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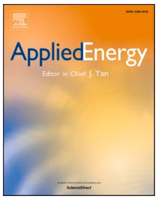

Assessing the energy and socio-macroeconomic impacts of the EV transition: A UK case study 2020–2050

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HIGHLIGHTS

- The energy and socioeconomic impacts of the UK's EV transition are not well known.
- We model energy changes to efficiency and fuel switch to electricity.
- Most significant impacts stem from energy system change not investment stimulus.
- The EV transition could realise an extra 0.5%/yr of GDP growth.
- But economy-wide rebound effects reduce energy savings from the EV transition.

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ABSTRACT

The electric vehicle (EV) transition is underway in the UK and many other countries worldwide, switching from fossil fuel powered internal combustion engine (ICE) road transport to EVs that can be powered by renewable electricity. Whilst the projected energy and carbon reduction impacts are well understood, we have only a partial view of the potential socio-macroeconomic effects of the EV transition, i.e. the impacts on GDP and jobs. Common energy-economy models feature only limited energy-economy integration, and only assign a small role for energy in economic growth. Thus whilst economic changes such as increases to investment can feed into macroeconomic impact assessment, the impacts of the energy system changes are potentially underestimated.

In response, we use a novel macro-econometric model – MARCO-UK – to conduct a whole system analysis with two main scenarios: an ICE baseline (with no EV transition) and 100% EV transition scenario to 2050. We investigate the effects of the scenarios on the UK's energy system (efficiency, energy services, rebound) and economic system (employment, GDP, debt), under different conditions of investment, rebound and electricity prices.

We find the most significant impacts stem from energy system changes, with annual economic growth rising from 1.71%/year (baseline) to 2.25%/year in the main EV scenario. In contrast, the impacts from economic investment changes are much lower in scale. Therefore, the socio-macroeconomic benefits of the EV transition may be underestimated. We also find that overall long-term economy-wide rebound in our central EV scenario is 76%, which means the energy savings from the EV transition may be less than hoped. Overall, our analysis identifies potential trade-offs regarding the labour market, levels of indebtedness, energy rebound and associated carbon emissions that should be taken into consideration.

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1. Introduction

1.1. The global EV transition is underway

In 2019 road transport [1] contributed 16% (6.0GtCO_2) to global carbon emissions (37GtCO_2). Most of road transport emissions come from passengers cars, and are therefore a priority mitigation sector in efforts to reduce global greenhouse gas (GHG) emissions. Many national Governments are planning a rapid transition away from fossil fuel powered internal combustion engine vehicles (ICEV) to renewable electricity based Battery Electric Vehicle (BEVs), as a key part of efforts to decarbonise and meet the climate targets of the Paris Agreement [2]. Fig. 1 shows the results of a survey of 33 global decarbonisation scenarios (from 18 models), where BEVs comprised a median of 56% of the vehicle fleet in 2050 2 °C scenarios and median of 87% in 1.5 °C scenarios. Those very high shares represent a very significant change from the 16 Million BEV stock in 2021 [3], which is only a 1.5% share of the global 1.1Bn car fleet. However, EV sales are rapidly increasing, representing 9% of global car sales in 2021, four times their market share in 2019 [3].

In the UK, a rapid transition to EVs is underway, and not before time, as the transport sector (of which road transport is the largest part) emitted 16% of total UK GHG emissions in 2021 [5]. However, the UK, after a slow start is now moving quickly through both renewable electricity installations (mainly offshore wind) and EV adoption curves. In 2010, renewable electricity comprised 7% of all UK electricity produced [5], whilst BEVs were $< 0.1\%$[1] of all road vehicles sold. In 2021, renewables formed around 40% of all electricity produced [5], with BEVs comprising 15% of all new road car sales in October 2023.[2] Various factors are playing a part in the rapid EV uptake in the UK, including setting phase out target of 2030 (now 2035) for new ICE cars [6]; EV grants to lower purchase costs[3]; rising diesel/gasoline prices; clean air zones in 13 UK cities[4]; lower EV car manufacturing costs and longer EV battery ranges [3].

1.2. EV modelling studies have been limited to climate and implementation impacts

Much of the literature effort to study the EV transition until now has been on two fronts. On one hand, the inclusion of EVs (combined with renewables) projections has been a key inclusion of energy-climate models to understand the carbon saving potential of EV transitions as they "*offer the largest decarbonisation potential for land-based transport*" [7]. On the other hand, studies have focussed on the technical aspects of EV roll out, such as understanding diffusion/take up rates [8], and deployment requirements of EV charging infrastructure [9,10].

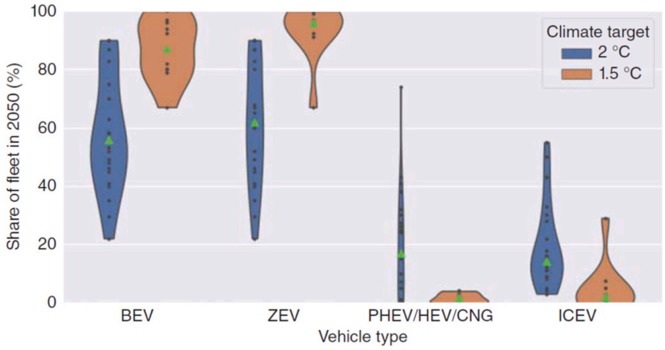

Fig. 1. Illustration of switch of road-based transport from ICEV to BEV in 33 surveyed decarbonisation scenarios for 1.5′C and 2.0′C Paris targets. [4], p.188.

In part, this focus reflects the immediate needs of policy makers charged with implementing GHG mitigation policies, to address key start up questions such as:

- *How large is the mitigation EV prize?*
- *What needs to be done to start/maintain EV take up?*
- *How will we best supply the renewables-based electricity needed for the low carbon EV transition?*

In part though it also reflects the strengths of key existing modelling types, as we now set out for three common types of models. First, energy system models (ESMs) and integrated assessment models (IAMs) are typically energy-sided, technology rich cost-optimisation models. They focus on EV deployment and technology cost curves, and can link to climate modules to understand the impacts of EV take up on future emissions. Examples at a European-wide level who studied EVs as part of a larger mitigation scenario include Capros et al. [11] using PRIMES, Neniškis [12] using MESSAGE, and Koasidis et al. [13] using GCAM. In the United States, adopting a whole systems approach, Carvallo et al. [14] study the technical, economic, and rate impacts of green technologies including EV infrastructures. In the UK, Calvillo and Turner [15] used the UK TIMES model (UKTM) to study the planned large-scale EV rollout in the UK in terms of network investments, changes in fuel use, fuel cost and emissions.

Secondly, Computational General Equilibrium (CGE) models have also been commonly used in EV studies. They are economically-sided models, in the neoclassical tradition. Examples at a European level include Tamba et al. [16] who used a CGE model to estimate the macroeconomic impacts across the EU of the EV transition. In the UK, a prominent example is Alabi et al. [9] who studied with the UK-ENVI CGE model the macroeconomic benefits of EV infrastructure network investment. Typical metrics reported by CGE studies include changes to GDP, GVA and employment.

A third type are Environmentally-Extended Input-Output (EEIO) models. These are again economic-sided models, which have detailed representation of economic sectors via their input-output structure based on national accounts, with energy/emissions environmental extensions used to determine energy/emissions sectoral intensities. Therefore, their strength lies in being able to estimate the impacts of potential changes in economic structure due to the EV transition, and outturn changes to key macroeconomic variables including sectoral GVA (and thus in sum, GDP) and employment. A prominent EV example is Dejuán, Portella-Carbó and Ortiz [17] who used EXIOBASE-3 to examine the global impact of the replacement in the EU of fossil fuels by 2050 in electricity generation, road transport, and households. Key variables reported were changes to yearly energy consumption, CO_2 emissions, and employment. Another example is. Ríos et al. [18], who used an EEIO model to estimate the impact of the increased use in Spain of electric cars (EV) on production, GVA, employment, and GHG emissions. In addition to these studies, the field has seen valuable insights from research utilizing a combination of EEIO and partial equilibrium models [19]. This integrative approach provides a comprehensive understanding of potential energy rebound by considering both the broader economic context and specific industry dynamics.

1.3. Macroeconometric models offer a different approach to understanding EV transitions

The three model types outlined above are the dominant macroeconomic energy-economy model types used in EV analysis, and have been useful up to this point to address deployment and implementation

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[1] https://obr.uk/box/the-transition-to-electric-vehicles/

[2] https://www.smmt.co.uk/2023/11/october-new-car-market-beats-pre-pandemic-levels-but-subdued-ev-growth-hinders-green-goals/

[3] https://www.gov.uk/plug-in-vehicle-grants

[4] https://www.gov.uk/clean-air-zones

questions. However, as we move into the world where the EV transition is fully underway, a greater awareness is needed of two key issues that have not been well covered to this point: (1) the impacts from the energy system changes on the economy, and (2) the broader socio-macroeconomic impacts of the EV transition. Limitations exist in the previously outlined three key types of models as to how they can provide this information. First, ESM/IAMs are technology-rich but are normally linked to a much more aggregate economic module or soft—linked model. Therefore, detailed economic impacts are limited. Second, conversely, the neoclassical KL(E) production function construction within CGE models give energy systems only a secondary, minor 'cost-share' [20,21] based role in economic growth. In addition, clearing markets and perfect substitution via endogenous prices does not take into consideration imperfect competition, macroeconomic disequilibrium and existing substitution rigidities between energy technologies, which can also be applied to partial equilibrium models. The effect is to limit the impacts of energy changes on the socio-economy. Last, EEIO models only access static IO table 'snapshots' i.e. for a given historical year, and also can report changes to only a few macroeconomic variables, such as employment, GVA and (in sum) GDP. Therefore, whilst they provide energy-economy insights well at the static/annual timescale, they are not ideally suited to future, long-run trend analysis or a reporting on a broader set of macroeconomic indicators [22].

As an alternative, macroeconometric models by their construction offer a credible, complementary approach to studying EV transitions and assessing the long-term dynamics of energy and economy systems. They are therefore well suited to the study of combined energy (EV transition) and economic (investment, production) questions, as the models are better balanced (than ESMs/IAMs or CGE models) and provide time-series impacts which the CGE and EEIO models cannot. Key examples in the climate change mitigation analysis literature include Mercure et al. [23] who used their E3ME global model to examine global mitigation policy, and Ulrich and Lehr [24], who used the PANTA - RHEI model to study potential economic effects of an *E*-mobility scenario in Germany. Last, the MEDEAS model has been used to study the limits of global transport decarbonisation scenarios [25].

However, whilst they are better suited to dynamic energy transition topics such as EVs, key limitations remain even with these models. To the best of our knowledge, none of these macroeconometric models extend their energy stage to the useful stage, or therefore, include thermodynamic energy efficiency. These are desirable features to extend the energy analysis to allow the quantification of energy services, and better include in the role of efficiency in economic growth and energy rebound pathways in the modelling framework.

In response, we have developed a new, enhanced macroeconometric model – MARCO-UK - which can address these limitations, and to study the EV transition question in the UK. The UK makes a good case study due to the available data, and the key fact it is undergoing at pace the EV transition. MARCO-UK is a Post-Keynesian Economics (PKE) model which is well balanced between energy and economy, and uniquely includes energy conversion/efficiency at the heart of the model. An overview of the model is given in Section 2, with more detailed structure given in the Supplementary Information (SI). The econometric model runs historically from 1971 to 2019, and is set up to run future analyses for 2020–2050. The robustness of the methods applied in this article is reinforced by the previous papers with MARCO-UK, that include a study of the role of energy in economic growth [26,27], a study of the socio-macroeconomic impacts of a rapid UK housing retrofit [28] and the impacts of different UK post-Brexit energy targets [29]. MARCO-UK is now version 2, which is now much more refined, including a transport sector. The model has the ability to study the energy impacts (of the economic changes) and the economic impacts of the energy system changes in an integrated dynamic time series response up to 2050. Moreover, we provide extensive information about the scenarios as well as their results (including a data repository) so that other modellers can replicate our analysis and contrast our outcomes [30].

1.4. Paper aims, objectives and structure

The aim of this paper is to use the MARCO-UK model to assess the socio-macroeconomic impacts of the EV transition in the UK up to 2050. The paper is structured as follows: Section 2 presents the methods and data (including the MARCO-UK model overview). Section 3 contains the Results and interpretation, and section 4 concludes.

2. Methods and data

2.1. MARCO-UK model overview

MARCO-UK[5] operates as a macro-econometric model rooted in post-Keynesian economic theory. Unlike models reliant on optimization-driven agent behaviour, MARCO-UK determines intertwined causal relationships between macroeconomic variables through econometric equations grounded in historical data. That means that our equations, as having passed all the required econometric validation checks, find historical evidence of those causal relationships for the analysed period (1971–2019) and country (UK). The model conceptualizes the economy as a non-equilibrium system, acknowledging that markets often operate under sub-optimal conditions, deviating prices and quantities from optimal, market-clearing levels. Post-Keynesians assert that prices are set by firms employing some form of mark-up pricing, recognizing that the interplay of supply and demand can influence prices in certain markets. The assumption prevails that, in most scenarios, not all resources are optimally utilized, allowing for spare capacity in the economy. This surplus capacity facilitates demand-led economic growth in both the short and long run. In the short term, production adapts to increased demand by maximizing capacity utilization, while in the long run, the economy's total capacity adjusts to demand through heightened investment levels. However, Post-Keynesian theory acknowledges that supply-side factors, particularly insufficient labour supply, can restrict production under unique circumstances.

MARCO-UK encompasses 183 socio-technical-economic variables, encompassing thermodynamic-based energy variables such as primary energy, final energy, and useful exergy, along with thermodynamic efficiency at primary-to-final and final-to-useful conversion stages. Notably, MARCO-UK stands as a pioneering whole-system energy-economy-wide model to incorporate thermodynamic (energy) efficiency and the useful stage of energy consumption, represented as useful exergy in Fig. 2. The integration of thermodynamic efficiency and useful exergy empowers an exploration of their respective roles in economic growth.

Useful Exergy (UEX) is the energy utilized at the final energy conversion stage just before exchanging for energy services. The final-to-useful stage, infrequently explored at an economy-wide scale, is highlighted in Fig. 2, where the majority of thermodynamic energy conversion losses occur. Including this stage in modelling frameworks holds potential for enhancing the evidence base for energy efficiency policies and understanding their impact on economic growth.

These energy variables are fully integrated into the model structure, departing from the conventional approach of loosely linking energy and economy modules. The main critique to econometric models is a side effect of their main strength: they rely on observed relationships among the components of a system in the past, which do not necessarily continue over long periods of future time. Whereas a significant body of the literature employing econometric models simply warn about this limitation, in this article we deal with it as best as we can, by analysing a wide variety of scenarios (including extremes that allow a better understanding of sensitivity) and applying potential constraints to them –like the maximum directrebound. In fact, the model is intentionally designed to accommodate exogenous variables, enabling the

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[5] A fuller description of the model's version 1 is contained in Sakai et al., (2019) whereas the detailed description of version 2 can be find in the SI

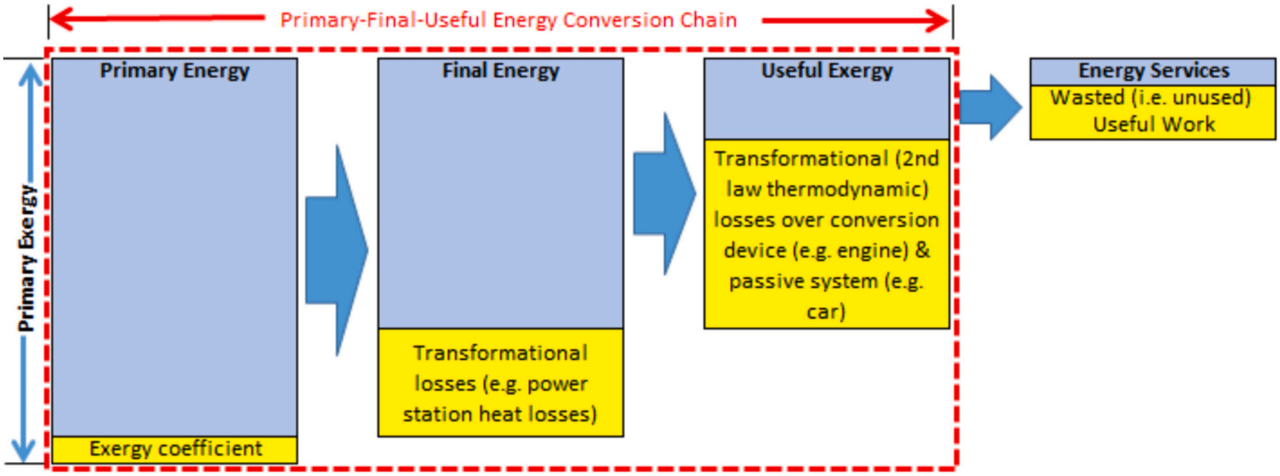

Fig. 2. MARCO-UK includes energy at primary-final-useful energy stages. (From [31]).

formulation of scenarios that deviate from historical trends, providing robust evidence supporting such deviations. Thus, MARCO-UK facilitates the exploration of ex-ante scenarios, investigating the macroeconomic effects of prospective policies. Positioned as a simulation model, recognised for its realistic approach compared to models grounded on rarely-observed equilibrium in markets, MARCO-UK as an econometric model is able to capture disequilibrium, propagate disturbances, and evaluate policy effects across the analysed system [32].

2.2. Model construction

Like other macroeconometric models, MARCO-UK contains two types of equations. The first type involves definitional relationships, also known as 'identities', which represent definitions of given variables and must hold true in all time periods. The second type of equations are known as 'behavioural' or 'stochastic', which contain parameters estimated econometrically. MARCO-UK contains 102 equations: 25 stochastic and 77 are identities. The main identities are given by the accounting definitions of gross domestic product (GDP). From the expenditure side, GDP is equal to the sum of Households (HH) and public (G) consumption, capital investment (I) and net exports (X-M) From the income side, GDP is defined by total national income: compensation of employees (W), gross operating surplus (PROFIT) plus net taxes on products (NET_TAX), resulting in Gross Value Added (GVA). These two identities must hold for each time period:

$$GDP = GVA = HH + I + G + (X - M) = W + PROFIT + NET\_TAX$$

Each of the components of GDP are estimated econometrically on an individual basis through a stochastic equation. The particular functional forms and choice of explanatory variables are empirically validated and tested using econometric techniques. HH depends mostly on wages and disposable income (positively) and consumer prices (negatively), I on the expectations to realise profits (via the profit rate, i.e. the ratio between profits and the gross capital stock), X on the rest of the world GDP and exchange rates and M on domestic growth of income, energy services and exchange rates. It is important to highlight the exergy-economy nexus. It effectively operates through capital investment (I), as expectations and "animal spirits"[6] are proxied by the evolution of profits and energy services (the more rapid energy services are growing, the higher expected demand would be considered). The same connection operates for HH, as greater exergy efficiency incentivise consumption -in turn, contributing to increased incentives for producers to increase investment. W depends on labour productivity and labour demand, NET TAXES is a fixed share of GDP and PROFIT depends on HH, G and income (W and disposable income). There are now 5 main sectors in MARCO-UK: Transport (TPT), Commercial, Public & Services (CPS), Agriculture, Forestry & Fishing (AFF), Households (HH) and Industry (IND) which, in turn, split into 12 sub-industries (see SI). Gross Value Added (GVA) is broken down in all of them except HH, as it does not produce GVA; Final Energy (FEN) is broken down in all of them, plus Non-Energy Use (NEU) and Not Elsewhere Specified (NES); Useful Exergy (UEX) is split in the 5 main sectors plus NES; Energy Prices (P_EN) are disaggregated by the 5 main sectors, and are a result of the fuels' prices and the sectors' final energy mix. A detailed description of the model dynamics and equations can be found in Sakai et al. [26,27], Nieto, Brockway and Barrett [28], and in the SI.

Fig. 3 shows a schematic of the relationships between energy and economic variables found at the core of the model. Blue arrows represent positive relationships -i.e. increase (decrease) leads to increase (decrease) - and red arrows negative relationships -i.e. increase (decrease) leads to decrease (increase). FEN_{sk} is endogenously estimated by sector "s" and the final energy mix obtained via exogenous shares for "k" sources: electricity (ELEC), oil products (OIL), coal & coal products (COAL), natural gas (NG), biofuels, waste and others (BIOWASTE).

$$FEN_k = \sum share\_fen_{sk} * FEN_s$$

$$FEN_s = f\left(\overbrace{expenditure\&income}^{+}, \overbrace{p\_en}^{-}\right)$$

Where expenditure & income relates to different macroeconomic variables such as the components of GDP - private (C) and public (G) consumption, investment (I) and imports (M)- and GVA by sectors. Typically, these variables have a positive effect on FEN, whereas P_EN has a negative effect. Once FEN demand is estimated, the useful exergy obtained depends on final to useful efficiency (uex_eff_s). Hence, useful exergy UEX_s is an identity as:

$$UEX_s = uex\_eff_s * FEN_s$$

Where uex_eff_s is estimated by combining the historical trend and the deviation from it, which is endogenously estimated with a stochastic behavioural equation, resulting in a function as the following:

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[6] The term "animal spirits" was first used by John M. Keynes in "The General Theory of Employment Interest and Money" and implies that economic decisions are grounded in the spontaneous nature of human behaviour, rather than in rational optimising mathematic calculation. The main consequence for Keynesian and post-Keynesian modelling is that aggregate demand importantly depends on the expectation of the economic cycle.

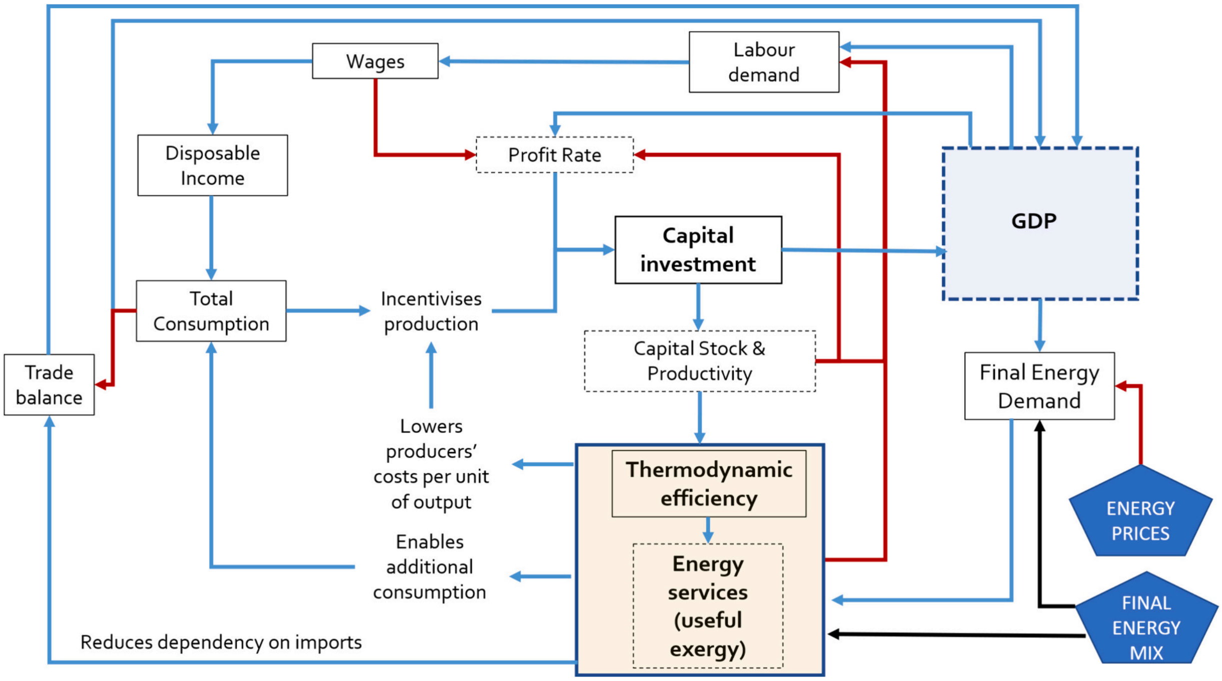

Fig. 3. *Schematic MARCO-UK model structure (adapted from Nieto* et al.*,* [29]*).*

$$uex\_eff_s = f\left(\overbrace{FEN\ mix}, \overbrace{trend}^{+}, \overbrace{capital\ stock\&productivity}^{+}\right)$$

The FEN mix imposes a variety of effects in useful efficiency depending on the sources and the sectors. For instance, in the TPT sector, the OIL share has a negative effect in efficiency whereas it is positive in the IND sector. However, as explained below, in this article, the endogenous estimation of efficiency is active in all sectors except TPT, where an exogenous rate has been applied to simulate the EV transition. Although Gross and Net Capital as well as capital and labour productivity also have diverse effects depending on the sector, overall effects have been evaluated as positive -i.e. the higher they are, the higher efficiency is.

Following Fig. 3, we can see that a key driver of the model is the efficiency-growth mechanism. If thermodynamic efficiency increases and allows for growing energy services, our model exhibits three different growth mechanisms, where an increase in efficiency leads to economic growth. First is profitability: the lowering of the producers' costs per unit of output incentivises production, potentially increasing the profit rate, and eventually fostering expanded capital investment. Moreover, it adds to the capital stock, reinforcing the initial efficiency growth. Second is Consumption: The ability to access more energy services with the same amount of final energy would potentially lead consumers to increase expenditure in other sectors, offsetting the initial increase in efficiency. This mechanism directly relates to the 'animal spirits' whereby increased expected demand would lead producers to expand production to satisfy it, inducing new capital investment projects to be unfolded. Third is Trade Balance: The increased capacity to produce and use energy services has historically led to a reduction in the necessity to import additional goods and services. Together, the three mechanisms lead to an increase in income and expenditure (GDP) that, in turn: (i) increases labour demand, total wages and disposable income, reinforcing consumption, and (ii) incentivises increased FEN expenditure, reinforcing the initial thermodynamic efficiency gains.

If the absence of counter-balancing mechanisms, all the above would lead to exponential growth. However, our model also exhibits other dynamics that stabilise growth. First is increased capital investment, which leads to the accumulation of a growing capital stock which tends to push the profit rate down. In addition, increased capital productivity turns labour demand less attractive to employers. Second, increased disposable income and consumption also can increase the demand for imported goods and services. Third, as the economy approaches to full employment, the increase in wages can create a downwards pressure on the profit rate. Fourth, growing energy prices would reduce the demand of final energy (FEN).

2.3. Scenarios and data

2.3.1. Overview of scenarios

Our modelling scenarios run from 2018 to 2050 in MARCO-UK, and feature a sequence of scenarios starting by the MARCO-UK Baseline simulation. Table 1 summarises the characteristics of all the scenarios simulated - detailed scenario data can be found in the data repository. Over that Baseline simulation, additional features have been included sequentially in order to isolate the effects of each additional characteristic. Key variables which are tested within these scenarios are the electrification of the vehicle fleet, rebound effects, electricity prices, capital and consumption expenditure and thermodynamic efficiencies. Due to the integrated model construction (see Fig. 3), changing these variables has a key effect on the model results. The baseline scenario keeps the current ICE-based road transport system in 2050, combined with current historical trajectories for all exogenous variables. Some scenarios (marked with an asterisk in Table 1) have been simulated for sensitivity analysis purposes. For the sake of clarity, their results can be fully consulted in the data repository, but are not included in the main Figures and Tables of this article. However, their implications are briefly discussed in section 3.4. The uncertainty associated with policy-simulation models like MARCO-UK has been addressed through the definition of the scenarios. First, the scenarios are sequential, meaning that each additional scenario includes the effects of one additional variable to better understand its effects. Second, these scenarios include different assumptions (e.g. different electricity prices, investment, rebound limits…) to test the variability of the key scenarios' variables.

2.3.2. Energy system changes

From the overview in Table 1, the following features set out below

Table 1

Summary of scenarios (*These scenarios have only been included to test sensitivity to key parameters. Thus, for the sake of clarity their results are not shown in the results section. However, they can be consulted in the data repository.)

KEY

NOT APPLIED / BASELINE	**APPLIED / LOWER**
APPLIED / MEDIUM	**APPLIED / HIGHER**

Scenario	Code	Electrification of transport				Efficiency of Transport increased		Rebound limits		Additional Expenditure		Electricity Prices
		Electricity share in transport (%)		Oil products share in transport (%)		Final to useful efficiency in the Transport sector (%)		Maximum increase in energy services over Baseline (%)		Increase over the Baseline's **Capital Investment** in year "t" (million GBP/year)	Increase over the Baseline's **Households' Consumption** (million GBP/year)	Variation from Base Year (2018=100)
		Base Year	**2050**	**Base Year**	**2050**	**Base Year**	**2050**	**Base Year**	**2050**	**Average (All period)**	**Average (All period)**	**2050**
Baseline	**_0**	**1.1**	1.1	**94.8**	94.8	**28.9**	Endog	**-**		-	-	102
Additional Expenditure	**_EXP_075***	**1.1**	1.1	**94.8**	94.8	**28.9**	Endog	**-**		+ 5,817	+ 7,816	102
	_EXP									+ 6,813		
	_EXP_125*									+7,810		
EV	**_EV_UNLIM ***	**1.1**	90	**94.8**	5	**28.9**	65.5	**-**		+ 6,813	+ 7,816	102
	_EV							**0**	**29**			
	_EV_ASI							**0**	**0**			
Electricity Prices	**EV_LOWP**	**1.1**	90	**94.8**	5	**28.9**	65.5	**0**	**29**	+ 6,813	+ 7,816	72
	EV_HIGHP											133

are included in all the EV scenarios, to which additional socioeconomic changes also described below are applied. The energy system changes affects the rate of electrification of the transport sector, transport sector's final-to-useful energy efficiency and the limit to the increase in transport energy services that can be obtained out of the efficiency gains.

2.3.2.1. Electrification of vehicle fleet. The suite of EV scenarios all assume that ICE-based road transport is phased out in 2050. This is a reasonable upper bound assumption, given the planned phase out of new ICE car/van sales in the UK by 2035 – which make up over 70% of UK transport emissions [33] - and that new cars have an average lifespan of ~14 years.[7] Although electric vehicles (EVs) cover BEV and other typologies like Hybrid Electric Vehicles (HEVs), BEVs dominate EV scenario deployment, as shown in Fig. 1. HEVs can be considered a shorter term 'transition' technology to reach full use of BEVs. Since our scenarios run to 2050 when HEV are anticipated to be obsolete, we refer to EVs (only) in our scenarios, but this essentially means BEVs. In these scenarios, the final energy mix of the transport sector shifts from mainly oil products (for ICEVs) in the base year to electricity (for EVs) by 2050. Electricity reaches around 95% of the transport final energy mix (see Appendix B).

The other key parameter that changes is final-to-useful efficiency of the transport sector, as a consequence of the transition to EVs. The evolution of this variable has been estimated off-model according to the method and calculations set out in the data repository, and is shown in Fig. 4. Essentially the transition to full EV scenarios doubles overall transport sector final-to-useful efficiency, as ICEVs are around 35% efficient, versus EVs which are over 70% efficient at translating energy into motion.

2.3.2.2. Energy services rebound. Based on the direct rebound literature for transport, we have assumed a limit in the net increase in energy services obtained out of efficiency gains. Following the meta-analysis of 74 primary studies by Dimitropoulos, Oueslati and Sintek [34], this limit would be in the range between 10 and 12% in the short term and 26–29% in the long term. Thus, in this scenario, energy services increase only up to the direct rebound limit. Once the rebound limit is reached, further efficiency gains push final energy use lower, instead of increasing energy services. In the model, this means final energy use of the transport sector $\left(fen_{tpt}\right)$ is no longer treated as a behavioural equation, but as an identity (of two behavioural equations):

$$fen_{tpt} = \frac{uex_{tpt}}{uex\_eff_{tpt}} \tag{1}$$

With uex_{tpt} being the useful exergy (energy services) of the transport sector and uex_eff_{tpt} the final to useful efficiency in the transport sector. As the numerator $\left(uex_{tpt}\right)$ is effectively constrained by the rebound limit, it is expected that this scenario allows for a reduction in fen_{tpt}. In a key model advance, to operate the rebound limit in the model, the following equation has been applied:

$$uex_{tpt} = \begin{cases} uex\_eff_{tpt} * fen_{tpt} \text{ if } uex_{tpt} < uex_{tpt}^{BL} * \gamma \\ uex_{tpt}^{BL} * \gamma \text{ if } uex_{tpt} \geq uex_{tpt}^{BL} * \gamma \end{cases} \tag{2}$$

With $\gamma \geq 1$ being the factor increase in energy services allowed by the rebound limit each year (e.g. if it is 29% increase by 2050, $\gamma = 1.29$). The equation means that only part of the doubling EV efficiency (in Fig. 4) translates as direct rebound in the transport sector, i.e. pushing up end transport service demand (useful exergy) versus baseline. The larger, remaining share of the final-to-useful efficiency gains then reduce final energy in transport, since transport energy services cannot increase further due to Eq. 2 constraints. In turn, savings (from lower energy spend) realise economic (consumer) savings from lower final energy spend, which then act as part of the overall growth mechanism as shown in Fig. 3, associated with an economy-wide rebound effect.

Three different rebound variants have been applied in this analysis. First, where we apply this literature rebound limit progressively as the electrification of the vehicle fleet is deployed in the simulation. This rebound cap holds for all the EV scenarios except for EV_ASI and EV_UNLIM. Second, in the EV_ASI scenario - which simulates the application of Avoid-Shift-Improve policies [35,36,37] - efficiency gains do not end up increasing the distance travelled per passenger -i.e. $\gamma = 1$. Third, the rebound limit is switched off in the EV_UNLIM scenario as a sensitivity analysis test, allowing all efficiency gains to translate to additional energy services.

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[7] https://www.smmt.co.uk/industry-topics/sustainability/average-vehicle-age/

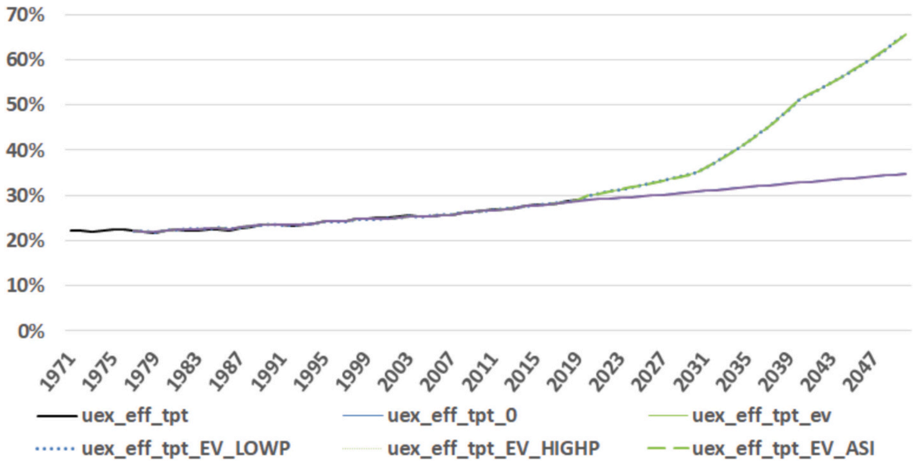

Fig. 4. Final-to-useful thermodynamic efficiency in baseline (ICE vehicle) and EV transition scenarios.

2.3.3. *Economic system changes*

2.3.3.1. Capital Investment and household consumption. We include the capital and consumption expenditures required to unfold the transition to 100% EVs. In order to quantify the figures of additional expenditures, we have applied the estimates found in the Balanced Net Zero (BNZ) scenario in the UK's 6th Carbon Budget [38]. Two important considerations have been made. First, we have split the expenditures between capital investment –when firms buy EVs for their productive processes- and consumption – when households purchase a private car - whereas the 6th Carbon Budget allocates all expenditure to investment. We argue that this is the correct approach not only due to its accordance with the System of National Accounts,[8] but also especially because the macroeconomic implications are very different. Second, we have added the often-disregarded expenditure required to increase the domestic productive capacity. However, capital investment necessary to increase the installed capacity of renewable electricity generation technologies (solar panels, on-shore and off-shore wind farms, etc.) are not considered in this analysis to isolate the direct effects of the shift from ICE- to EV-based transport. By the same token, neither have we included the capital investment in the ICE baseline fossil fuel based energy system (i.e. oil extraction, petroleum refining and distribution).

With that purpose, we have taken into consideration several key aspects: the stock of EV vehicles' to 2050 (49 million EVs in the BNZ); the average pre-pandemic domestic productive capacity; the ratio of vehicles produced over imported, and the rate of scrapping of the new cars. It has been assumed that the % increase over that maximum capacity in the number of vehicles required to produce yearly, entails an equivalent increase of the base year's manufacturing sector's gross capital stock that is added as gross fixed capital formation (investment). Considering the high uncertainty of these figures, a sensitivity analysis has been conducted considering three variants in the production-to-imported ratios of 0.75, 1 and 1.25 –for instance, 1 implies that as many new vehicles are produced domestically than imported. Compared to the effects of the increase in efficiency, the effect of the variation in this parameter is very small. Thus, these variants have not been included in the main analysis -though their results can be consulted in the data repository. Only the central (_exp) scenario is contained in the main analysis shown in this paper.

Thus, we have three different expenditure categories: investment in new EVs made by firms, consumption of new EVs made by all economic agents (especially households) and investment in the additional manufacturing capacity. Scenario "_exp" is implemented to test the effects of additional expenditure alone, so then the effects of electrification and efficiency gains can be clearly isolated. The medium additional expenditure estimates are the ones used in all the other EV scenarios (i.e. _"exp_075" and "exp_125" are disregarded). The additional expenditure profiles are shown in Fig. 5:

2.3.3.2. Energy prices. The uncertainty associated with the evolution of electricity prices has been addressed by first adopting the "medium" BEIS[9] forecasts as the central estimate. Then, in order to check for extreme scenarios that allows for a broader view of the sensitivity of the results to prices, our own "low" and "high" scenarios have been set to be lower and higher than the corresponding BEIS forecasts, which present a comparatively lower variability. The effects of different evolution of electricity prices are assessed in scenarios "_EV_lowp", "_EV" and "_EV_highp". With that purpose, we apply to our modelling framework different price forecasts to 2050 using the UK Government published datasets [39] which give low, medium and high energy price forecasts, summarised in Fig. 6.

In the model, fossil fuel prices are taken exogenously -assuming that these prices are set internationally and that the UK has negligible capacity to influence them- and follow the BEIS' medium forecast. As it would not be justified to assume the same for electricity -its price is normally set domestically, especially as fossil fuels are being phased-out from the electricity mix- two other variants have been estimated, simulating lower (*_EV_lowp*) and higher (*_EV_highp*) electricity prices.

3. Results and interpretation

3.1. *Overview*

Table 2 summarises the differences in key variables under the modelling scenarios, based on the scenario results for 2018 and 2050 shown in Appendix C. Detailed timeseries results for all variables are shown in the data repository. In this section, we present economic and energy results are separately, before discussing key implications and comparing baseline versus EV main scenarios.

3.2. *Socioeconomic system effects*

In socio-economic terms, the outcomes analysed resulted in being relatively more sensitive to the electrification of the vehicle stock than to

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[8] UN System of National Accounts: https://unstats.un.org/unsd/nationalaccount/sna.asp

[9] Buildings, Energy & Industrial Strategy (BEIS) department, now Department for Energy Security and Net Zero (DESNZ)

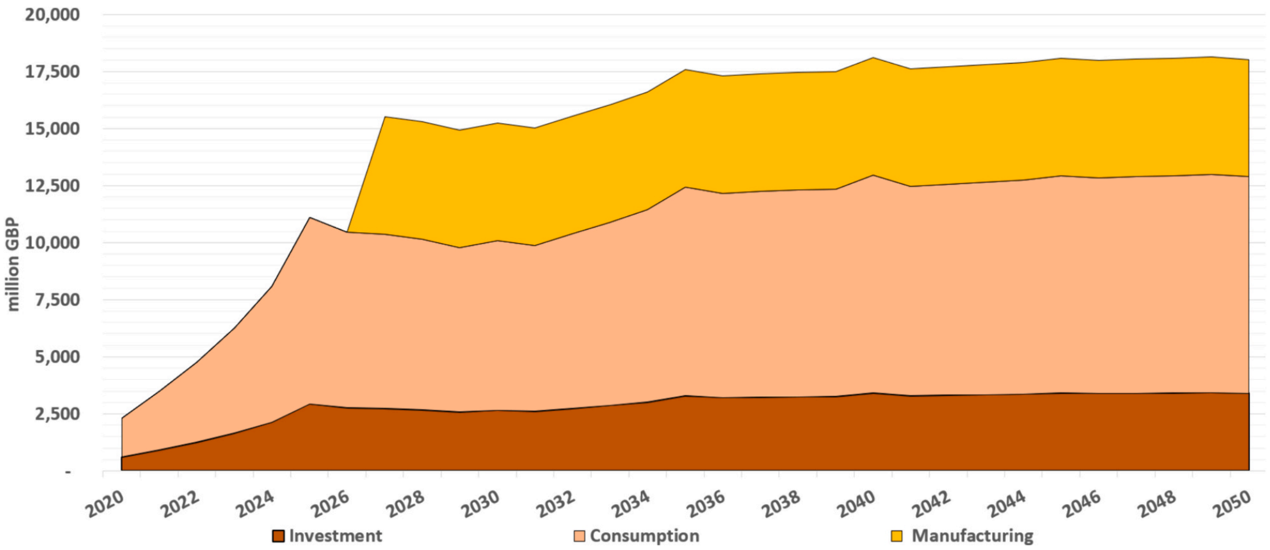

Fig. 5. Additional investment and consumption profiles (refer to data repository for detailed build up).

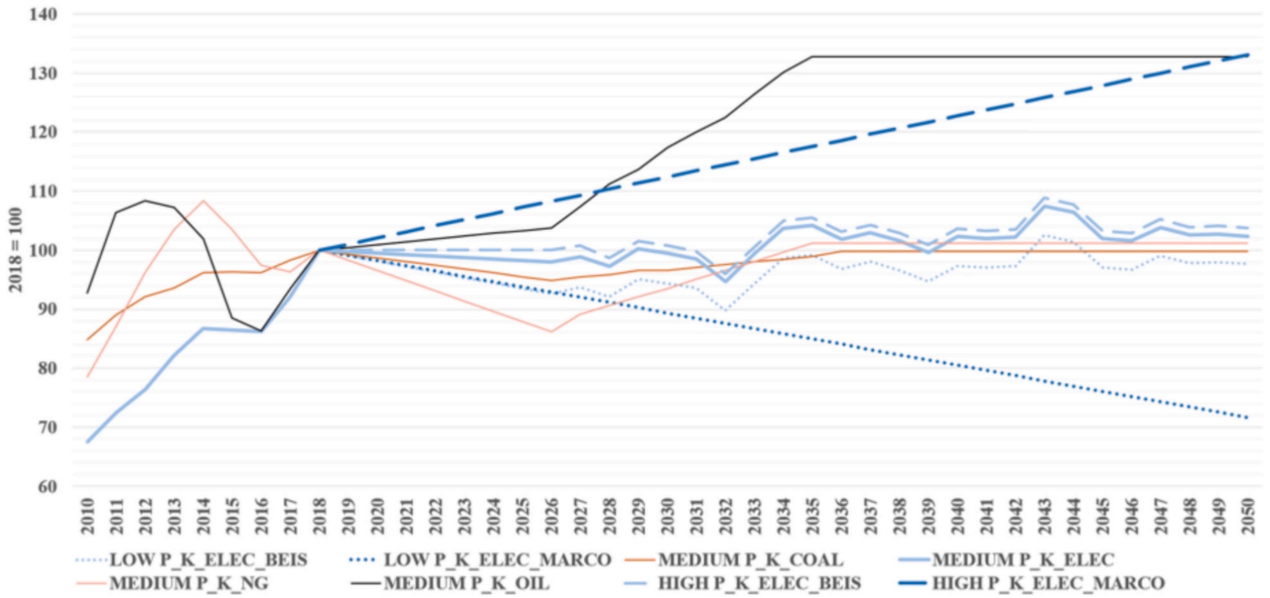

Fig. 6. Energy prices used in modelling scenarios for electricity and road fuel: Low, medium, high (based on BEIS data – [38]).

additional capital expenditure. Moreover, constraints to energy rebound also showed high importance in the determination of the results.

All EV scenarios show greater economic growth and employment compared to the ICE Baseline scenario. The efficiency gains of the full EV scenarios activate reinforcing growth mechanisms (see Fig. 3). The increase in the profit rate and energy services induce a rise in expected demand, leading to higher investment. Similarly, the expansion of disposable income promotes households consumption. Therefore, the effects of improved efficiency of the transport sector spread throughout the overall economy. By scenarios, the _EV scenario shows significant real GDP growth (18.22% higher vs baseline by 2050 and a 2.25% vs 1.71% CAAGR). The scenario with lower electricity prices (_EV_LOWP) would add 0.03 percentage points to GDP yearly, whereas higher electricity prices in _EV_HIGHP could reduce GDP growth by −0.03 percentage points yearly. Even in the ASI scenario, GDP growth would be higher than the Baseline given that the efficiency benefits spread throughout the rest of the sectors.

The energy efficiency-growth nexus becomes evident in our scenarios as those where there is no EV transition (Baseline and _EXP), or the rebound in energy services is capped tighter (ASI), these scenarios result in lower economic growth than the other scenarios. While the Baseline estimates 1.71% average yearly GDP growth, the capital investment only (i.e. no energy system/EV transition) _EXP scenarios yield only marginally higher 1.72–1.73% average yearly GDP growth. In contrast, the non-ASI EV scenarios yield 2.22%–2.28% average yearly GDP growth, demonstrating it is efficiency gains and not the investment itself that drives economic growth in the EV transition. The productive role of a new energy carrier (in this case electricity) with higher end-use efficiency (EVs versus ICEVs) to increase economic growth has a precedent: Kander and Stern [40] set out how Sweden's energy transition in the 20th Century from biomass to fossil fuels led to an increase in exogenous technical change that consequently led to higher economic growth. Linking Kander and Stern's study to our analysis is the work of Santos, Borges and Domingos [41], who found a statistically significant relationship between total factor productivity and aggregate energy efficiency (measured as final-to-useful efficiency gains, of the type

Table 2
Summary of key variable changes (versus baseline and 2018 values) under difference scenarios.

Variable	% Difference Scenario in 2050 vs Baseline in 2050					
	Baseline	EV	EV_LOWP	EV_HIGHP	EV_ASI	EXP
GDP	–	18.22	19.29	17.29	1.56	0.19
GFCF (capital investment)	–	25.12	26.08	23.11	1.61	0.46
Employment	–	2.19	2.33	2.17	0.11	9.88
Total Final Energy	–	−2.76	−1.01	−4.15	−14.30	0.16
Fossil fuels consumption		−31.55	−30.04	−32.74	−38.16	0.15
Transport Final Energy	–	−31.65	−31.65	−31.65	−46.92	0.06
Transport Energy Services	–	28.78	28.78	28.78	0.00	0.00
	Compound annual average growth rates (CAAGR) vs Base Year values (%)					
GDP	1.71	2.25	2.28	2.22	1.76	1.72
GFCF (capital investment)	0.66	1.37	1.40	1.32	0.71	0.68
Employment	0.43	0.50	0.50	0.50	0.43	0.73
	% Difference 2050 vs Base Year					
Total Final Energy	17.03	13.79	15.85	12.17	0.29	17.21
Total Fossil Fuels	15.80	−20.74	−18.99	−22.11	−28.38	15.98
Transport Final Energy	10.69	−24.34	−24.34	−24.34	−41.25	10.76
Transport Energy Services	34.77	73.55	73.55	73.55	34.77	34.75
	% over GDP by 2050					
	Base Year	**Scenarios**				
Trade Balance	**−1.7**	−7.92	−7.95	−7.89	−1.56	−0.38
Households' savings	**0.9**	−8.01	−7.92	−8.12	−6.27	−5.81

included by MARCO-UK).

The EV transition also stimulates a boost in labour demand, as shown in Fig. 7. Most of the additional employment would be created during the decades where the manufacturing and purchasing of new EVs takes place -i.e. the 2030s. However, our results also identify potential constraints to the labour market. Firstly, after the initial surge in labour demand growth, it starts to slow down once most of the new EVs are already active. In fact, if ASI policies in the transport sector aimed at declining energy consumption are applied, employment falls could fall below the baseline. Secondly, as a consequence of the rapid employment demand growth, the labour market could be put under significant strain as the labour force might fall short of the required demand. The reasons that explain both issues are related. The EV transition and the efficiency gains that it would bring about, would produce a significant increase in

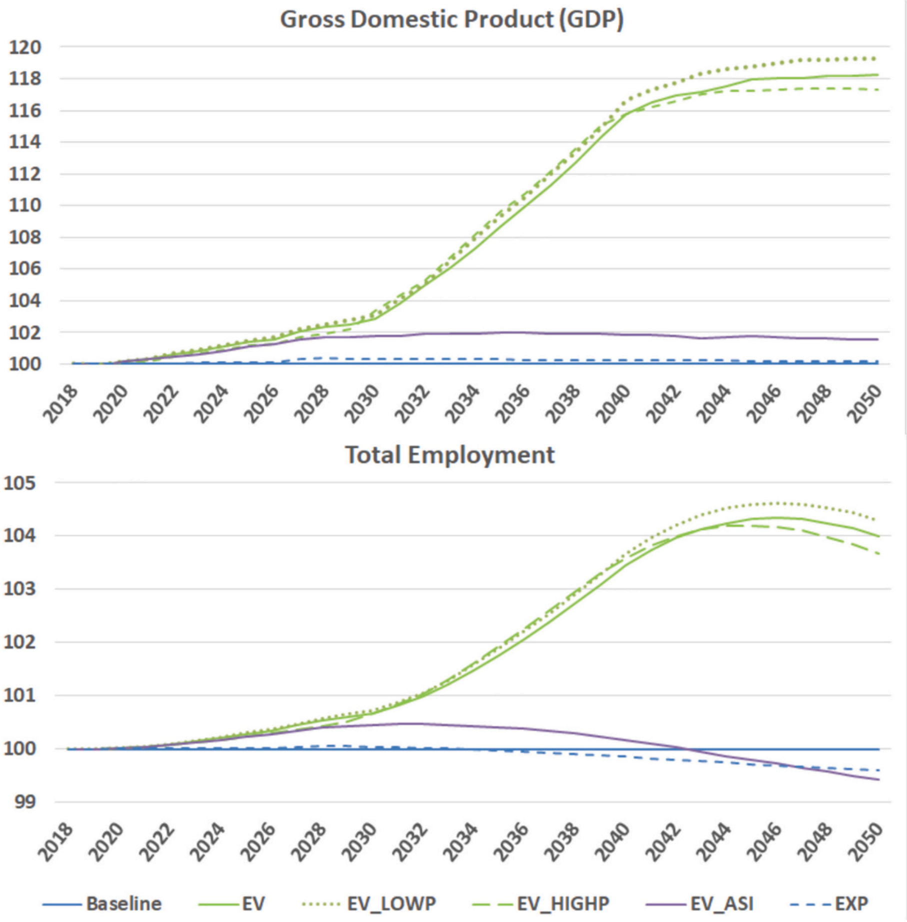

Fig. 7. GDP (top) and Employment (bottom) impacts of the EV Transition by scenarios. Baseline = 100.

labour productivity. Let us next define GDP as the multiplication of labour demand by labour productivity. In all _EV scenarios, GDP grows faster than labour productivity. However, once the cap in the growth of energy services, the difference narrows, driving labour demand lower. The tighter the energy services cap is, the more is labour demand constrained -see differences between _EV and _EV_ASI. Should the cap be removed (as in _EV_UNLIM), labour demand grows faster -making the second drawback more intense[10](see Fig. 7). On the other hand, despite that tendency, GDP growth remains higher than labour productivity, explaining how labour demand could grow faster than labour supply.

Finally, all EV transition scenarios also show a worsening of the trade balance (TB) and households' savings (see Table 2). The TB (Exports-Imports) results in around −8% over GDP vs −1.7% in the Baseline by 2050, in all EV scenarios except ASI. That scenario contains the worsening of the Trade Balance to −1.6% while delivering the transition to EVs. The same pattern is observed in households' savings. It drops to around −8% in the EV transition scenarios except ASI (−6.2%) compared to the +0.9% in the Baseline. Two factors explain these results. Firstly, the exceptional amount of investment and expenditure required to finance the transition grows faster than income, which could lead to an imbalance both in the private (households' saving rate) and the external (TB) sectors. Secondly, it could reflect the necessity to grow imports from auxiliary industries for manufacturing, such as EV batteries, machine parts and raw materials.

3.3. Energy system effects

Fig. 8 shows the main energy system results. The energy service demand for transport shows significant increases in all EV scenarios, as far as the energy service rebound cap allows it to grow. Under all EV scenarios, the final energy demand for transport and overall fossil fuels in 2050 decrease sharply versus the ICE baseline scenario. The higher reduction in fossil fuels consumption is seen in the ASI scenario (−38% vs base year by 2050) whereas the lowest impact (−30%) is attributed to the scenario where lower energy prices increase demand and rebound (_EV_LOWP). Such reductions are expected, as due to the switch to (more efficient) EVs, as energy services are constrained within the 0% to 29% direct energy service demand rebound limit, which means the final energy has to reduce in all EV cases, except EV_UNLIM. Only the EV_ASI scenario is able to attain net overall reduction in total UK-wide final energy use, as shown in Fig. 8d.

The final-to-useful energy (exergy) efficiency shown in Fig. 8 for transport actually shows the exogenous input profiles, as this variable is an input to our analysis. The impact of this transport efficiency increase (from ICEs at ~35% to EVs at ~70% final-to-useful energy efficiency) propagate its effects to the overall socioeconomic and energy system. As a consequence, the whole system useful energy efficiency (the energy services obtained per unit of final energy used in the economy) grows in all scenarios above the baseline projection, increasing from 21.6% in the base year to 29–30% in all EV scenarios. It is worth mentioning that the EV_ASI scenario still implies a significant increase in transport energy services, as it follows the baseline energy services growth in the transport sector (35% higher in 2050 than 2018). In addition, higher energy prices promote more efficient behaviour, but at the expense of lower employment and -potentially- increasing energy poverty.

3.4. Implications of the different measures in the EV transition

It is instructive to study the effects of the different measures contained within our scenarios. Firstly, by comparing the Baseline with the _EXP scenario, we can see the effect of just the capital investment by itself. This change alone would create only a very small amount of additional jobs versus the EV scenarios, starting to decline afterwards (see Fig. 7). If there was an active policy to promote domestic manufacturing and thus, additional investment would be required to expand the country's manufacturing capacity, the results would be nearly the same. In particular, GDP growth would only be 0.02 points higher in the _EXP125 scenario, as can be seen in the data repository. These results show that it is not the amount of expenditure what really matters, but how and where it is spent. This is a relevant result in the light of the findings of the EV scenarios.

Second, to study the effect of transport sector efficiency, we compare the Baseline with the central EV scenario that, not only includes the abovementioned additional expenditures, but also the switch from ICEs to EVs. Considering the _EXP results, we can observe in the EV scenario that most of the economic growth and employment creation can be attributed to the energy efficiency brought about by the EVs. However, this comes at the expense of increasing total final energy demand and debt, as both the trade balance and the households' savings would be expected to deepen their negative imbalance. Although the switch from ICEs to EVs itself entails a great reduction in fossil fuels consumption, the overall increase in final demand could put the electricity system under strain, as it transitions towards 100% renewable, increasing electricity prices. As the _EV_HIGHP scenario shows, that would offset part of the initial GDP and employment positive effects. On the other hand, the negative macroeconomic imbalances could suggest the necessity to implement monetary and/or fiscal policy to fund the transition. Another option would be to prioritise the domestic production of an increasing share of the EVs supply chain. This way, the requirement to increase imports of machine parts would be eased and the trade balance would potentially improve.

Third, the effect of transport energy rebound can be analysed by comparing the EV and EV_ASI scenarios, which are the same except the transport sector energy services rebound limit. Importantly, energy rebound in the wider economic system can be assessed as our model allows three key channels for rebound (see also Sakai et al. [26,27]): 1. Efficiency gains reducing costs of energy services - boosting household consumption; 2. Investments required for infrastructure (e.g., EV charging installations, manufacturing, etc.), and 3. Increased production of cars/batteries is 100% is to be met manufacturing domestically (is either that or importing, i.e. offshoring environmental impacts -and jobs).

Overall final energy demand shows modest reductions for all non-ASI EV scenarios of between −1.0% to −4.2% versus 2050 ICE baseline scenario. Overall, this is a smaller reduction than perhaps expected (EV_ASI scenario has a comparable reduction of −14.3% in 2050), but is due to economy-wide rebound effects of between 64%–91%, as shown in Table 3:

The total rebound for the central EV is 76%, very similar to the ~65% average ranges reported in a review of over 30 studies by Brockway et al. [42]. Under low energy prices, economy-wide rebound increases to 91%, within the 78%–101% estimated by Berner et al. [43]. At the other end, the EV_ASI avoids the large rebound effects via an avoid-shift-improve framework, whereby energy services are provided with lower energy demand, and in this case some further energy savings are realised, leading to an overall energy rebound of −25%.

Fourth, the EV transition could entail different strains to the labour market: in the growth phase (2020–2035) when facing potential labour supply shortfalls - especially at the peak EV manufacturing time (see section 3.2), and in the decline/constrain phase (2035–2050) when the demand for new employment creation slows. In order to overcome the former (labour supply) issue, there would be at least three potential ways to address it. Firstly, labour productivity largely increases in the transport sector, but policy-makers could facilitate that it spreads to other sectors more intensely. Secondly, via an increase in population. Thirdly, by pulling inactive population to activity, i.e. increasing the activity rate. Of course, this would potentially reinforce the rebound in

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[10] In fact, in the _EV_UNLIM scenario, the unemployment rate goes negative, suggesting that it is not a realistic scenario. Its results can be consulted in the data repository, though.

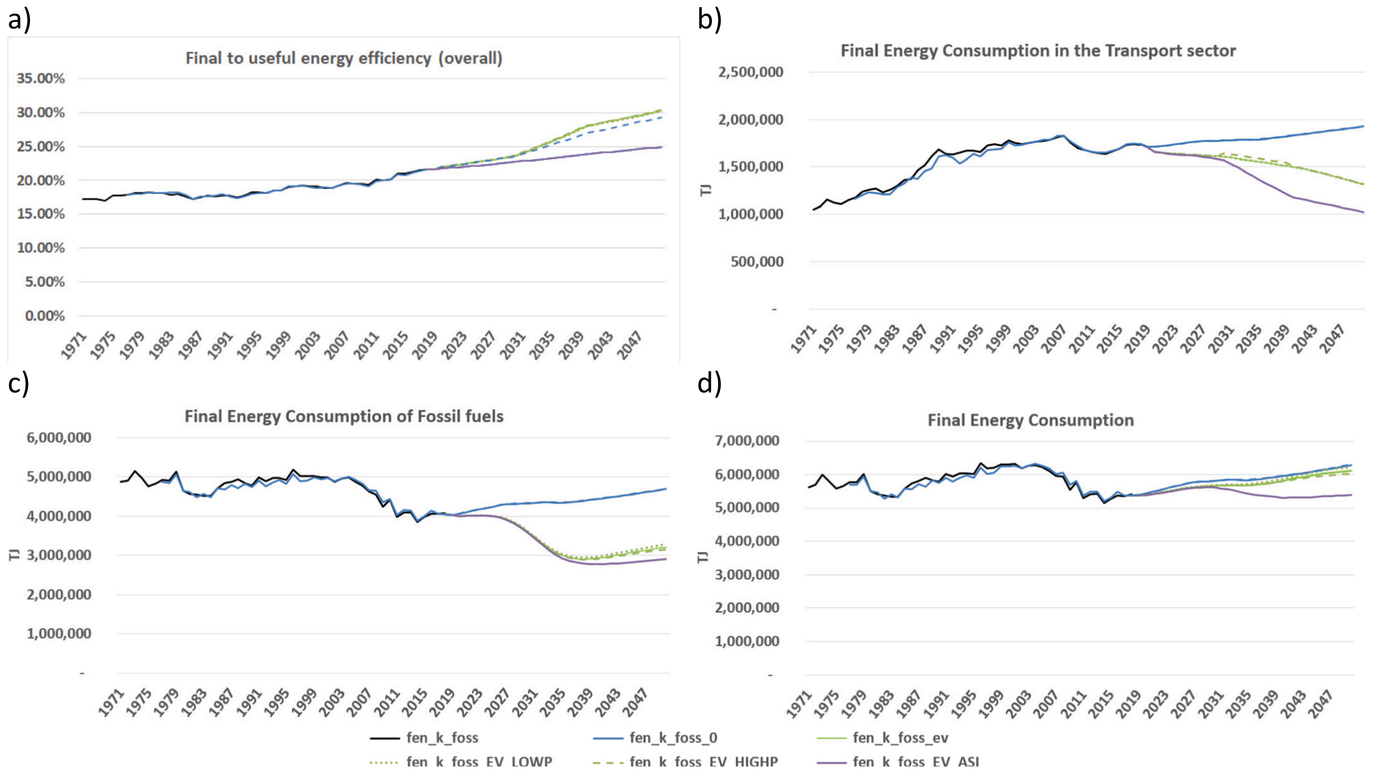

Fig. 8. Overview of energy results by scenarios. a) overall thermodynamic (final-to-useful)energy efficiency (%); b) Final energy demand in the transport sector (TJ); c) Fossil fuels consumption (TJ); d) Total final energy use (TJ).

Table 3
Economy-wide rebound estimations.

Estimating rebound in 2050	EV scenario			
	EV_ASI	EV	EV_LOWP	EV_HIGHP
expected saving (TJ)	718,522	718,522	718,522	718,522
actual saving (TJ)	899,251	173,828	63,420	261,181
overall rebound %	−25%	76%	91%	64%

final energy consumption. Regarding the latter (excess labour) issue, the response could be twofold. First, to let energy rebound effects go unchecked leading to additional economic growth (and labour demand), but which may bring contradictions with energy and (probably) climate targets. Or secondly, anticipate these effects and implement industrial policy to promote other low-carbon sectors, or even reduce working time.

Fifth, the deterioration of the trade balance is explained by the fact that, in this article, the sectoral structure of the UK's economy remains untouched. Consequently, the increased demand for EVs and machine parts would be highly dependent on imports. *Re*-shoring strategies and industrial policy to promote a new batteries industry could potentially overcome the negative tendency of the trade balance.

Some of the previously mentioned undesired effects can be compensated, as it is found in the _EV_ASI scenario, where the rebound in additional energy services obtained out of useful energy efficiency is evaluated. In this scenario, the Transport sector energy services rebound is limited to 0%, simulating a scenario where the efficiency growth is directed to only reduce final energy use, instead of increasing the distance travelled by economic agents. We find that despite that cap - GDP, employment and overall energy service demand still are slightly higher compared to the Baseline. However, as expected the big change is the dramatic reduction in transport sector final energy use, equal to −41% in absolute terms compared to the base year. This scenario also shows the greatest reduction in fossil fuels consumption (−28%) and it is the only one that does not significantly increase total final demand – suggesting this scenario would deliver the greatest GHG emissions reduction. Finally, the _EV_ASI scenario also reduces the macroeconomic imbalances to the minimum. Therefore, a good balance between macroeconomic and environmental objectives is found in this scenario. The Avoid-Shift-Improve (ASI) measures potentially required to manage useful energy demand would imply additional investment, such as promoting mass transport, shift to rail, urban planning, etc. Given the relatively small positive GDP and employment effects of capital investment itself shown in _EXP and its potential negative effects on macroeconomic imbalances, policy-makers could aim at minimising it. For instance, reducing the stock of vehicles -which is complementary to increasing mass and rail transit- would potentially significantly reduce expenditure on EVs and re-direct it to the ASI measures.

3.5. Comparing ICE baseline versus central EV scenario

Comparing the baseline to central EV scenario results is perhaps the most realistic comparison, and enables us to assess the overall scale of the changes from an ICE-based to EV-based transport system. Referring to Table 1, the central EV scenario contains a full switch to 100% EVs, long-term transport energy service demand rebound limited to 29% following the literature, and runs central energy prices.

In terms of detailed results (see Appendix C), GDP in the central EV scenario is £684Bn (18%) larger in 2050 than the baseline ICE scenario. It is this broad economy-wide economic growth that induces additional energy use and large rebound effects. Employment increases by 1.77 million additional jobs in the peak year (2046) versus the baseline scenario (+2.2%). For the energy system impacts, we find a reduction in transport energy demand of -610TJ/year in 2050 (−32% versus baseline scenario), compared to a reduction in overall energy demand of -173TJ/yr (−3% versus baseline scenario), due to the large (76%) overall energy rebound shown in Table 3.

3.6. Study limitations

There are of course limitations to highlight for our study. The first is that we set nearly the whole transport sector to switch to EVs. In reality this is unlikely, as aircraft and heavy goods vehicles are unlikely to be fully electric. However, road transport is the largest source of carbon emissions [33] and within that category, light duty vehicles (cars, vans) are the largest component, and are expected to be almost fully EV. Our simplified modelling assumption therefore provides an upper bound of the magnitude of socioeconomic impacts from the EV transition. The second limitation relates to debt. In this article, our model shows that higher economic growth may come at the expense not only of energy rebound but also of raising debt levels. Therefore, the increased external and households' debt should feedback the overall performance of the economy, which is outside of our analysis. Economic growth prospects might be nuanced if the rise in indebtedness is not sufficiently addressed.

In addition, since the study focuses on the UK, the findings might not be generalizable to other regions or countries with different socioeconomic and energy landscapes. Moreover, these scenarios are subject to uncertainty, starting with the identification of electricity as the main final energy source of the vehicle stock as planned in current policies. However, other energy sources such as hydrogen or biofuels could potentially play a more important role in the automotive transition.

4. Conclusions

Our analysis set out to examine the macro-socioeconomic impacts of energy and economic changes to the UK transport system caused by the EV transition. We used a novel (MARCO-UK) thermodynamic-based macroeconometric model, that is uniquely able to explore such impacts due to its energy-economy balance of construction, blended with the crucial extension of the energy system to the useful stage (at energy services). These features enable both thermodynamic efficiency and energy service rebound to be included, alongside energy prices, investment and other macroeconomic variables. Considering the EV transition, most models are typically suited for looking only at the economic effects in a sector or, at most, also to the indirect effects on other sectors. A core benefit of MARCO-UK is its ability to capture the economy-wide effects of the increased final-to-useful efficiency that occurs due to the EV transition. By including the stimulating effects of efficiency gains on economic growth, our results suggest that the economic impacts of the EV transition have been underestimated.

We find that the energy inputs (efficiency, rebound) – hitherto largely unseen by conventional energy-economy macroeconomic models – yield significant economic growth, on average 2.25%year versus 1.71%/year for the baseline. Additionally, direct and economy-wide rebound is an important variable which has a keen influence in the results: overall long-term economy-wide rebound in our central EV scenario is 76%. In contrast, the economic changes to the transport system (investment, household consumption, energy prices) have much less impact on the wider economic system. Thus, the benefit of our alternative modelling approach can be seen.

The EV transition's sharp rise in GDP and employment may be greeted by policy makers, who seek a solution for low economic growth and the declining labour productivity. Our analysis shows that the EV transition may unlock the new economic growth they are seeking. However, the significant efficiency gains delivered by the switch from ICEs to EVs may be heavily offset by rebound (depending on energy prices), making the decrease in overall energy consumption more modest. The rapid deployment of EVs would also require a large increase in expenditure that, on the one hand, has the potential to deliver a decades-long period of near full employment. However, that might lead to increased levels of external and households' debt too, adding strain on the labour market. Increased indebtedness is not only a potential source of financial instability, but also generates an incentive to increase GDP growth to repay debt servicing, intensifying energy rebound effects. In addition, while policy-makers might be interested in pursuing labour productivity gains released by the EV transition, it makes higher GDP growth necessary -further intensifying energy rebound- to maintain the level of employment. Our results also suggest that, despite the overall positive macroeconomic impacts expected from the EV transition, policy-makers should pay attention to potential drawbacks, including distributive effects.

Two key policy directions could help overcome these potential drawbacks and conflicts of socioeconomic and environmental goals. The first is the application of measures within an Avoid-Shift-Improve (ASI) framework, alongside the EV transition, to reduce energy demand. Second, in order to reduce fossil fuels consumption rapidly enough to meet climate goals, it could be necessary for greater deployment of renewables (i.e. to achieve a 100% renewables electricity mix sooner than currently planned) to cover the increased electricity use of the EV scenarios.

CRediT authorship contribution statement

Jaime Nieto: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Paul E. Brockway:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Funding acquisition, Conceptualization, Investigation, Formal analysis. **Marco Sakai:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **John Barrett:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Supplementary Information (SI) – contains detailed structure and equations of MARCO-UK. The data associated with this paper (mainly, exogenous by-default assumptions, scenarios and full results) is available from University of Leeds at https://doi.org/10.5518/1523

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Appendix A. List of acronyms and symbols

AFF	Agriculture, Forestry & Fishing sector
ASI	Avoid-Shift-Improve
BEV	Battery Electric Vehicles
BNZ	Balanced Net Zero pathway (for UK’s 6th Carbon Budget)
CAAGR	Compound Annual Average Growth rate
CGE	Computational General Equilibrium
CPS	Commercial, Public & Services sector
EEIO	Environmentally-Extended Input-Output
EU	European Union
EV	Electric Vehicles
FEN	Final Energy
GDP	Gross Domestic Product
GFCF	Gross Foxed Capital Formation
GHG	Greenhouse Gas
GVA	Gross Value Added
HEV	Hybrid Electric Vehicles
HH	Households sector
IAM	Integrated Assessment Model
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IND	Industry sector
k	subscript - fuel source
M	Imports
NES	Not Elsewhere Specified
NEU	Non-Energy Use
P_EN	Energy Price
PKE	Post-Keynesian Economics
s	subscript – sector
TFP	Total Factor Productivity
TJ	Terajoules
TPT	Transport sector
UEX	Useful Exergy
W	Wages
X	Exports
γ	transport sector rebound parameter

Appendix B. Scenario energy fuel shares

The input values for the energy fuel shares of both main scenarios are shown in Fig. B1. Baseline energy use stays at around 95% oil-based fuel. EV scenarios are ~90% electricity-based by 2050, with ~5% oil-based and ~ 5% biofuels.

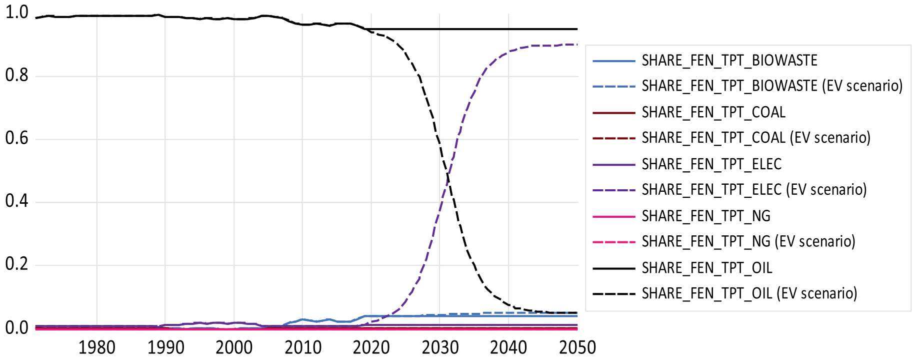

Fig. B1. Fuel shares between oil and electricity for the baseline and EV scenario.

Appendix C. Key results data

Table C1 gives the summary results for 2018 and 2050 for the main scenarios for key variables. These datasets are used to create the Tables and Figures in the main paper. Timeseries results for these variables can be found in the Data repository.

Table C1
Summary of 2018 and 2050 scenario results for key variables.

Variable	Units	Raw value in 2018					
		1a	2b	2c	2d	2a	1b
		Baseline	EV	EV_LOWP	EV_HIGHP	EV_ASI	EXP
GDP	million GBP	**2,182,151**	2,182,151	2,182,151	2,182,151	2,182,151	2,182,151
GFCF (investment)	million GBP	**397,040**	397,040	397,040	397,040	397,040	397,040
Employment	thousands	**32,927**	32,927	32,927	32,927	32,927	32,927
hourly wages	GBP	**19.53**	19.53	19.53	19.53	19.53	19.53
Trade Balance (over GDP)	%	**−1.0%**	−1.0%	−1.0%	−1.0%	−1.0%	−1.0%
Saving (over GDP)		**0.9%**	0.9%	0.9%	0.9%	0.9%	0.9%
Total Final Energy	TJ	**5,373,964**	5,373,964	5,373,964	5,373,964	5,373,964	5,373,964
Transport Final Energy		**1,742,081**	1,742,081	1,742,081	1,742,081	1,742,081	1,742,081
Fossil Fuels		**4,053,727**	4,053,727	4,053,727	4,053,727	4,053,727	4,053,727
Energy Services		**1,159,884**	1,159,884	1,159,884	1,159,884	1,159,884	1,159,884
Transport Energy Services		**497,845**	497,845	497,845	497,845	497,845	497,845

Variable	Units	Raw value in 2050					
		1a	2b	2c	2d	2a	1b
		Baseline	EV	EV_LOWP	EV_HIGHP	EV_ASI	EXP
GDP	million GBP	**3,758,946**	4,443,685	4,484,052	4,408,910	3,817,479	3,765,994
GFCF (investment)	million GBP	**490,724**	613,972	618,699	604,123	498,620	492,965
Employment	thousands	**37,777**	38,604	38,659	38,598	37,819	41,511
hourly wages	GBP	**25.29**	25.74	25.92	25.61	25.42	25.20
Trade Balance (over GDP)	%	**−0.3%**	−7.9%	−7.9%	−7.9%	−1.6%	−0.4%
Saving (over GDP)		**−5.9%**	−8.0%	−7.9%	−8.1%	−6.3%	−5.8%
Total Final Energy	TJ	**6,288,978**	6,115,150	6,225,558	6,027,797	5,389,727	6,299,045
Transport Final Energy		**1,928,384**	1,318,127	1,318,127	1,318,127	1,023,559	1,929,495
Fossil Fuels		**4,694,371**	3,213,097	3,284,107	3,157,592	2,903,129	4,701,496
Energy Services		**1,565,704**	1,851,674	1,877,155	1,831,147	1,578,085	1,567,905
Transport Energy Services		**670,923**	864,006	864,006	864,006	670,923	670,854

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.123367.

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