogen fuel cell vehicles) as part of the transitional actions within the transport sector contribute to carbon dioxide (CO_2) emissions reduction (Li et al., 2017; Thalmann and Vielle, 2019; Zhang et al., 2018). Karkatsoulis et al. (2017) use a CGE framework to consider the role of transport in enabling deep CO_2 emission reduction in European Union (EU) and the decomposition of the impacts on key macroeconomic indicators such as GDP, investment, private and public consumption, exports and imports based on reference and decarbonisation scenarios.

The literature also includes some examples, where CGE is employed to assess direct and indirect impact of different policies options around incentivising and/or enforcing the deployment of electrification of transportation under different market conditions and regulations using economic and policy-based instruments (e.g., taxes, subsidies and pricing schemes) (Abrell, 2010; Hirte and Tscharaktschiew, 2013). Robson et al. (2018) provides a review of CGE development and modelling for transportation. Other CGE studies explore household transport demand, consumption, and expenditure patterns and behaviors over different timeframes that may influence the total energy demand, welfare cost and carbon taxes under different emissions reduction scenarios (Berg, 2007; Dai et al., 2012; Rajbhandari et al., 2019).

Some CGE studies focus primarily on the model design, architecture and formulation particularly in terms of the different approaches on how to introduce low carbon vehicles, alternative fuels and other energy technologies within model structure or functions (Karplus et al., 2013; McFarland et al., 2004; Shahrokhi Shahraki and Bachmann, 2018). Several studies focus on how to link CGE to other modelling frameworks (e.g. energy system and transport models) in order to better represent and/or capture technological details, physical demand and performance of different transportation choices and modes (Schaefer and Jacoby, 2005, 2006); Del Granado et al., 2018; Krook-Riekkola et al., 2017; Pietzcker et al., 2014).

Other questions considered in the wider literature include cost effectiveness and benefit analysis of different low carbon vehicles (Hao et al., 2020) and life cycle assessment and economic impacts of expanding charging infrastructure (Javid et al., 2019). Attention is also given to socio-technical, and socio demographic factors influencing willingness to pay and adopt EVs as well as the implications of consumer preferences, response and attitudes to the sustainability of the transition to low-carbon vehicles (Chen et al., 2020; Codani et al., 2016; Duluweera et al., 2020; Glitman et al., 2019; Noel et al., 2019).

Our contribution adds to this growing literature by focussing on two interacting but fundamentally quite different phases of enabling and realising EV rollouts: the impacts of costly upfront network upgrade activity and the EV rollout itself, where the former may act to constrain any expansionary power associated with the latter. For instance, we consider, whether the main source of expansionary power associated with the stronger and relatively high value added/high value wage domestic supply chain content of the UK electricity industry demonstrated in Turner et al. (2018) may be offset due to the price pressures emerging from the network upgrade activity and the cost recovery programme in the presence of a national labour supply constraint and associated wage adjustment. In line with other studies, we do set this contribution in the context of linking information flows between economic focussed CGE and other types of models. Here, we set particular focus on drawing information on network upgrade costs and implications for private transport delivery to inform CGE scenario simulations from an energy system model with more detailed treatment of energy supply and use specifications and other technical characteristics (Bataille et al., 2006; Drouet et al., 2005; Schaefer and Jacoby, 2006). However, our more central focus is on using the applied case of investment in UK electricity network upgrades to enable extensive EV rollout with a view to identify the types of drivers of and constraints on wider economy expansion that may or may not be present and/or differ

[3] This rate is calculated by converting UK unemployment in 2010 as published by Office of National Statistics (ONS) https://www.ons.gov.uk/employmentandlabourmarket/peoplenotinwork/unemployment#timeseries to full time equivalent (FTE) for modelling purposes.

in other national contexts.

4. Results

Here we present and explain our results, starting with the UKTM energy system scenario simulations, focussing on the outcomes for the required electricity network upgrade cost, which then inform our CGE simulation of interacting enabling and realising stages to report the nature and timing of economy-wide impacts. This section concludes with consideration of key sensitivity analyses.

4.1. Evolution of electricity network upgrade costs

In Section 2.1, we discuss how the network upgrade cost requirements vary for the scenarios we examine. Fig. 2 shows how the total network upgrade cost derived from the energy system model informs the evolution/pattern of the network upgrade cost to 2050 and the cost recovery by 2090, for each of the three scenarios simulated in the CGE model. In all three cases, the EV rollout is the same and builds up at a rate of 20% by 2030, 80% by 2040 and 99% by 2050 (see Supplementary material 3 Fig. S1). However, the timing and spread of the upgrade cost under the three scenarios is different. In the slow scenario, the adoption of smart EV charging takes longer than in the other two scenarios, leading to a considerably larger need for network upgrade cost. In addition, the slow rate of 'smart charging' adoption translates to larger upgrade requirements in the earlier years of electrification of transport, £8billion by 2030. This amount is 57% and 14% higher than that of the fast (£6.7bn) and central (£3.2bn) scenarios respectively for the same year.

These differences are driven by larger share of 'dumb' (non-smart) charging (i.e., peak-time charging - see, Supplementary material 3 Fig. S2 and S3) in the slow case up to 2040, which increases the pressure on network capacity. For our scenarios where large upfront upgrades are necessary by 2030 (i.e., the slow and central scenarios), the wider adoption of smart EV charging, leads to gradual reduction in the additional network upgrade cost required. The combination of smaller total cost and faster adoption of smart charging means that in our central scenario the spending requirement reduction is faster compared to the slow scenario. On the other hand, the fast scenario does not require a large up-front upgrade cost, with total network upgrade costs more evenly distributed from 2030 to 2050. This implies that for the fast scenario consumer responses enable more gradual and overall lower network upgrade cost, triggering more moderate increases in price of electricity, and thereby constraining the adjustment process less than in the other two scenarios.

4.2. Long-run economy wide impacts of enabling and realising the EV rollout

The different network upgrade costs, and the EV rollout they enable, effectively act as a series of demand shocks in an economy-wide setting. However, only the EV rollout will deliver sustained wider economy impacts, with the alternative network upgrade cost scenarios that enable it triggering transitory stimuli only. Thus, a central characteristic of our CGE model simulations is that – given common wider economy constraints applying to all three scenarios – the nature and composition of the long-run outcomes results will be invariant across all three scenarios. The transition process, on the other hand, *is* sensitive to the different network upgrade cost scenarios, we examine this in Section 4.3. Table 2 summarises the long-run results for some key macroeconomic indicators, which emerge after the economy has fully adjusted following the completion of the network upgrade activity in 2050 and recovery of costs at 2090, with reporting relative to the unchanging 2010 base year values given by the SAM, where the economy is assumed to be in equilibrium.

The key driver of the sustained boost to GDP (ultimately rising to 0.162% higher than it would otherwise be) is the shift away from relatively import intensive petrol/diesel towards electricity where, in the UK, the supplying sector supports a relatively strong domestic upstream supply chain. Crucially, we find that household adoption of EVs, and the switching to the use of electricity to fuel them, provides the main source of expansionary power due to the stronger and relatively high value-added domestic supply chain components of UK electricity relative to refined fuel supply chain. This outcome is in line with the findings in Turner et al. (2018), which examine the existing supply chain linkages underlying the multipliers of the UK electricity vs. refined petroleum supply chains. Underlying this is a boost to both intermediate and final (mainly household) demand for UK goods and services that is sufficient for most UK industries – crucially excluding those supplying conventional vehicles and fuel - to enjoy net increases in activity expansion. Fig. 3 reports the pattern of long run impacts on sectoral employment gains that underpin the net positive effects on total employment (0.12% or 29,329 additional full-time equivalent (FTE) jobs). The shift in sectoral employment favours higher wage sectors (e.g., among the aggregated Service sector[4]) so that there is a sustained increase in real earnings (0.22%).

Note that both GDP and real earnings from employment grow proportionately more than employment. This reflects a change in the composition of activity characterised by a higher average wage employment (the UK average wage increases by 0.1%) and increased productivity (increasing by 0.04% in Table 2). While not reported in Table 2, we also note that the sustained economic expansion ultimately enables an estimated £354million per annum savings accruing to the public budget. This could be important in considering how, wider economy returns to the public purse from enabling the shift to EVs could be used, for example in replacing lost revenues from petrol/diesel taxation.

However, the sustained expansion of the UK economy is constrained by price and income effects in the presence of the lasting labour supply constraint. Meeting what is ultimately a sustained demand stimulus driven by increased household spending (0.18%) where costs of production across the economy are affected particularly by a higher nominal wage rate (0.29%), which causes a sustained increase in output prices across the economy (see Fig. 4), and a sustained increase in the CPI (0.162%). This dampens real gains in household spending, while constraining and changing the composition of real GDP expansion, with a sustained decrease in total export demand (0.35%). UK imports also fall, in part because of the reduced reliance on petrol and diesel. However, as the sensitivity analyses in Section 4.4 show, the quantitative results in Table 2 are sensitive to what we assume about wage adjustments and the trade response to different changes in UK price levels.

Fig. 3 shows net positive long-run changes in employment in most sectors resulting from a combination of shifts and increases in domestic consumption demand set against falling export demand, and associated supply chain impacts in both cases. The biggest beneficiary is the UK electricity sector, which becomes the main provider of private transportation fuel, with the increase in the price of its output (0.15% in Table 2) having more limited impact given the largely non-traded nature of activity and inelastic domestic demand. Smaller gains are observed in sectors where households mainly spend their income, such as 'Wholesale and Retail Trade', 'Accommodation and Food Service Activities' and the heavily aggregated 'Services' sector. As may be expected, conventional vehicle manufacturers and the producers of refined petroleum fuels are the main losers. However, other, more export intensive industries such as 'Chemicals and Pharmaceuticals' and 'Electrical Manufacturing' suffer net losses due to the competitiveness impacts of the sustained

[4] UK domestic service industries such as technical and other professional services (including e.g. finance and insurance) constitute around 67% of the share of indirect and induced output-employment multiplier impact of the UK electricity industry's supply chain (Turner et al., 2018).

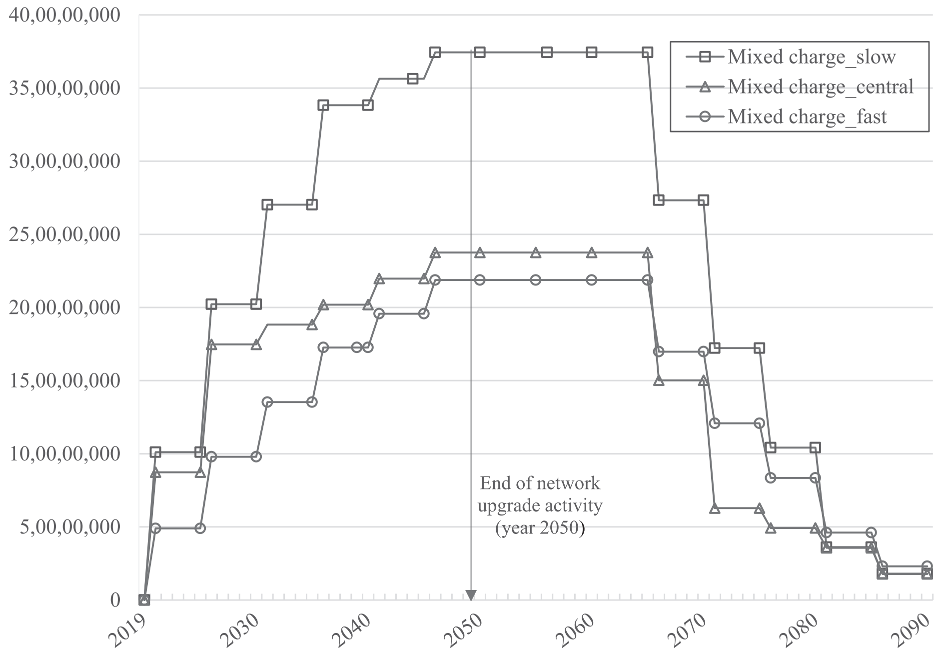

Fig. 2. Evolution of total network upgrade cost and repayment for central, fast and slow scenarios to enable the 99% EV rollout by 2050.

Table 2
Long-run impacts (% change relative to base year) on key macroeconomic indicators associated with the 99% EV penetration in the UK by 2050, enabled by electricity network upgrades.

Macroeconomic indicator	Base year values (2010)	Central scenario (Bargained real wage, BRW) (% change relative to base year)
Real gross domestic product (£million)	1,306,294	0.162%
Employment (FTE)	24,930,573	0.118%
Real earnings from employment (£million)	801,407	0.223%
Real household spending	891,463	0.175%
Real average wage (£)	32,146	0.105%
Productivity (£ GDP per employment FTE)	52,397	0.044%
Nominal wage rate (indexed)	1	0.291%
Real wage rate (indexed)	1	0.128%
Consumer price index (indexed)	1	0.162%
Price of Electricity output (indexed)	1	0.152%
Imports (£million)	117,186	−0.287%
Exports (£million)	351,557	−0.349%

increase in labour costs.

4.3. *The evolution of impacts on key macroeconomic 'well-being' indicators*

Given the timeframe involved in enabling and realising the rollout of EVs to the extent of 99% penetration in the private fleet by 2050, it takes a long time to reach the new long-run equilibrium results presented in Section 4.2. Just how the economy transitions, not least in the early years when there are likely to be significant levels of new costly decarbonisation activity - where the question of 'who pays' may be particularly politically contentious – is a key policy concern. Fig. 5 shows the evolution of impacts on GDP, employment, and real household spending under the central, fast and slow network upgrade cost scenarios to enable the 99% EV penetration by 2050.

The combination of greater upfront, and overall, network upgrade cost requirements in the 'slow' scenario triggers a faster and higher adjustment trajectory in the price of electricity (Fig. 6), which rises steeply from the early 2030s, reaching a peak of 0.34% by 2050 (end of network upgrade activity), before decreasing steadily and smoothening out to the long run. This coincides with a markedly slower trajectory of gains in real household spending in Fig. 5. Underlying this is real earnings from employment growth that outpaces employment in all timeframes and scenarios, with the implication that the UK enjoys real average wage growth from the outset regardless of the network upgrade cost and path. However, real spending is dampened by the increasing CPI generally, and the rising price of electricity therein, with electricity spending taking an increasingly larger share of the household consumption basket with the shift to EVs before levelling off in the mid-2040s and 2050s. This is maximised when repayment of network upgrade cost through electricity bills is at its highest level, with recovery of early and later network upgrade costs having a cumulative impact due to the practice of spreading cost recovery over 45-year asset lifetimes.

Over time, the sustained driver of wider economy expansion and of public budget gains (see Fig. 7) becomes the shift to fuelling vehicles using electricity, which unlocks value in relatively high wage and GDP-intensive domestic supply chains. Similarly, after an initial slump, where employment grows faster than GDP in the very early periods (where the only real source of economic expansion is in network upgrade spending on construction activities), UK labour productivity (GDP/employee/hour of work) also grows throughout most of the transition timeframe.

On the other hand, rising prices across the UK economy, reflected in the trajectory of the CPI – including sustained impacts on the price of electricity as a particular area of policy concern in any policy involving increased electrification - does constrain and drive the change in the composition of real GDP expansion. Fig. 6 shows that the trajectory of falling export demand is similar across all three scenarios, with a maximum decline of 0.37% drop soon after 2050 before levelling off at the 0.35% long-run decline reported in Table 2. However, as we see in Fig. 6 there is limited difference in the export losses between the central and slow scenarios, where the main difference is the price of electricity. This indicates that despite the importance of the electricity cost for the level of household spending (see Fig. 5), the difference in electricity prices have limited impact on the competitiveness of UK exporting

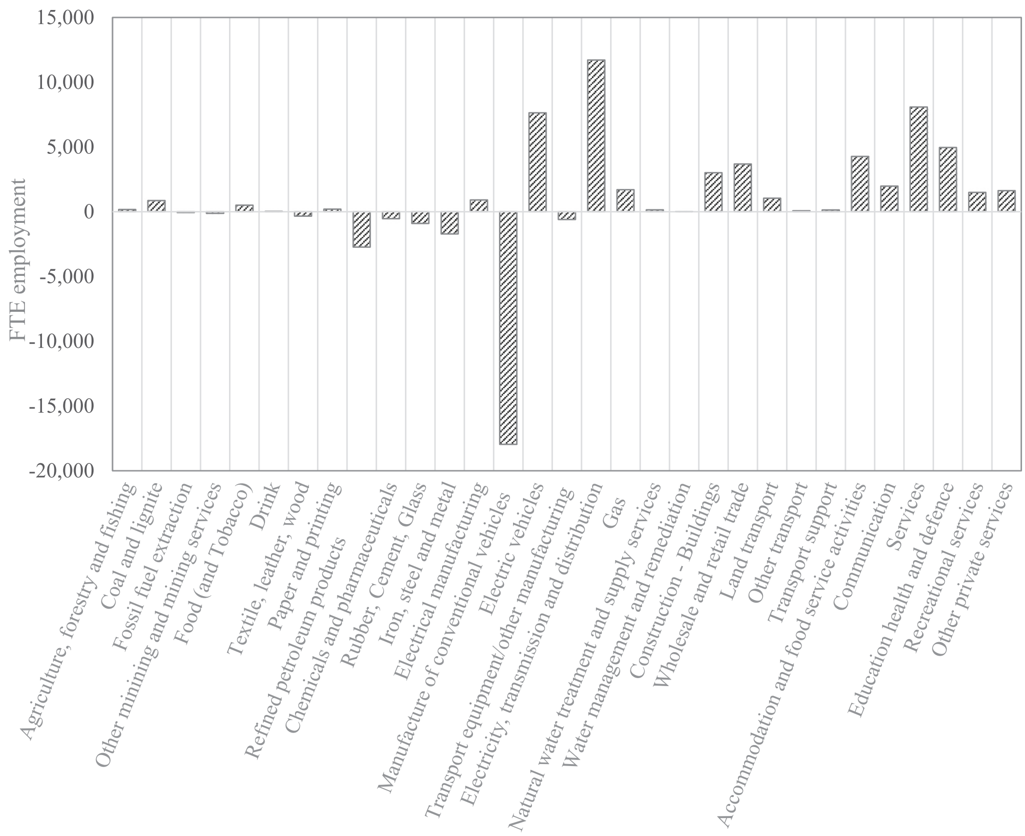

Fig. 3. Long run impacts of sectoral employment (FTE change relative to base year) from 99% EV penetration in the UK, enabled by electricity network upgrades.

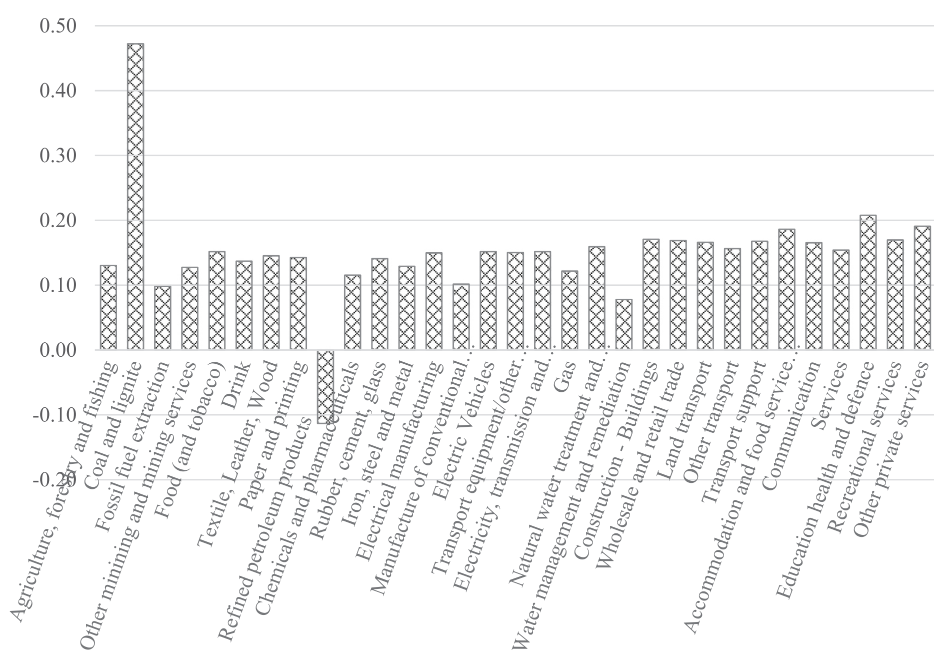

Fig. 4. Long run impact on sectoral output prices (% change relative to base year) from 99% EV penetration in the UK by 2050, enabled by electricity network upgrades.

sectors.

4.4. Sensitivity analysis

We find that the key determinants of the outcomes reported in Sections 4.2 and 4.3 are (a) what we assume about the price responsiveness of export demand (where empirical data to inform elasticities is limited in the UK case); (b) the impacts of rising wages in the presence of a national labour supply constraint.Taking the former first, as discussed in Section 2.2.6, we assume that domestic and imported goods are

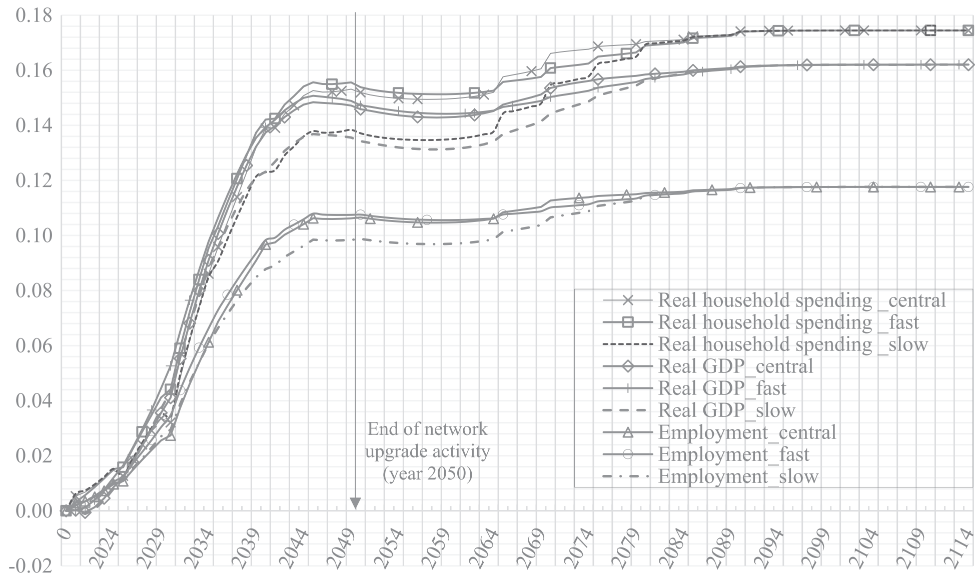

Fig. 5. Evolution of net impacts (% change relative to base year) on UK GDP, employment and household spending for central, fast and slow scenarios to enable the 99% EV penetration by 2050.

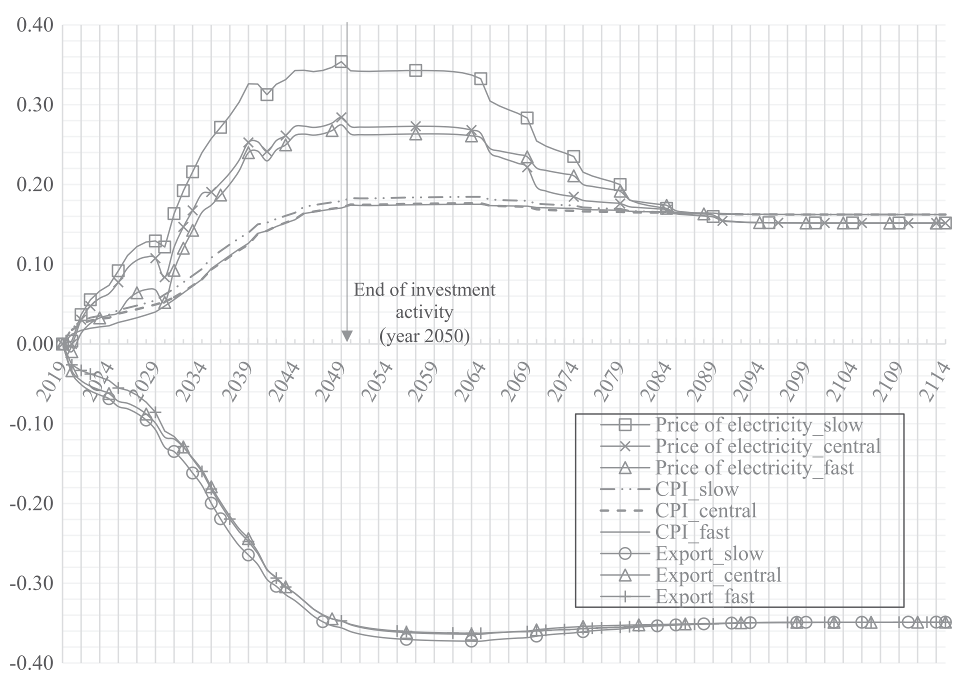

Fig. 6. Evolution of net impacts (% change relative to base year) on UK price of electricity, the CPI and exports for central, fast and slow scenarios to enable the 99% EV penetration by 2050.

imperfect substitutes. This applies to goods used by UK consumers and industries but also for goods consumed in the external regions, where we assume an export price sensitivity of 2.0 in the central case scenarios above. The latter is the crucial determinant of the extent of the sustained expansion reported. Table 3 shows how the long run impacts on key macroeconomic indicators are impacted by raising or lowering this elasticity.

Table 3 shows that with a lower, export price sensitivity of 1.2, we observe higher sustained boost and economic expansion reflected in greater GDP (0.189%), employment (0.139%) and household spending (0.209%) gains relative to the base (2.0) case, where the effective negative competitiveness impacts of higher prices are greater. This is accompanied by even greater productivity and average wage gains. The greater expansion does generate more pressure on nominal wage rates and (while not shown here due to space constraints) output prices, but the lower trade responsiveness ultimately mitigates the negative impacts. The opposite is true when we introduce a higher export price sensitivity. Here the impact of the domestic price pressures on the CPI is only more limited in the final column of Table 3 because the offsetting contraction in export demand triggered by even minimal price pressures reduces the extent of the wage pressure driving further price increases. In short, the results in Table 3 demonstrate that domestic demand driven growth has more expansionary power where price effects have less impact on the competitiveness of exports.

Thus, it becomes even more crucial to understand the source(s) and driver(s) of domestic price pressures. For example, we found that the

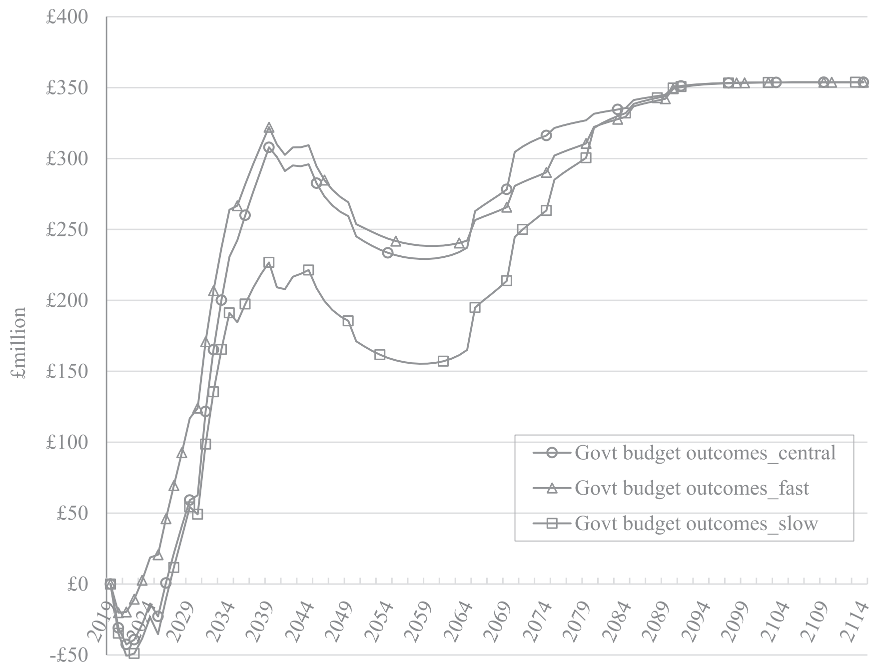

Fig. 7. Evolution of government budget outcomes (£m change relative to base year) associated with the 99% EV penetration in the UK by 2050, enabled by electricity network upgrades.

Table 3
Long-run net impacts (% change relative to base year) on key macroeconomic indicators associated with the 99% EV penetration in the UK by 2050, enabled by electricity network upgrade and varying export price sensitivity of (1.2), (2.0) and (4.0) [all BRW].

Macroeconomic indicator	Base values	Export price sensitivity (% change relative to base year)		
		(1.2)	(2.0)	(4.0)
Real gross domestic product (£million)	1,306,294	0.189%	0.162%	0.124%
Employment (FTE)	24,930,573	0.139%	0.118%	0.087%
Real earnings from employment (£million)	801,407	0.268%	0.223%	0.158%
Real household spending	891,463	0.209%	0.175%	0.126%
Real average wage (£)	32,146	0.129%	0.105%	0.071%
Productivity (£ GDP per employment FTE)	52,397	0.050%	0.044%	0.038%
Nominal wage rate (indexed)	1	0.348%	0.291%	0.209%
Real wage rate (indexed)	1	0.152%	0.128%	0.094%
Consumer price index (indexed)	1	0.196%	0.162%	0.114%
Price of electricity output (indexed)	1	0.179%	0.152%	0.113%
Imports (£million)	117,186	−0.194%	−0.287%	−0.414%
Exports (£million)	351,557	−0.256%	−0.349%	−0.475%

extent of transitory increase and adjustment path of the price of electricity is sensitive to the magnitude of electricity network upgrade cost and timing of the cost recovery (as shown in Fig. 6). However, we also found that the upgrade cost has no influence on the long-run economy-wide impacts. Thus, we turn our attention to wage determination as a key driver of prices across the economy in the presence of a lasting labour supply constraint. The presence of wage pressures drives lasting price pressures across the UK economy, cushioning demand and restricting the long-run economy-wide expansion that could be possible from what is effectively a demand shock as UK households shift their delivery of personal transport services to EVs and electric fuelling. Therefore, the second element of our sensitivity analysis is to consider how the impacts reported in Table 2 are affected if the real wage does not adjust.

In Table 4, the second data column reports the impacts on the selected macroeconomic indicators from fixing the real wage (FRW) relative to the central case in the third. Here imposing FRW depicts what the outcomes would be if wage pressures where effectively removed, with some small wage adjustments in place to maintain the purchasing power of workers.

Recall, that one of the key outcomes demonstrated under our central BRW scenario is that household adoption of EVs, and the switching to

Table 4
Long-run net impacts (% change relative to base year) on key macroeconomic indicators associated with the 99% EV penetration in the UK by 2050, enabled by electricity network upgrades under bargained real wage and fixed real wage assumptions.

Macroeconomic indicator	Base values (2010)	Fixed real wage (FRW) (% change relative to base year)	Central scenario (Bargained real wage, BRW) (% change relative to base year)
Real gross domestic product (£million)	1,306,294	0.385%	0.162%
Employment (FTE)	24,930,573	0.334%	0.118%
Real earnings from employment (£million)	801,407	0.317%	0.223%
Real household spending	891,463	0.257%	0.174%
Real average wage (£)	32,146	−0.017%	0.105%
Productivity (£ GDP per employment FTE)	52,397	0.051%	0.044%
Nominal wage rate (indexed)	1	0.015%	0.291%
Real wage rate (indexed)	1	0.000%	0.128%
Consumer price index (indexed)	1	0.015%	0.162%
Price of electricity output (indexed)	1	0.031%	0.152%
Import(£million)	117,186	−0.385%	−0.287%
Export (£million)	351,557	−0.005%	−0.349%

the use of electricity to fuel them, shift the economy to higher and sustained quality GDP and employment. In the first instance, we find/observe that the shift to higher quality GDP still holds even with FRW, given that GDP increases (0.385%) more than employment (0.334%) as reflected by the productivity (GDP per employee) gains (0.051%). On the other hand, when we turn attention to consider the quality employment and/or employment gains, the outcome is mixed. Minimising the wage pressures via a FRW assumption allows for greater consumption demand, both domestically and abroad, compared to our central case, as there is a significantly smaller increase in prices (reflected by the CPI). The implication is that with smaller labour costs, jobs are created and retained across the UK economy. As in the BRW case, there are significant employment gains in higher wage sectors (e.g aggregated 'Service' sector), partly linked to the switch from fossil fuels to electricity as the main fuel for private transportation.

However, we also see that there are considerable employment gains in sectors offering wages below the national average (£32,147), such as 'Accommodation and Food Services' (£17,816) and 'Wholesale and Retail Trade' (£26,219). The change in the composition of economic activity leads to the fall in the average real wage. However, there are two important points to consider here. First, the average wage does not reflect the different compensations of employees within each sector, therefore is not a perfect measure to understand the changes in the quality of employment. Secondly, despite the apparent fall in average wage it is key to highlight that this is driven by more employment opportunities in sectors requiring less specialised workers. As such this outcome could be politically important if there a scope to alleviate poverty among UK households by creating additional jobs.

Overall, a fixed real wage then allows for a higher sustained GDP expansion, associated with greater gains in employment, real household earnings and spending. Note that while cutting of real wage growth causes a net reduction in the average real wage, household earnings rise as a result of increased employment opportunities, while the smaller increase in prices will equate to a greater level of household spending (0.257%).

5. Summary of key outcomes

Our scenario simulation analysis demonstrates that investment in electricity network upgrades to support the EV rollout has the potential to help shift a transitioning economy like the UK onto a pathway with higher and better quality GDP, as reflected by the impact on labour productivity, earnings, and average wage trajectories in all three network upgrade scenarios simulated under our central scenario. The key driver in the UK case analysed here is the shift to fuelling vehicles using electricity, where the domestic electricity industry has extensive high value added/GDP supply chains, and away from more import-intensive petrol/diesel. This outcome reinforces some of the previous findings in Turner et al. (2018) on the strength and impact of the UK electricity supply chain. However, where there are any lasting constraints on the economy – here in terms of the UK labour supply (where any flow migration in and out of the economy becomes increasingly limited by that nation's exist from the EU) – price pressures will constrain the transition path and long run outcome of what is effectively a domestic demand driven expansion. Moreover, where price pressures lead to relative competitiveness loss, this will further change the composition of GDP, with export-dominated sectors suffering alongside those supplying conventional vehicles and fuel.

We also find that what happens to the price of electricity also acts to constrain gains in real household spending power in particular. While we have not focussed on impacts within different household income groups, this is generally a concern for UK policymakers and regulators. Our results show that, particularly in timeframes where the costs of the network upgrade must be recovered from consumers, and most notably where slow consumer responses to 'smart' charging capability, electrification of transport is likely to put pressure on UK electricity prices, which are already relatively high to begin with (Eurostat, 2019). Where the electricity industry also faces sustained pressure on labour costs as the constrained economy expands, this feeds through to lasting impacts on the electricity bills of all users, but with household consumption baskets impacted through the dual impacts of greater reliance on higher cost electricity as they shift to using EVs to deliver personal transport needs.

6. Conclusion

In this paper, we have set out to consider questions around the wider economy impacts and consequences of the interaction of enabling and realising the rollout of EVs and the associated large-scale electricity network upgrade cost. Our scenario simulations suggest that in the case of the UK investment in electricity network upgrades to facilitate the EV rollout will both drive a wider transitionary expansion and enable the economy to move onto a higher and sustained trajectory. The expansion delivers ongoing and cumulative public budget returns that may play a role in balancing the fiscal implications of shifting away from relatively highly taxed current fuel sources. However, the transition path is impacted by both the level and timing of the network upgrade cost and both the adjustment process and long-run outcome will be constrained by price pressures driven by rising wage costs where the labour supply is constrained. Moreover, the extent of the impact of such constraints depends on export demand responses as sectors across the UK economy lose competitiveness.

However, a range of further research questions and challenges emerge. In the UK context studied here, findings around the impacts on real household spending power in general and electricity prices in particular are issues of policy and regulator concern. Thus, the scenario analyses reported here should extend to update the model framework as data developments allow. This is important to capture any differences in production processes and/or input requirement of EVs sector and to begin to consider impacts in different household income groups, and to address questions around how benefits/costs of the expansion align or not to more direct benefits of the EV uptake (where there is much debate over affordability in the UK). Another avenue for future research is further sensitivity analysis to explore the potential impacts of varying elasticity of substitution between the CES combination of fuel and vehicles in the model structure.

A more generic challenge is to consider the extent to which the types of findings here may apply in other nations which, while potentially similarly supply constrained, may face different challenges in terms of the level and nature of infrastructure investment required to support increased EV penetration and, crucially, how the network upgrade is funded. Moreover, all nations will have different needs and priorities in terms of the role of electrification in meeting net zero alongside other energy and climate policy ambitions. In a UK context, learning from this EV-focussed research also delivers important insights in terms of the implications of engaging in, and funding, large-scale electricity network upgrade, and the importance of considering what is gained and lost in moving from one means of delivering energy dominated services to another.

Data availability statement

The 2010 UK Social Accounting Matrix (SAM) data underpinning the economic wide system analysis in this study are openly available at https://doi.org/10.15129/7b6e088f-c9ef-4ec4-9df7-58c46ec23d67. The energy system analyses that informs the economy-wide analysis in this study is based on multiple open data sources, including academic literature and UK government databases, including the Department for Business, Energy & Industrial Strategy (BEIS), Driver and Vehicle Licensing Agency (DVLA) and Department of Transport (DfT). More information on the related data sets is available at https://www.ucl.ac.uk/drupal/site_energy-models/sites/energy-models/files/uk-times-ove rview.pdf and http://www.climatexchange.org.uk/reducing-emissions/using-times-model-developing-energy-policy/

Declarations of interest

None.

CRediT authorship contribution statement

Oluwafisayo Alabi: Project administration, Investigation, Formal analysis, Writing – original draft. **Karen Turner:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Antonios Katris:** Investigation, Formal analysis, Writing – original draft. **Christian Calvillo:** Investigation, Formal analysis, Writing – original draft.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2022.106001.

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