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Analysing the impacts of a large-scale EV rollout in the UK – How can we better inform environmental and climate policy?

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ABSTRACT

Electrifying transport to meet local pollution and overall net zero carbon ambitions is now a key UK policy focus, but this will have important impacts on the energy system, the economy, and the environment. Understanding the changes that the electrification of transport will bring is crucial for developing sustainable policies for net zero goals and a just transition. A literature is emerging to analyse the impact of a large-scale penetration of electric vehicles (EVs), but generally limiting focus to the implications for the electricity network. In this paper, we aim to provide insight on the wider energy system impacts of the expected EV rollout in the UK, in terms of fuel changes, energy costs, CO_2 emission reduction and network investments; and how different EV charging strategies increase or mitigate the impacts of the expected large-scale penetration of EVs. Results show that non-smart and/or decentralised charging will require considerably larger investments on the network to accommodate new EV demand. Network reinforcement costs are passed to the consumer via increased electricity prices and, albeit reduced, emissions shift from the transport to the power sector. These results show the importance of considering the whole energy system and the wider economy, to avoid carbon leakage and to maximise the effectiveness of policies.

1. Introduction

As part of their actions to tackle climate change and local pollution, a number of countries around the world are pushing ambitious targets to electrify transport. The aim is both to reduce greenhouse gas (GHG) emissions and to improve air quality in urban centres [1]. In the UK, the Government has moved forward a previously set target of all new cars and vans to be effectively zero direct emission by 2035 [2,3], and National Grid (the British Transmission System Operator) expect an overall EV penetration over 90% on the private car fleet by 2050 [4]. Other countries have also increased their efforts in the decarbonisation of transport. For instance, Ireland, Iceland, Denmark and the Netherlands have set a similar ban on petrol and diesel cars by 2030, whereas Norway, which currently shows the largest EV uptake in Europe, has set the target for 2025 [5].

Such a major shift is likely to bring important challenges to the energy system, as the new electric load to charge EVs is likely to require new generation capacity and considerable network reinforcements. Moreover, these required changes to the power system will require important investments, the cost of which will ultimately be paid by consumers. Many studies have been developed to address these challenges, with particular focus on the impacts of a large penetration of EVs on the power network, using power system and network models. However, this neglects other potentially important impacts and, thus, policy implications outside the electricity sector. For example, the impact on fuel use, consumer costs and wider emissions. Similarly, EV charging strategies have been widely studied, analysing potential benefits for the power system, but the impacts of the location of the charge in the network (centralised vs decentralised) has not received much attention and the focus has not extended beyond the power sector.

The objective of this paper is to provide insight on the potential impacts of the planned large-scale EV rollout in the UK in terms of network investments, changes in fuel use, fuel cost and emissions. We use the UK TIMES whole energy system model [6] to analyse a large EV penetration case. We have selected this model as it covers the whole integrated energy system (supply, conversion and demand, across all sectors: agriculture, services, residential, industry, transport) and not only the power sector. We consider an EV penetration reaching 90% of total travelled car kilometres by 2050, and considering five different types of EV charging scenarios. These scenarios vary in where the

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charging take place (centralised or decentralised) and the ‘smartness’ of the charge (working between the extremes of ‘smart’ and ‘dumb’ charging).

Decentralised charging is assumed to occur in a widely spread way. For instance, charging at home, work places, on-street parking, etc. From the network point of view, we consider that decentralised charging takes place at distribution level. Centralised charging, on the other hand, is considered to occur in a more concentrated way, similar to what is currently the case with petrol/diesel service stations. We assume that these especially designed EV charging areas are located as close as possible to the transmission network (i.e. in motorways and/or parking lots in the outskirts of cities) to reduce the need of investments in the network. ‘Dumb’ charging equates to charging at peak hours, when people come back from work and electricity demand is highest, and ‘Smart’ charging only occurs when it is cheaper to do so (mostly overnight).

The TIMES model is actively used to inform policy decision-making in the UK, and with the Scottish Government using a Scotland regional model version to identify decarbonisation pathways [7]. Also, National Grid (the British TSO) and the UK department for Business, Energy and Industrial Strategy (BEIS) use the UK TIMES framework for their analyses [8]. The work developed in this paper aims to provide policy-relevant insight on the wider effects of the electrification of transport, analysing the implications of a large penetration of EV under different charging scenarios, and discussing best practices on informing energy policy. We make two new contributions. First, to conduct an analysis of the impact of the EV rollout in the UK, in terms of fuel changes, energy costs, CO_2 emission reduction and network investments. Second, to analyse these outcomes in the context of different EV charging strategies. We then propose and discuss further questions to extend and complement the analysis developed in this paper. A forthcoming work [9] presents an example of this, developing an economy-wide analysis informed by this work, considering other potential impacts in the energy system and the economy, including GDP growth, job creation and costs for different household groups. This interaction between this paper and the work presented in Ref. [9] provides further insight on economic and social costs and benefits, relevant for effective policy making.

The rest of the paper is structured as follows. Section 2 presents a brief review of existing studies analysing the impacts of large-scale EV penetration on the power network or the wider energy system. Section 3 describes the methodology used in this paper. Section 4 shows the considered EV charging scenarios. Section 5 shows the results and discussion of the analysis and section 6 presents the conclusions of this study.

2. Existing studies of large-scale EV penetration impacts

There are several studies analysing the impacts of a large-scale EV rollout at both city level and country level. Most studies to date have focused mainly on the impacts on the power system, including the need of network investment and/or extra generation capacity. However, other areas affected by a large-scale penetration of EVs have been overlooked, such as the changes in fuel use and cost in car travel, or emission reductions.

2.1. City level studies

Blokhuis et al. [10] analyse the potential increase in electricity peak load resulting from the introduction of heat pumps and EVs in the city of Eindhoven, The Netherlands. They use electricity demand profiles, expected population growth and other projections to compute the increase in peak load demand. They conclude that under worst-case assumptions, peak loads in Eindhoven increase with 200% until 2040 and that the necessary network investment for facilitating this 2040 peak demand is in the range of € 305–375 million. However, impacts on fuel costs or emissions are not considered.

González et al. [11] analyse the implementation of EV fast charging stations in a medium size Latin American city (Cuenca, Ecuador). They consider social, geographic, and technical aspects to determine the location and minimum infrastructure needed and the impact on the distribution network for a 10% EV penetration scenario. They use a power system modelling tool for the analysis, concluding that, for the considered EV scenario, the required network investments are relatively low (around 1.2 M USD), which can be offset by the savings on cheaper fuelling for EVs, relative to internal combustion vehicles. However, only a very low EV penetration level is considered and the focus is limited to the distribution level of a city, not taking into account the wider power network or the rest of the energy system.

Calvillo et al. [12] present an analysis of how different levels of EV penetration and ‘smart’ charging can be used to exploit synergies between different energy systems within cities. The authors take a residential district in Madrid, Spain, as the case study and use a microgrid-type cost-minimisation model, they conclude that coordinated smart charging not only can reduce peak load, but it could provide storage to other distributed resources and systems as well. This study assesses optimal EV penetration levels and the economic benefits for EV owners. However, it does not analyse network costs, benefits due to emission reductions or wider impacts on the energy system.

2.2. Country level studies

Su et al. [13] calculate the future EV charging demand in New Zealand up to 2040, using a multivariate probabilistic model that considers uncertainty in EV fleet composition, market shares, and charging patterns. They conclude that there will be a potential shortage of generation installed capacity in New Zealand based on future EV uptakes; and that coordinated EV charging strategies can flatten the load curve, postponing the need for investment on network reinforcements. This study does not include more detail on impacts on the network, energy costs or emissions.

Pudjianto et al. [14] develop a range of numerical simulations based on different distribution network topologies (urban and rural) in the UK, assessing the need and the cost of network reinforcements required to accommodate the electrification of transport and heat. They conclude that under current passive distribution network and demand, the electricity peak its likely to increase up to 2–3 times, and that significant distribution network reinforcement will be required. However, the transmission network is not modelled and the impact on energy costs or CO_2 emissions is not considered.

Heuberger et al. [15] analyse the impact of a spatially distributed large-scale rollout of EVs in the UK electricity system under CO_2 emissions reduction targets. The authors use the power system model: Spatially granular Electricity Systems Optimisation model (ESONE). The authors conclude that EV demand profiles correlate well with offshore and onshore wind power production, reducing curtailment and boosting generation. Note that this analysis focuses only on the power system, in particular in the energy mix and transmission network, with little detail on the distribution level.

Küfeoğlu and Pollit [16] analyse the current distribution network tariffs faced by four main household customer groups in Great Britain (GB) under various uptake scenarios for EVs and PVs up to 2030 (up to 50% penetration). Results show that, due to the current network charges calculation structure, as PV penetration increases, the distribution tariffs increase for all customers regardless of whether someone owns a PV or not. On the other hand, as EV penetration increases (larger demand), the distribution tariffs decrease for all customer groups. However, this analysis only focuses the distribution tariff structure no considering the transmission network, network expansion needs, effects on the energy mix, or GHG emissions.

Taljegard et al. [17] present a study on how the electrification of the Scandinavian and German road transportation sectors will influence investments in new electricity generation capacity up to year 2050. The authors use a cost-minimisation investment model and an electricity dispatch model for this analysis. The results obtained show that with a cap on CO_2 emissions, the additional electricity demand for transport is met mainly by increases in wind power and coal power plants in combination with carbon capture and storage. This study analyses the impacts of EVs in the electricity generation energy mix in a multi-region study, but does not look into wider impacts on the energy system, including changes in energy use and emissions in other sectors.

2.3. The wider impacts of the EV rollout

The review above reflects the fact that many studies from around the world have begun to emerge with a very policy relevant focus of analysing the challenges that a large-scale penetration of EVs will bring. In addition, most of the reviewed studies assess the importance of smart charging and V2G as a way to reduce peak demand and the need of increased generation and network expansion. However, these studies vary in their scope, with some of them analysing city level impacts whereas others present country level analysis. Note that the aim of this review is to analyse papers that focused on impacts of a large-scale EV rollout. Therefore, this is not a comprehensive review of EV related works, which could present very different focuses (e.g. EV technologies, optimal charging strategies and control for individual EVs, demand response, smart grids, etc).

From this review, we have noticed that there has been a lack of attention to the implications of the EV rollout outside the power sector. For example, studies have commonly omitted the impacts on fuel use, consumer costs or emissions, which are important policy concerns. Moreover, most of these studies use electric network models and/or economic dispatch models (used to decide how much generators produce and when), both of which are limited in scope to the power sector. The use of whole energy system models is rare in this type of EV analysis. Here we consider how the use of whole energy system models like TIMES could provide important insight on the impacts of the EV rollout in other sectors (e.g. Agriculture, residential, services, industry, etc.), which are normally overlooked in power system models. Thus, this work constitutes an important step in understanding the fuller social and economic impact of a large-scale EV rollout.

3. Methodology

In this section, we describe the methodology used to analyse the energy system impacts of the expected EV rollout in the UK. For this, we use the UK TIMES (UKTM) energy system model [6] to test the impact of different EV charging strategies in a context of high EV penetration. Therefore, we first describe the TIMES model. Then, we review other necessary information for the analysis, including the future car demand projections in the UK (including private passenger travel in cars and vans, but not considering buses or heavy good vehicles), the details of the expected EV penetration and the parameters that characterise EVs in the model. We also present the electric network reinforcement cost parameters, which are required to compute the level of investment needed to accommodate the new EV loads.

3.1. Modelling framework

The Integrated MARKAL-EFOM System (TIMES) is a bottom-up energy system-wide model, which considers all the processes of the energy system. The TIMES model generator is developed by the Energy Technology Systems Analysis Programme (ETSAP), which is a project run at the International Energy Agency [18]. TIMES has been used widely to analyse different policy questions including decarbonisation scenarios, as in Refs. [19,20], or the energy system impacts of specific technologies and policies, as in Refs. [21,22].

The UK TIMES model considers all the processes that transform, transport, distribute and convert energy to supply energy services (see Fig. 1). The inputs (exogenous variables and parameters) of the model are: service demand curves, supply curves (e.g. primary energy resources such as wind power or availability of imports), and techno-economic parameters for each technology/process (e.g. technology efficiencies and availability factors, investment cost per capacity unit, O&M cost per unit of production, etc). The outputs (endogenous variables) include: energy and commodity flows and marginal costs, technology installed capacities, emissions, etc.

UKTM is a single region model of the UK, used for medium to long-term analysis of energy systems. The time horizon in UKTM runs until 2050, with time periods of 5 years, and taking 2010 as the base year. To reduce complexity in the optimisation model, TIMES considers only some representative time-slices that work as an average of the elements of that time period. UKTM considers 16 time slices: four time divisions within a year representing seasons (spring, summer, fall and winter), and four daily divisions for each season (night, day, evening peak and late evening).

The sectors considered in the model include: industry (organised by subsectors: cement, pulp and paper, food and drinks, petrochemicals, etc.), agriculture and land use, transport, residential, services and the power sector. The power system in TIMES includes a very large number of generation technologies and also models the transmission and distribution networks. The representation of these networks is limited due to the single region aspect of UKTM. However, it is useful to assess if current network capacity would be enough to accommodate the expected generation and demand.

Moreover, UKTM is a partial equilibrium model-generator assuming perfectly competitive markets and full foresight. The model uses linear-programming to find a least-cost energy system (calculated as sum of investment, fixed and variable operation and maintenance (O&M), and import and export costs/revenues for all the modelled processes), able to meet specified energy service demands, according to a number of user constraints. The TIMES objective function minimises Net Present Value (NPV) [24], as in the equation:

$$\min(NPV) = \min\left(\sum_{r=1}^{R}\sum_{y\in YEARS}\left(1+d_{r,y}\right)^{REFyear} * ANNCOST(r,y)\right)$$

Where:

- ***NPV*** is the net present value of the total cost for all regions (the TIMES objective function);
- ***ANNCOST(r,y)*** is the total annual cost in region ***r*** and year ***y*.** This includes capital costs (investment and decommissioning), operation and maintenance cost, and a salvage value of all investments still active at the end of the horizon;
- $\boldsymbol{d_{r,y}}$ is the general discount rate;
- ***REFyear*** is the reference year for discounting;
- ***YEARS*** is the set of years for which there are costs, including all years in the horizon, plus past years (before the initial period) if costs have been defined for past investments, plus a number of years after EOH where some investment and decommissioning costs are still being incurred, as well as the Salvage Value; and
- ***R*** is the set of regions in the area of study. The UKTM version we are using is a single region model so $R = 1$.

The model uses demand projections as the main driver of the energy system. In other words, the model finds the least cost energy system configuration (technology mix and energy flows) to meet the expected demand. So the technology selection by the model is based on the cost-effectiveness of the technologies, considering their performance, capital, operation and maintenance, and fuel costs. Also, to avoid 'penny-switching' (i.e. dramatic technology changes in a short period of time, triggered by a small cost saving), technology adoption constraints are set in the model trying to replicate realistic technology adoption scenarios.

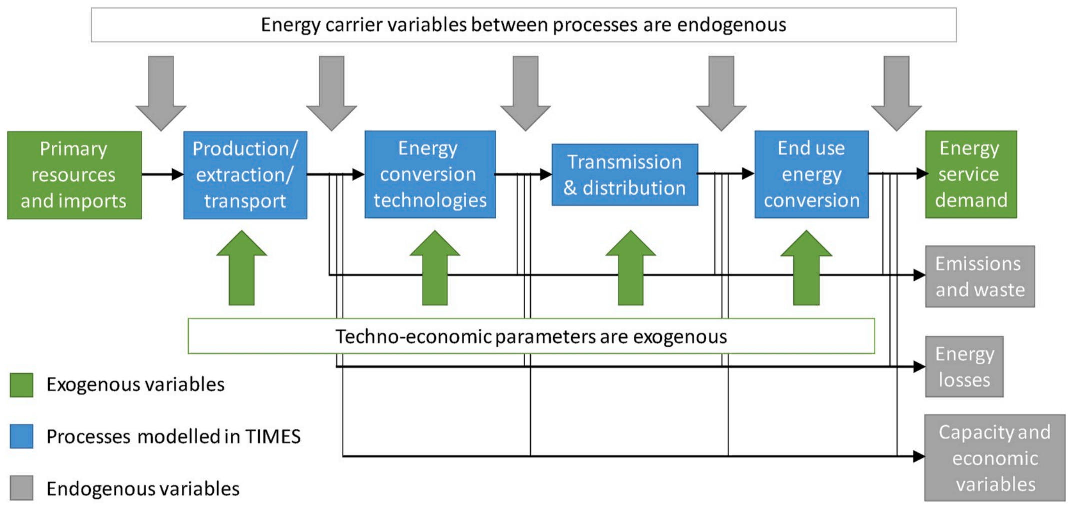

Fig. 1. Modelling of the energy system in TIMES (Calvillo et al., 2017).

A more detailed description of the UKTM model and its database can be found in Ref. [23,25] and official TIMES documentation can be found in Ref. [24,26].

3.2. Scenario data

This section describes the main data inputs and parameters used in this study to represent car transport and EVs in UKTM, as well as the expected network reinforcement costs. An overview of the data and assumptions used in UKTM for other sectors can be found in Ref. [25]. Note that these input parameters apply to all considered scenarios in this study, unless it is explicitly mentioned otherwise.

3.2.1. Car demand and EV rollout projections

Table 1 shows the expected UK car transport demand up to 2050 used for this analysis. The table shows that there is an assumed growth of almost 50% of total private car and vans demand by 2050, relative to the year 2010. Note that these projections are based in travelled kilometres, which are independent of car type or ownership method. These car demand values are based on Department of Transport (DfT) Road traffic forecasts 2015 for England and Wales. This is assumed to be representative of the whole UK [27].

Fig. 2 shows the EV rollout projection used in this study. For all scenarios, except the base case (with no EV penetration), we implement EV technology-use constraints to meet the car demand described in Table 1, but following the expected penetration of EVs shown in Fig. 2, which is around 20% by 2030, 80% by 2040 and 90% by 2050. This means that, for instance, from the 527.1 billion of travelled km in 2050 (see Table 1), around 474.3 billion of km (90%) will be covered by EVs and 52.7 billion of km (10%) by other types of vehicles.

Note that this EV penetration scenario is based on the SPEN RIIO-T2 Electricity Scenarios 2018 consultation [28] and National Grid Future Energy Scenarios FES2018 [4]. Also, note that this expected EV penetration applies to all considered EV charging scenarios described in section 4.

3.2.2. Technology parameters required for this study

Technology parameters are other important inputs for TIMES, as they describe the cost and performance characteristics of technologies. Based on these parameters, the model can decide on the most cost effective way to meet the energy demands. Note that the parameters shown in this section are the same basic parameters used in other UKTM studies, and they have not been specially modified for this paper.

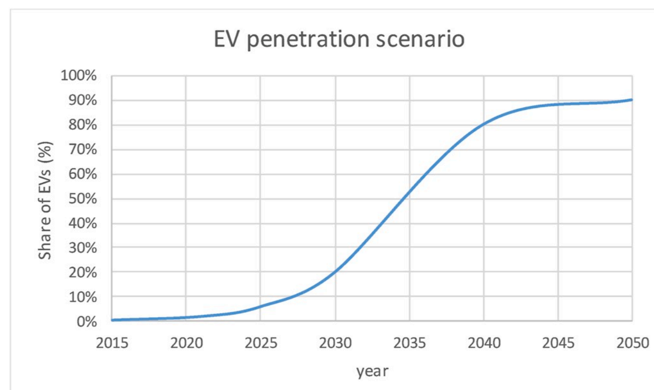

Fig. 2. Considered EV penetration for all EV charging scenarios.

Table 2 summarises the main EV parameters used in UKTM. The EV technical efficiency are expected to increase in the future, whereas vehicle upfront costs and operation and maintenance costs are expected to decrease. In particular, these costs are reduced considerably from the first commercial options in 2010 to current costs, and it is expected to continue to decrease in the future. These projections roughly align with the forecasts provided by Bloomberg New Energy Finance [29] and the International Energy Agency [30].

Table 3 shows the considered capital investment, operation and maintenance costs per capacity unit for network reinforcements. These parameters are used to compute the total cost of all new network capacity implemented in the energy system as a result of the increasing EV demand. These costs parameters roughly align with different network reports including the analysis developed by Kiani Rad and Moravej [31], IEA ETSAP [32] and the Electricity Networks Strategy Group [33].

Table 1
Car transport demand projections.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Billions of travelled km	353.9	376.3	405.4	435.5	453.2	472.0	488.8	507.4	527.1
Demand growth index (relative to 2010 level)	0%	6%	14%	23%	28%	33%	38%	43%	49%

Table 2
EV parameters used in this study.

	Car type	2010	2020	2030	2040	2050
Lifetime (years)	All	12				
Technical efficiency	EV	1.45	1.62	1.75	1.84	1.89
(Vehicle km/MJ)	Diesel	0.41	0.54	0.54	0.56	0.58
	Petrol	0.40	0.45	0.45	0.47	0.48
	Hybrid°	0.57	0.64	0.64	0.67	0.68
VEHICLE COST[a]	EV	43.21	22.06	20.92	19.77	18.63
(K£/vehicle)	Diesel	12.84	13.06	13.39	13.39	13.39
	Petrol	12.49	12.39	12.62	12.62	12.62
	Hybrid°	16.59	13.13	13.13	12.97	12.81
Fixed operation &	EV	2.93	1.68	1.62	1.55	1.48
maintenance cost[a]	Diesel	1.52	1.53	1.55	1.55	1.55
(K£/Vehicle)	Petrol	1.50	1.50	1.50	1.50	1.50
	Hybrid°	1.74	1.53	1.53	1.52	1.52

[a] 2010 prices; °Non-plug-in hybrid vehicle.

Table 3
Transmission and distribution network reinforcement cost parameters used in this study.

	Technical lifetime (years)	Investment costs[a] (M£/GW)	Fixed operation & maintenance cost[a] (M £/GW)
Transmission	40	628.26	6.34
Distribution	25	328.13	12.61

[a] 2010 prices.

4. EV charging scenarios description

Five different EV charging scenarios are analysed in this study. These scenarios are compared with a base scenario where no EV penetration takes place. The five EV scenarios consist in four 'extreme' EV charging scenarios and one 'mixed' charging scenario. The motivation of the extreme scenarios is to find a set of boundary cases encompassing the range of potential impacts of the expected EV rollout, including the maximum and minimum investment costs. Also, this allows us to analyse a framing case of what would happen if 100% of EVs were to be charged in a certain way. Certainly, any of these scenarios in isolation is unlikely to happen and a mix of charging approaches is most likely to be the case. Therefore, we also propose a mixed charging scenario that would give us a more realistic idea of the EV rollout impacts and the extreme scenarios will provide information on maximum and minimum values.

These EV charging settings will have important interactions with the energy system and implications of the energy costs for the final consumer. The location of the charge will impact the nature and level of network investment (e.g. decentralised charging will require investment in the distribution and transmission networks, whereas centralised charging will only require investment in the transmission network). Also the 'smartness' of charge, due to the timing of EV demand, impacts both on network investments (i.e. 'dumb' charging is likely to require an increment on network capacity whereas 'smart' charging will use the available network capacity and will require lower level of investments) and on the electricity generation mix and its related emissions.

We believe that the selected scenarios give a range of outcomes that can provide valuable insight for policy makers and network operators.

The considered scenarios are:

- Base scenario (No EVs, used as a benchmark)
- Decentralised 'dumb' charging
- Decentralised 'smart' charging
- Centralised 'dumb' charging
- Centralised 'smart' charging
- Mixed charging (50% smart - 50% dumb; 60% decentralised - 40% centralised).

As shown in Fig. 3, these scenarios vary in where the charging take place and the 'smartness' of the charge. **Decentralised** charging is assumed to occur at widely spread way, at distribution level (i.e. charging is done at home or at work in the city), whereas **centralised** charging is assumed to occur before the distribution level. That is, in motorways, or big parking lots in the outskirts of cities, similar to the 'park and ride' schemes [34]. **'Dumb'** charging consist in charging at peak hours (in our study, this is considered between 17h and 20h), when people come back from work and electricity demand is highest, and **'Smart'** charging only occurs when it is cheaper to do so (off-peak times). Fig. 4 shows profile examples of 'dumb' and 'smart' charging. Note that the figure shows different examples of 'smart' charging. This is because we assume smart charging to take place whenever it is better for the energy system, from a cost-minimisation point of view. In other words, we allow the UKTM model to freely decide the timing of the charging. Moreover, the smart charging profiles are not static, as they are likely to change with the increase of EV penetration and other demands for electricity. This flexibility of smart charging is important to consider to avoid concentrating demand and creating a new 'peak time', defeating the purpose of smart charging.

By default, EV charging in TIMES is done in a decentralised 'smart' way (the model decides when charging scenarios in TIMES, we created a constraint making the EVs to be charged at peak time in the 'dumb' charging scenarios; and for the centralised charging scenarios we created a second type of EV with the only difference that can be charged before the distribution level. For the mixed scenario, the car demand is split between the two types of EVs (for centralised and decentralised charging) and each EV type has to charge 50% at peak time and 50% at off-peak time (for 'dumb' and 'smart' charging).

5. Results and discussion

In this section, we analyse and discuss the results of the five EV charging scenarios considered. The scenario results are analysed one at a time and compared with a base scenario with no EV penetration.

These EV scenarios are likely to have important impacts across the energy system. We focus our analysis to a number of policy-relevant variables including: changes in the energy mix and its related emissions, increased network investments, and changes in car energy use and energy costs for the final consumer.

5.1. Base scenario

The base scenario, not considering any EV penetration, is used as the benchmark to compare against the five EV charging scenarios. Fig. 7 (on the left-hand side) shows the fuel use changes for car transport for the base demand (see Table 1). In this base scenario, a small share of bio

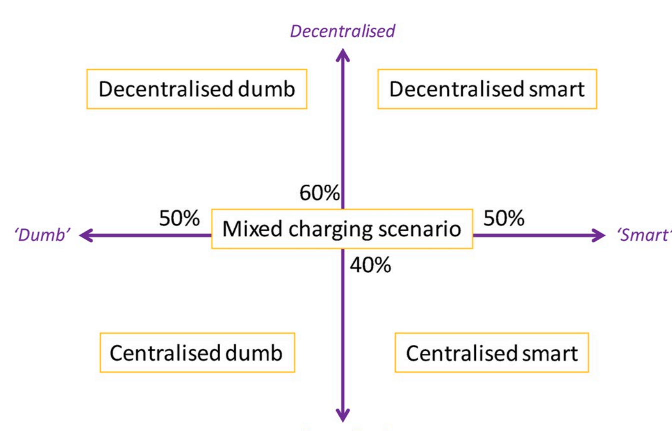

Fig. 3. The five EV charging scenarios.

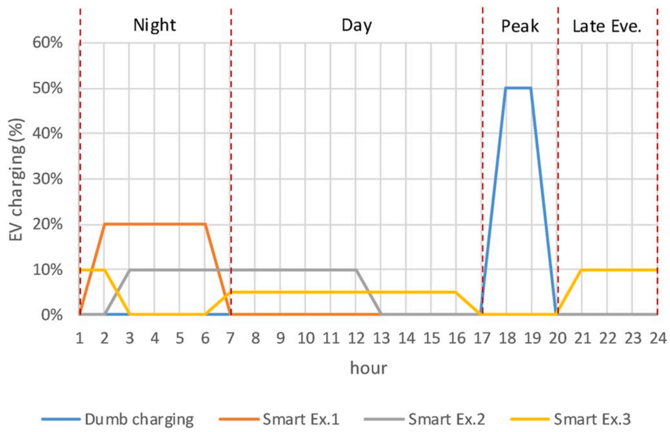

Fig. 4. EV demand profile examples for 'dumb' and 'smart' charging.

fuels are used, mainly in the form of biodiesel, up to 2020. The use of petrol and diesel stays stable up to 2020, and then use of diesel steadily decreases until 2045 when is no longer used. However, petrol partly replaces diesel and its use increases slightly from 2035. This exchange of fuels is caused by the replacement of conventional petrol and diesel cars by hybrid petrol-electric cars (non-plug-in, such as the Toyota Prius [35]). Petrol-electric hybrids are considerably more efficient than the conventional petrol only cars, so the model selects this new technology, as it is more cost-effective. This technology change makes the total fuel use to be lower in 2050 than in 2010, even though the demand in travelled km is almost 50% greater (see Table 1).

Fig. 8 (on the top left-hand side) shows the fuel costs for car transport for the base demand with no EV penetration (base scenario). In this base scenario, the fuel costs increase steadily up to 2050, which is a result of the increase of petrol prices over time.

The fuel costs are calculated as the product of energy use and energy price. The prices in TIMES are calculated as marginal cost to produce/deliver an extra unit of the commodity. In the case of fossil fuels in UKTM, the marginal cost is dependant of the cost of oil and fuel imports (exogenous to the model), and of refinery process and distribution costs (endogenous to the model). The marginal cost for electricity includes the cost of generating it, which depends on the technology mix used, and the cost of transport and distribution of it (considering both network investment and maintenance costs). Naturally, extra electricity generation that requires new investments on generation or network capacity will have higher marginal costs than electricity that can be generated and delivered with existing infrastructure.

For the sake of brevity, other relevant results from the base scenario will be described as they are compared with the other EV charging scenarios in the following sections.

5.2. Decentralised 'dumb' charging scenario

We start analysing EV scenarios with the results of the decentralised 'dumb' scenario, which is expected to be the 'worst' possible EV charging scenario in cost terms. This is because the peak-time decentralised charging will require important network capacity expansion in both transmission and distribution networks. We use this scenario as a starting point to analyse the potential improvements we can achieve as we move to 'smarter' and more centralised way to charge EVs.

The EV rollout implemented in TIMES creates a shift of fuels in car travel, from using mainly petrol and diesel to electricity. This translates to a considerable extra need of electricity generation and potentially extra network capacity, to enable the transmission and distribution to deliver additional electric power to the EVs.

Fig. 5 shows the model results on network investments for new transmission capacity. It shows that no new transmission capacity is required until 2030, and this is when new investment starts to occur. This reflects the fact that the existing capacity is enough to meet demand up to that point. The base case (blue solid line) show a steady increase in investment from 2030 to 2050, responding to the need of replacing old infrastructure and meeting with increasing demand in the power system (not related to EVs). In the decentralised 'dumb' charging case (with the marker), as expected, there is larger need of network investments, responding to the extra load created by the EVs. Also, the investment decisions follow the points where the biggest EV penetration occurs, 2030 and 2040, reaching around three times the level of investment of the base case.

The new investments for the distribution network are shown in Fig. 6. The base case (blue solid line) also presents some new investments in the distribution network increasing from 2020 to 2035 and then decreasing in 2040, to increase again for 2050. The decentralised 'dumb' charging scenario (marker), as expected, requires considerable distribution network reinforcements to accommodate the new EV demand at peak times. It shows similar sharp increases in investment requirements as in the transmission network, in years 2030, 2040 and 2050, following the marked increase of EV penetration of those years. This is particularly evident for 2040, where the EVs reach 80% penetration. Considering the costs of both transmission and distribution network reinforcements, this charging scenario requires 77.2% more investments than in the base case without EV penetration.

Fig. 7 shows the fuel (energy) use changes for car transport (including petrol, diesel, LPG, biofuels and electricity). In the decentralised 'dumb' charging scenario (shown in the centre of Fig. 7) the fuel use for car transport is similar to the base case up to 2020. After this point, diesel use falls more rapidly than in the base case, disappearing in 2035. Petrol use also decreases relatively quickly from 2020, whereas electricity use increases due to the EV penetration. Moreover, the total use in absolute values in 2050 is 50% less than the base case. This is caused of the increased energy efficiency of EVs, relative to conventional cars (in this study EVs are assumed to be slightly over three times more efficient than conventional petrol cars, in terms of km travelled per unit of energy input).

Fig. 8 shows the fuel costs for car transport for all scenarios (including petrol, diesel, LPG, biofuels and electricity). In the base scenario (top-left of Fig. 8), the fuel costs increase steadily up to 2050, which is a result of the increase of petrol prices overtime, mostly caused by the exogenous assumption of cost increases from imported oil. The decentralised 'dumb' charging scenario (top-centre in Fig. 8) show considerably greater 'fuel' costs from 2030 onwards, which for 2050 are 78.6% higher than in the base scenario. These increased costs relate to considerably higher electricity prices, reflecting the large network investments required to accommodate the extra decentralised load at peak hour.

Fig. 9 shows the total sectoral emissions for all scenarios and Fig. 10

Fig. 5. Transmission network investment for all scenarios.

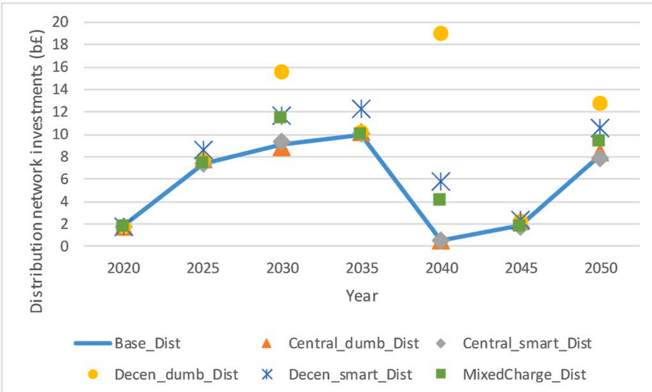

Fig. 6. Distribution network investment for all scenarios.

shows the electricity generation mix for all scenarios. The sectors are agriculture (AGR), electricity (power sector, ELC), hydrogen production (HYG), industry (IND), residential (RES), services (SER), and transport (TRA). In this EV charging scenario, as expected, transport related emissions decreased approximately 32% relative to the base scenario. However, the extra electricity required to fuel EVs has produced an increase of 32.5% on electricity production (see Fig. 10), which translates to an increase on emissions in the power sector of 48.6%. Other sectors do not show significant changes.

Overall, the decentralised 'dumb' EV charging scenario results in a reduction of 4.3% in total CO_2 emissions relative to the base case. However, the shift in sectoral emissions observed shows that it is important to take a whole-system approach and to consider renewable and 'clean' energy production policies in addition to transport policies, to avoid shrinking any potential climate benefits produced by the EV rollout.

5.3. Decentralised 'smart' charging scenario

The next scenario to analyse is the decentralised 'smart' one. This scenario will allow us to identify potential improvements due to having 'smart' EV charging (at off-peak times, when is cheaper to charge) instead of 'dumb' charging (assumed to be at peak time), but in the same decentralised context.

The decentralised 'smart' charging scenario also requires larger investment in both transmission and distribution networks than in the base case (shown with the ✻ marker in Figs. 5 and 6), but considerably lower than in the decentralised 'dumb' case (the ⬤ marker). The extra network investments in the decentralised 'smart' scenario are relatively small until 2035 and then grow in 2040, but not to the same level to the decentralised 'dumb' one. The total network reinforcement costs for this EV charging scenario are 38% greater than in the base case, but 50.6% lower than in the decentralised 'dumb' charging scenario. These results show that the 'smartness' of charge has effectively reduce the need of network reinforcements to support the EV rollout by around half.

Fig. 7 shows (on the right-hand side) the fuel use for the decentralised 'smart' charging scenario. Energy use in the decentralised 'smart' scenario is very similar to the decentralised 'dumb' one, showing that the required electricity to fuel EVs is practically the same regardless of the charging strategy. The small differences between them relate to small variations in EV uptake, the use of conventional fuel vehicles (e.g. biodiesel and diesel cars are phased out slightly sooner in the decentralised 'dumb' case due to a slightly higher EV penetration in years 2025–2035) and network loses. However, the difference in total fuel use is not that great. Note that this similarity in fuel use applies for all five EV charging scenarios considered in this study. Therefore, for the sake of brevity, the figures detailing fuel use for the remaining EV charging scenarios will not be included.

Car transport fuelling costs, on the other hand, can vary greatly between scenarios, caused to changes in electricity costs to 'fuel' (charge) the large-scale rollout of EVs. The decentralised 'smart' EV scenario (top-right in Fig. 8) has very similar total fuel costs to the base case, with a relatively small cost increase of about 6% in 2050. However, there is a noticeable difference with decentralised 'dumb' case with 78.6% greater costs in 2050, relative to the base scenario without EVs. This difference in costs relate to considerably higher electricity prices produced by the large network investments required in the decentralised 'dumb' scenario.

The CO_2 emission production in the decentralised 'smart' charging scenario (see Fig. 9) does not differ much from the decentralised 'dumb' one. In this case, transport emissions are reduced by 32.5% relative to the base case (practically the same of the previous scenario). The increase in emissions in the power sector is 42.3%, a smaller increase than in the decentralised 'dumb' scenario (48.6%). The overall emissions in this decentralised 'smart' scenario are 6.5% lower than the base case, which is an improvement from the decentralised 'dumb'.

The total electricity generation in this scenario is very similar to the previous one (see Fig. 10). However, the difference in emissions is caused by an increase on nuclear capacity and less generation with natural gas. The difference on emissions is, therefore, attributed to the electricity production in peak time, which is mostly supplied by more polluting technologies, such as gas, than during off-peak times.

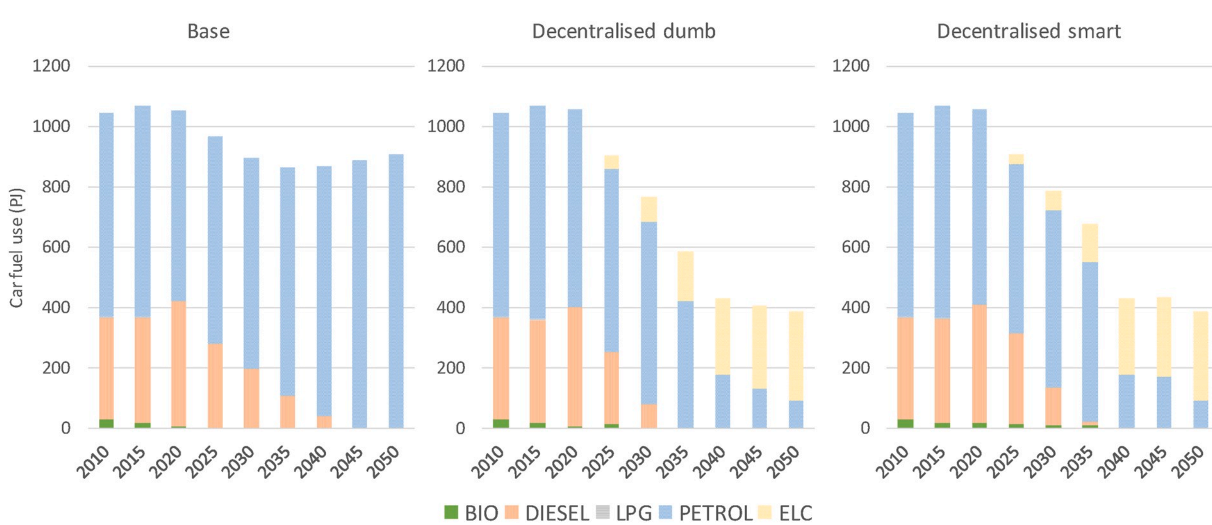

Fig. 7. Car transport energy use per fuel type from year 2010–2050 for the base, decentralised 'dumb' and decentralised 'smart' EV charging scenarios.

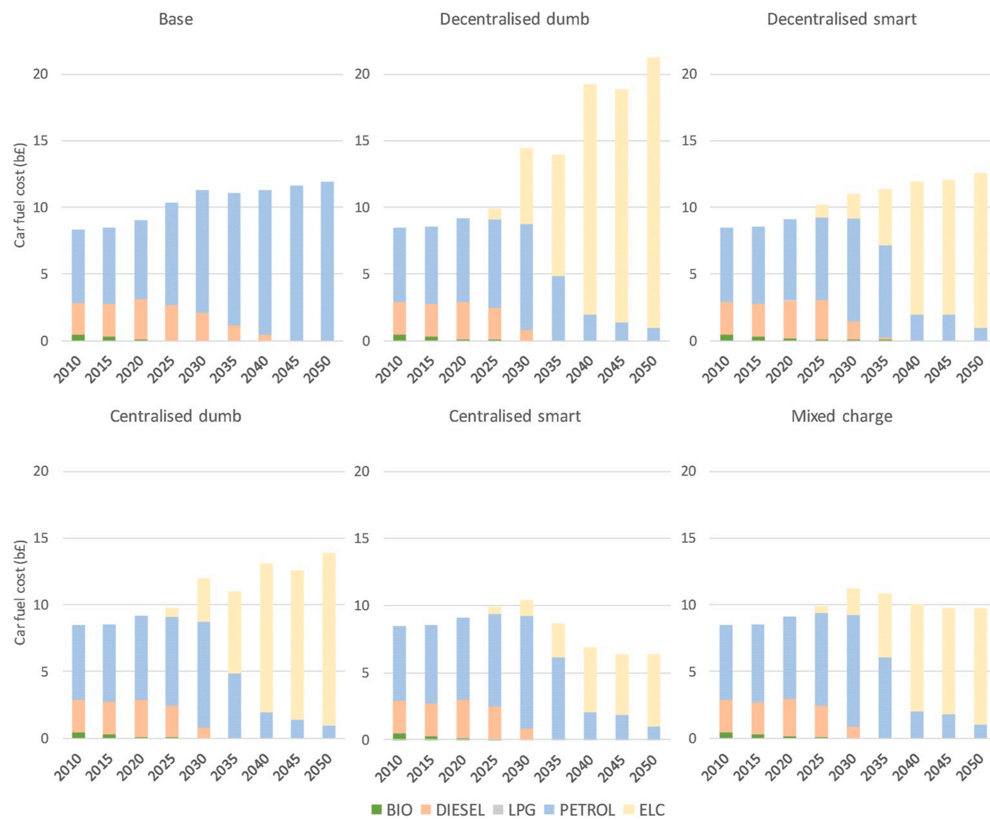

Fig. 8. Car transport energy cost per fuel type from year 2010–2050 for all EV charging scenarios.

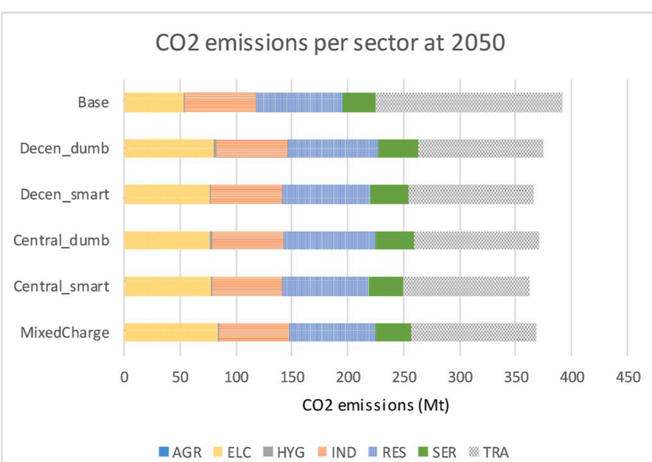

Fig. 9. CO_2 emission production per sector at 2050 for all scenarios.

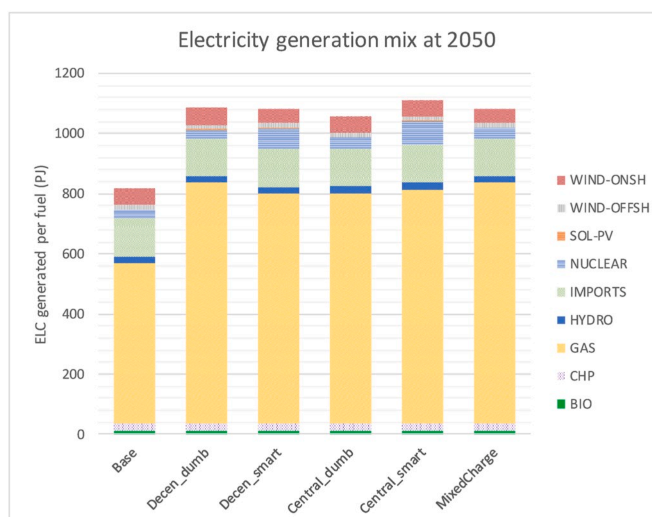

Fig. 10. Electricity generation per fuel type at 2050 for all scenarios.

5.4. Centralised ‘dumb’ charging scenario

Next, we analyse the potential impacts of moving the location of charging from a decentralised point (e.g. at individual households) to a centralised location, assumed to be as close as possible to the transmission network (e.g. parking lots in the outskirts of cities), so there is little or no need for reinforcements at the distribution network level.

The centralised ‘dumb’ scenario mostly needs network reinforcements at transmission level (the ▲ marker in Fig. 5) and almost no investment at distribution level, relative to the base case (see the ▲ marker in Fig. 6). Moreover, the investment in the transmission network in this scenario is very similar to the decentralised ‘dumb’ case (see Fig. 5). This similarity between ‘dumb’ charging scenarios suggesting that the location of charge does not affect significantly the transmission network capacity requirements.

The bottom-right area in Fig. 8 shows the ‘fuelling’ costs for car transport in the centralised ‘dumb’ scenario. This EV scenario has 16% higher fuel costs in 2050 than the base case, but it is considerably lower than in the decentralised ‘dumb’ case (78.6%). This shows that there are potential important savings to be made if we move to a more centralised approach to charging (closer to the transmission network, reducing investments on distribution). Nevertheless, the fuel costs in this centralised ‘dumb’ scenario are greater than in the decentralised ‘smart’ one (16% vs 5.8%, relative to the base case), so the importance of the smartness of charge should not be overlooked.

The CO_2 emission reductions in this centralised 'dumb' scenario (Fig. 9) bear similarities to the decentralised 'dumb' one. They present the same reduction in the transport sector (32.7%) but a smaller increase of emissions in the power sector (42.5% vs 48.6%), caused by lower electricity generation, especially from gas generators (Fig. 10). The smaller network losses in delivering the electricity to EVs results in this generation capacity reduction. The overall emission reduction of the system in the centralised 'dumb' case is 5.1%, which represents a small improvement from the decentralised 'dumb' case, but does not reach the same level of the decentralised 'smart' case (6.5% reduction). This shows that the smartness of charge is potentially more effective in reducing emissions than the location of charging.

5.5. Centralised 'smart' charging scenario

We now analyse the centralised 'smart' charging scenario, which is the last one of our extreme EV charging scenarios. This scenario is the 'best' one of the four extremes in terms of costs, so it will allow us to analyse the effects of both location and 'smartness' of charge, comparing it with previous scenarios.

Figs. 5 and 6 show the investments for new network capacity for the centralised 'smart' scenario (the ◆ marker). Similar to the centralised 'dumb' case, this scenario show relatively low investment requirements in the distribution network. For the transmission network, the investment pattern is comparable to the one in the decentralised 'smart' scenario but with a lower investment peak in 2040. This scenario has 8.4% greater network reinforcement costs relative to the base case. However, it has considerably lower costs compared to the other three scenarios above. The extra investment costs are about one third the size of what they are in the centralised 'dumb' or even lower than in the decentralised 'smart', showing that both the location and the 'smartness of charge are important in reducing the cost to accommodate the expected EV demand.

The bottom-centre area in Fig. 8 shows the fuel costs for car transport in the centralised 'smart' scenario. This scenario is the first one where the fuel costs for car transport drops, relative to the base case, reaching a reduction of almost 50% by 2050. Even though the electricity prices are slightly higher than in the base case, due to the network reinforcement costs, the reduction in total fuel use due to the improved efficiency of EVs (see Fig. 7) results in this cost savings.

Fig. 9 shows the total sectoral emissions for the centralised 'smart' charging scenario. This scenario shows similar outcomes as previous ones in terms of a reduction in transport sector emissions and an increase in power sector emissions. However, in this case electricity production is larger than in previous scenarios, with slightly more nuclear and onshore wind capacity (see Fig. 10). The overall emissions by 2050 are reduced by 7.5%, relative to the base case. Analysing the total emission reductions from all four extreme scenarios, it can be seen that the 'smart' charging scenarios present greater reductions (7.5% in centralised 'smart' and 6.5% in decentralised 'smart') than the 'dumb' ones (5.1% centralised 'dumb' and 4.3% decentralised 'dumb'). The difference in emissions between 'smart' and 'dumb' scenarios is attributed to the electricity production in peak time, which is partly supplied by more polluting technologies (i.e. gas, see Fig. 10) than during off-peak times.

5.6. Mixed charging scenario

Lastly, we analyse the mixed charging scenario where we consider that EVs are charged as a combination of 'smart' and 'dumb' charging (50/50%) and of centralised and decentralised charging (40/60%, see Fig. 3). It is impossible to know how EVs will be charged in the future, so this scenario was designed as a balanced approach between EV charging options. Also. this scenario tries to replicate a more realistic case, as we believe that the four extreme EV charging scenarios reviewed before would be unlikely to happen, but their analysis provides important insights on the range of potential outcomes that the expected large-scale EV penetration could bring.

The network investments for the mixed scenario (the ■ marker in Figs. 5 and 6) falls in between the scenarios previously reviewed. The overall network reinforcement costs for the mixed scenario is 18.9% greater than in the base case. Certainly, this scenario does not minimise the cost of investment requirements to the extent observed in the 'best' possible scenario (centralised 'smart' with 8.4%) but it performs better than the decentralised 'smart' (38%) or the centralised 'dumb' (24.5%) scenarios. This shows that the cost relation between charging scenarios do not follow a linear path and that the combination of some degree of 'smart' and centralised charging could be more effective in reducing network investment costs than to focus only in one of the two aspects (i.e. 100% centralised charging but 'dumb' or 100% 'smart' charging but decentralised).

The bottom-right area in Fig. 8 shows the fuel costs for car transport in the mixed scenario. This scenario also has lower fuel costs than the base case (18.2% lower in 2050), but does not reach the same level of savings of the centralised 'smart' (46.3% lower in 2050). This relates to the network costs shown in Figs. 5 and 6, and shows that it is reasonable to expect real long-term savings in fuel cost for EV users, even if network reinforcement costs are incurred and passed into consumers.

The total sectoral emissions and electricity mix for the mixed charging scenario are shown in Figs. 9 and 10. This scenario shows a similar emission pattern to previous scenarios. All the reviewed EV scenarios present an increase in electricity generation (ranging from 29% to 36%, relative to the base scenario) and reduction in overall CO_2 emissions relative to the base case, with the 'smart' charging scenarios presenting greater reductions (6.5%–7.5%) than the 'dumb' ones (4.3%–5.1%). For the mixed charging scenario, the emissions reduction is −5.9%. As expected, this value falls between the 'smart' and 'dumb' scenarios previously analysed.

5.7. Discussion of results

We believe that this study and the selected scenarios provide valuable insight on the potential impacts of the expected rollout of EVs. Also, the outputs of this study could be used to inform further economic and social impact analysis, contributing to extend our understanding on the wider effects of the electrification of transport.

Analysing the results above, it is evident that a high EV penetration scenario will require considerable power network reinforcements to be able to accommodate the new EV loads. This raises new questions regarding how investments are made and how they are paid for. A potential first question is how the required investment should be spread. The investment in network reinforcement will increase the activity in the power and construction sectors, among others. Looking at investment results from TIMES (Figs. 5 and 6), it is clear that the model concentrates most of the network investments in years 2030 and 2040, responding to the increase in EV demand. In a real implementation context, if the investment is concentrated in a short period of time (i.e. 2-3 years), it is likely to create negative wider economy impacts as the sectors involved need to draw in additional (but scarce) labour and capital resources. We consider this in a forthcoming work that introduces economy-wide modelling [9].

The construction and labour capacity constraints in the power sector are likely to be lessened if the spending and upgrade activity are spread over a longer timeframe. However, the current UK regulatory policy is to avoid investment before need, with the objective of reducing the risk of stranded assets (see Ofgem's price control remit [38]). The regulator approach seems to be sensible in this regard, but it could ultimately involve higher costs to the consumers and lower economic benefits from the EV rollout.

A second key insight from our results is in terms of the impact to the consumer. We can see from the TIMES energy costs results (see Fig. 8) that the level of network investment required impacts electricity prices.

In the UK, it is expected that the funding of the necessary network upgrade will be recovered through electricity bills, over the life of the asset. This increase in electricity price will affect all energy consumers, not only EV users. Therefore, it is important to consider how consumers may be impacted through both energy bills and the costs of other goods and services (as companies are likely to pass on their increased energy costs through their own prices). The impact on low-income households, which might not own or have access to an EV and, thus, not benefit from the potential fuel cost savings due to the increased car efficiency, is particularly relevant for policy makers wishing to avoid creating regressive EV policies.

A third question addressed here focuses on the wider impacts of changing from fossil fuels to electricity in car transport. There is an important benefit in emission reductions from the switch on fuels (see Fig. 9), especially if the new electricity generation is achieved with renewable sources. Moreover, we believe that moving away from petrol and diesel could have further benefits in the wider UK economy. It is commonly argued that fossil fuels are an important source of tax revenue to the UK government and losing that revenue could create an important gap in the public purse [39]. However, based on the findings of linked economic modelling work [9,40], we believe that the uptake of EVs could trigger other benefits that could potentially offset any losses incurred. The reason behind this is that the petrol/diesel industry are part of an import-intensive supply chain (i.e. there is extensive leakage of value from the UK), whereas the UK electricity industry has strong domestic supply chain linkages, so the growth of this industry is likely to have a greater positive impact in the wider UK economy [40].

The implementation of centralised and smart charging are likely to reduce the need for network investments. Therefore, a last question could be set on what policies and/or business models could be implemented to facilitate the optimal allocation of charging points and smart charging. There is a number of policy/market drivers examples addressing this, including time-of-use electricity tariffs and demand response programmes, which could be user-managed or supplier-managed [36]. However, it is important that the costs and benefits of the smart charging and demand-side management of EVs are shared in a just way [37] (i.e. non-EV users paying for the network costs and not receiving the economic benefits from demand response programmes).

The TIMES model is an important tool for energy policy analysis with several examples of its use in policy decision making worldwide [18]. However, the energy network representation is limited in TIMES. In particular, UKTM is a single region model. This means that the modelled energy networks do not incorporate explicit treatment of the geographical location of generation and demand points, or the intrinsic complexities of the network. Therefore, the network investment costs obtained in this study should be considered as rough estimates, and other more specific types of power system models (such as PLEXOS or SEDM [41]) could further help inform network costs. Nevertheless, we believe that the type of TIMES results generated here provide important insights in terms of the order of magnitude of such costs and allow to compare the impact of the 'smartness' and the location of EV charging. In addition, the TIMES model provides a whole system view approach, producing several other relevant results, such as changes in energy use for transport, changes in marginal fuel costs, changes in emissions, etc. All these results and analysis enable the basis of the contribution of this paper, in providing important insight for both the social sciences and policy makers.

6. Conclusions

The UK Government, as part of their strategy to tackle climate change and improve air quality in cities, is setting up policies for a large-scale EV rollout. The current policy expectation is that most cars and vans will be electric by 2050. Moreover, the move towards EV mobility will bring important changes to the energy system. This study provides insight on the wider effects of the electrification of transport, analysing the implications of a large penetration of EV under five different charging scenarios. We have analysed the impacts of these scenarios in terms of network investment needs to accommodate the increasing EV demand, changes in fuel use and fuel costs for the final consumer and changes in CO_2 emissions.

The results obtained show the importance of the 'smartness' and location of EV charging for network reinforcements costs. Also, network investment costs are passed to the final consumers as an increase in energy marginal costs (energy prices). Therefore, a charging scheme with higher network investment and more expensive electricity generation will translate to higher energy bills to final consumers. This will not only affect the costs of charging EVs, but of all electricity-powered services across the energy system as well. This could create a cascading effect, increasing prices in other non-energy goods and services. These cost increases are an important burden particularly for those in lower incomes, who might not even benefit from having an EV. It is, therefore important to consider these outcomes while designing energy tariffs and EV policies, making sure that there is a reasonable balance of costs and benefits across the whole economy.

Looking into CO_2 emissions, all EV scenarios presented a similar reduction in emissions for the transport sector. However, we observe a shift of sectoral emissions as the power sector increased their emissions (extra generation to meet EV demand), effectively reducing the potential climate benefits of the introduction of EVs. These results show the importance of a whole system approach to tackle climate change, where there is no emission transfer to other sectors or 'outsourced' to other countries.

The type of study proposed in this paper provides valuable insight on the implications on network investments and energy costs of different types of EV charging options. Moreover, this study brings other important points of discussion on the EV rollout, including the timing of network investments, the economic impacts to consumers (direct and indirect), and the potential benefits to the wider economy. Therefore, we see this analysis as necessary first step for further research on the full implications of the EV rollout in the energy system and the wider economy.

As future work, we will plan to use other models in combination with TIMES to expand the results obtained here and to be able to respond some of the questions described in this section. For instance, macroeconomic models such as Computable General Equilibrium (CGE) model can be used to provide insight on how network costs could be paid for and what impacts do they have in the wider economy [9]. These types of 'whole system' models are also widely used by policy decision makers, including the Scottish and UK Governments [42,43]. The CGE model can complement TIMES analysis, providing insight in terms of overall economic growth (GDP changes), job creation and wealth distribution across different consumer groups, which could help us to understand who ultimately pays for the large-scale rollout of EVs.

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.

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