Assessing the Impacts of Large EV Penetration in the UK – Analysis of Network Investments and Changes in Fuel Use

Christian F. Calvillo*[1], christian.calvillo@strath.ac.uk
Karen Turner[1], karen.turner@strath.ac.uk
Keith Bell[2], keith.bell@strath.ac.uk
Peter McGregor[3], p.mcgregor@strath.ac.uk

* Corresponding author

[1] Centre for Energy Policy, International Public Policy Institute, University of Strathclyde.
McCance Building, 16 Richmond Street, Glasgow, G1 1XQ.
[2] Department of Electronic and Electrical Engineering, University of Strathclyde.
Royal College Building, 204 George Street, Glasgow, G1 1XW.
[3] Fraser of Allander Institute, University of Strathclyde.
199 Cathedral Street, Glasgow, G4 0QU.

Abstract

The electrification of transport has been identified as a key policy area, which has multiple implications on the energy system, the economy, and the environment. Focusing on electric vehicles (EV), several examples of studies analysing the impact of a large scale penetration of EVs can be found in the literature. However, these studies usually focus only on the implications for the electricity network. Therefore, the challenge is to understand how the expected rollout of EVs affects the energy system in different dimensions, within and beyond the electric sector.

With the aim of identifying wider impacts of a large rollout of EVs in the UK and to inform effective analysis of energy policy, we use the UK TIMES model to implement four different EV charging scenarios, varying on the timing (i.e. 'smartness') of the charge and the location on where it happens. We conclude that 'dumb' and decentralised charging will require considerably larger investment on the network than the 'smart' and centralised counterparts. The location and 'smartness' of EV charging it is, therefore, an important consideration to mitigate potential negative impacts on the power system and to reduce energy and fuel costs for the final consumer. Moreover, we have found that a shift of emissions occurs from the transport to the electric sector. These results show the importance of following a whole system approach in energy policy analysis, to maximise the effectiveness of policies and to avoid carbon leakage.

Key words: Electric Vehicles; Energy System Models; Energy Scenarios; Energy Policy; TIMES.

1. Introduction

As a part of their actions to tackle climate change and air quality concern, a number of countries around the world are pushing ambition targets for the decarbonisation of transport. One of such actions is the widespread roll-out of electric vehicles (EV). In the case of the UK, the Government has set the target of all new cars and vans to be effectively zero direct emission by 2040 (UK Government, 2018), and other sources such as National Grid (the British TSO) expect an overall EV penetration of 90% by 2050 (National Grid, 2018).

A large penetration of EVs is likely to bring important challenges to the energy system, potentially requiring new generation capacity and network reinforcements (Su et al., 2019). For instance, Blokhuis et al. (2011) analyses the potential electricity peak load increases due to sustainable energy transitions. The authors take the city of Eindhoven to analyse the effects of the introduction of heat pumps and EVs on peak load projections, concluding that under worst case assumptions, peak loads in Eindhoven increase with 200% until 2040. Also, the study estimates 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.

Pudjianto et al. (2013) also analyse the growth of electricity loads caused by the electrification of transport and heat. The authors develop a range of numerical simulations on different distribution network topologies (urban and rural) in the UK, assessing the need and the cost of network reinforcements required to accommodate future load. The study concludes that under current passive distribution network and passive demand approaches, electricity peak demand its likely to increase up to 2–3 times and significant distribution network reinforcement will be required, costing up to £36bn across the period 2010–2050. Note that this study does not include the transmission network in their analysis and it does not analyse the impact on energy costs or CO2 emissions.

It has also been recognised that the timing (‘smart’ vs ‘dumb’) and location (at home vs at a centralised charging point) of EV charging could potentially increase or mitigate the undesired impacts of the EV roll-out (Sanchez-Miralles et al., 2014). The benefits of ‘smart’ charging has been studied widely. For instance, Calvillo et al. (2017) present an analysis of how different levels of EV penetration and ‘smart’ charging can be used to exploit synergies between different systems within the cities, concluding 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 final consumers. However, it does not analyse network costs or benefits due to emission reductions.

Many studies have been developed to address some of these challenges. However, most of them fail to analyse the implications of a large penetration of EVs outside the power sector, not considering, for example, the changes on fuel use and consumer costs. The objective of this paper is to provide insight on this issue, by modelling four types of EV charging scenarios, using the UK TIMES model, under a high EV penetration context. These scenarios vary in where the charging take place and the 'smartness' of the charge. Decentralised charging is assumed to occur 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. 'Dumb' charging consist in 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 work developed in this paper aims to provide 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. Note that this analysis does not give a full wider-economy picture, but it is a key step along that path.

2. Methodology (Model description and base scenario)

TIMES is a bottom-up an energy system-wide model, which considers all the processes of the energy system. The model considers all the processes that transform, transport, distribute and convert energy to supply energy services (see Figure 1).

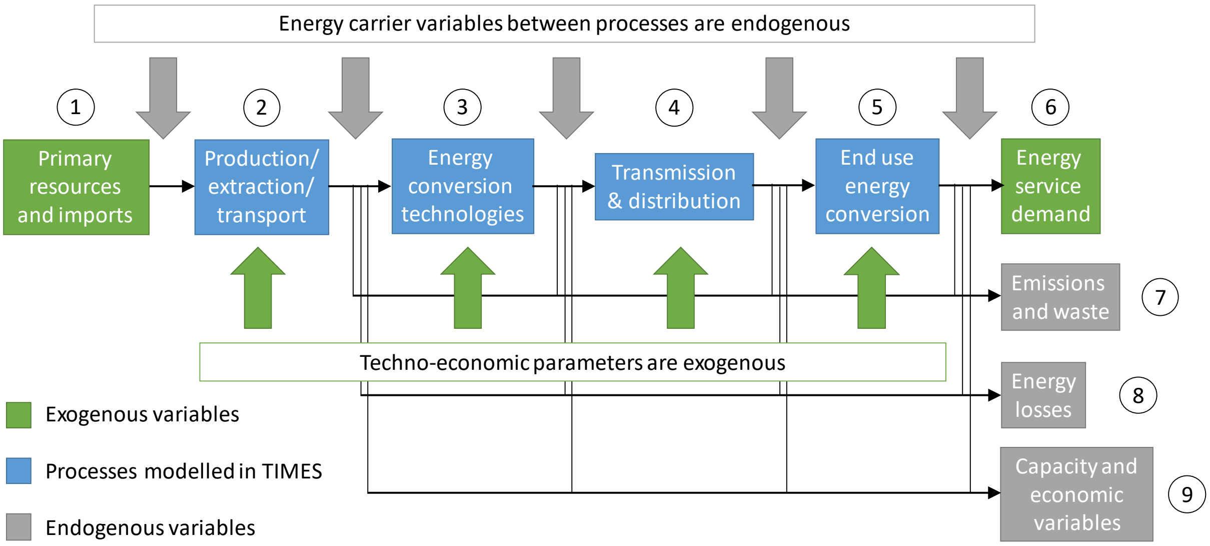

Figure 1. Modelling of the energy system in TIMES (Calvillo et al., 2017)

TIMES uses linear-programming to find a least-cost energy system, able to meet specified energy service demands, according to a number of user constraints. A more detailed description of the model can be found in Calvillo et al. (2017) and official documentation can be found in Loulou et al. (2004, 2005).

The UK TIMES model (UKTM, version V.1.2.2) is used in this study to test the impact of different EV charging strategies in a context of high EV penetration. See (UCL, 2014) for more information on the UK TIMES model.

UKTM is a very large model with thousands of variables, parameters and constraints. UKTM differs from other TIMES versions on parameters and input data used, which should reflect the characteristics of the country or region modelled. However, the general structure of the models is similar, so the insights obtained here are very likely to be useful and applicable to other TIMES models.

3. Parameters and scenario description

Four different EV charging scenarios are analysed in this study. These scenarios are compared with a ‘business-as-usual’ base scenario with no EV penetration. Figure 2 shows the difference between the scenarios, varying in where the charging take place and the ‘smartness’ of the charge. **Decentralised** charging is assumed to occur 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 big parking lots in the outskirts of cities, similar to the ‘park and ride’ schemes (Mills and White, 2018). **‘Dumb’** charging consist in 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).

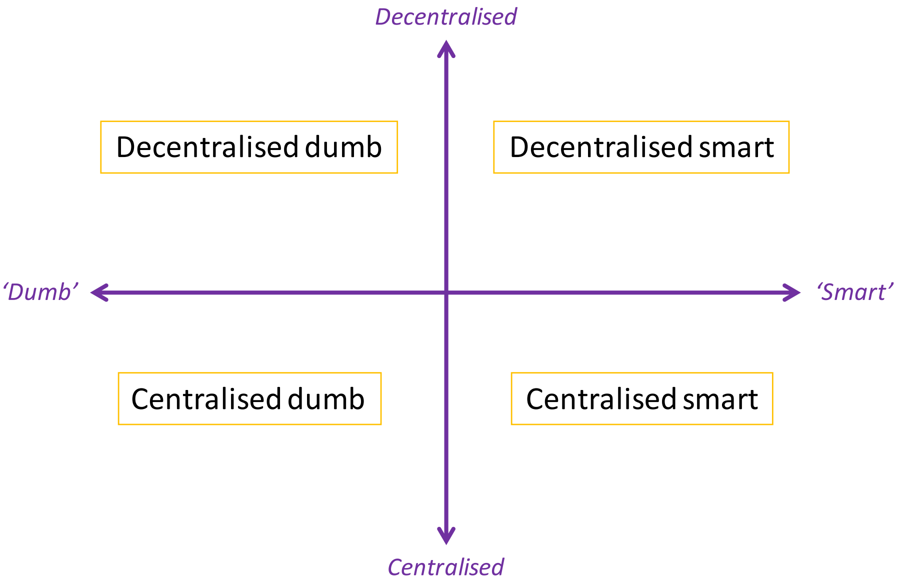

Figure 2. The four EV charging scenarios.

3.1 EV parameters

Figure 3 shows the EV rollout projection used in this study. The expected EV penetration is around 20% by 2030, 80% by 2040 and 90% by 2050, which applies to all four EV charging scenarios described above. This EV penetration scenario is based on the SPEN RIIO-T2 Electricity Scenarios 2018 consultation (SPEN, 2018) and National Grid Future Energy Scenarios FES2018 (National Grid, 2018).

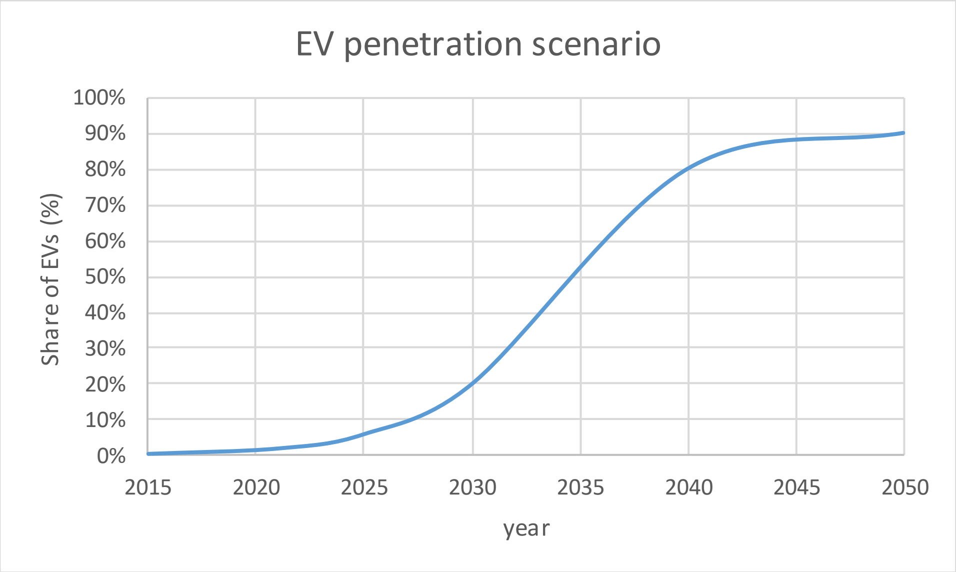

Figure 3. Considered EV penetration for all EV charging scenarios

Table 1 summarises the main EV parameters considered in this study. 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 (2018) and the International Energy Agency (2018).

Table 1. EV parameters used in this study.

	2010	2020	2030	2040	2050
Lifetime (years)	12				
Technical efficiency (vehicle km/MJ)	1.45	1.62	1.75	1.84	1.89
Vehicle cost* (k£/vehicle)	43.21	22.06	20.92	19.77	18.63
Fixed operation & maintenance cost* (k£/vehicle)	2.93	1.68	1.62	1.55	1.48

**2010 prices*

3.2 Network reinforcement cost parameters

Table 2 shows the considered capital investment, operation and maintenance costs for network reinforcements. These costs apply for all new network capacity implemented in the energy system as a result of the increasing EV demand. These costs roughly align with different network reports including the analysis developed by Kiani Rad and Moravej (2017), IEA ETSAP (2014) and the Electricity Networks Strategy Group (2012).

Table 2. Transmission and distribution network reinforcement cost parameters used in this study.

	Technical lifetime (years)	Investment costs* (m£/GW)	Fixed operation & maint. cost* (m£/GW)
Transmission	40	628.26	6.34
Distribution	25	328.13	12.61

**2010 prices*

4. Results and discussion

UKTM produces a very large quantity of results for all sectors in the energy system. For the sake of brevity, only results related to power network investments, car energy use and technology changes, and CO2 emissions are reviewed here (changes in other sectors are not analysed).

Figure 4 shows the network investments for new transmission and distribution capacity under the different EV charging scenarios and the base case. For the transmission network (Figure 4.a), no new capacity is required until 2030, where new investment occurs, especially for the 'dumb' charging scenarios (3 to 4 times the investment of the base case). However, the smart charging scenarios present a smaller difference relative to the base scenario. In 2040, the increasing penetration of EVs, reaching 80% in 2040, creates the need for extra transmission network capacity for that year, reaching the b£12 in the 'dumb' charging scenarios, which is approximately three times the investment of the base case. Interestingly, the decentralised 'smart' scenario also presents an important increase of investment (around b£10), contrasting with the centralised 'smart' alternative (around b£6 of investment in 2040), suggesting that not only the smartness of the EV charge affects the required transmission capacity, but the location where the charging takes place is important as well. In 2050, extra network investment is needed relative to the base scenario, but there is little difference between charging scenarios.

The investments on new distribution network capacity (Figure 4.b) show important difference between the centralised and decentralised scenarios. As expected, the decentralised charging requires considerable distribution network reinforcements, whereas the investments on centralised charging do not vary significantly from the base scenario. This is because the charging in the centralised scenarios is assumed to occur before the distribution network, so this part of the network is not directly affected. Moreover, it is clear that the 'smartness' of EV charging has a great impact on distribution investments, where the decentralised 'dumb' charging requires considerably more investment than the 'smart' case, especially for the large EV penetration increment in 2040 (see yellow checked columns in Figure 4.b).

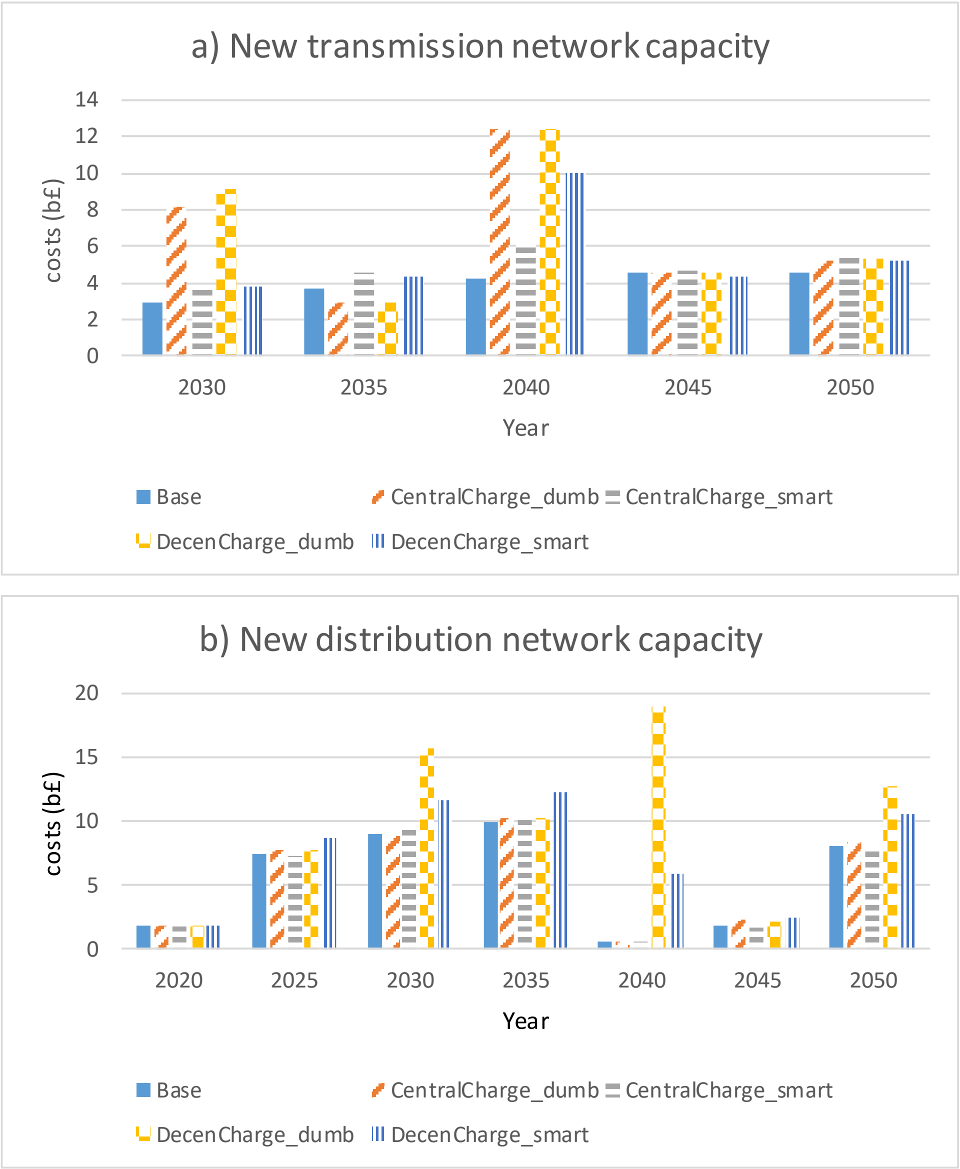

Figure 4. New transmission and distribution network investment across scenarios.

Figure 5 shows the total investments of new network capacity, relative to the base scenario. These total values are calculated as the sum of the transmission and distribution network investments in each EV scenario (see Figure 4) minus the equivalent investment made in the base case (which is assumed as investment that needed to be carried out independently of the presence of EVs).

Figure 5 shows the large difference in investment costs between scenarios, where the ‘best’ case is the centralised-smart charge scenario with b£4.9 total investment and the ‘worst’ case is the decentralised-dumb charge scenario with b£45.3. Moreover, the importance of the smart charge is evident, as the scenarios implementing smart charging require less than half the investment of their ‘dumb’ counterparts. Also, the figure shows how the investments in TIMES react to the increase points in EV demand. So in 2030, with 20% EV penetration, and 2040, with 80% EV penetration, is where the largest investments are made.

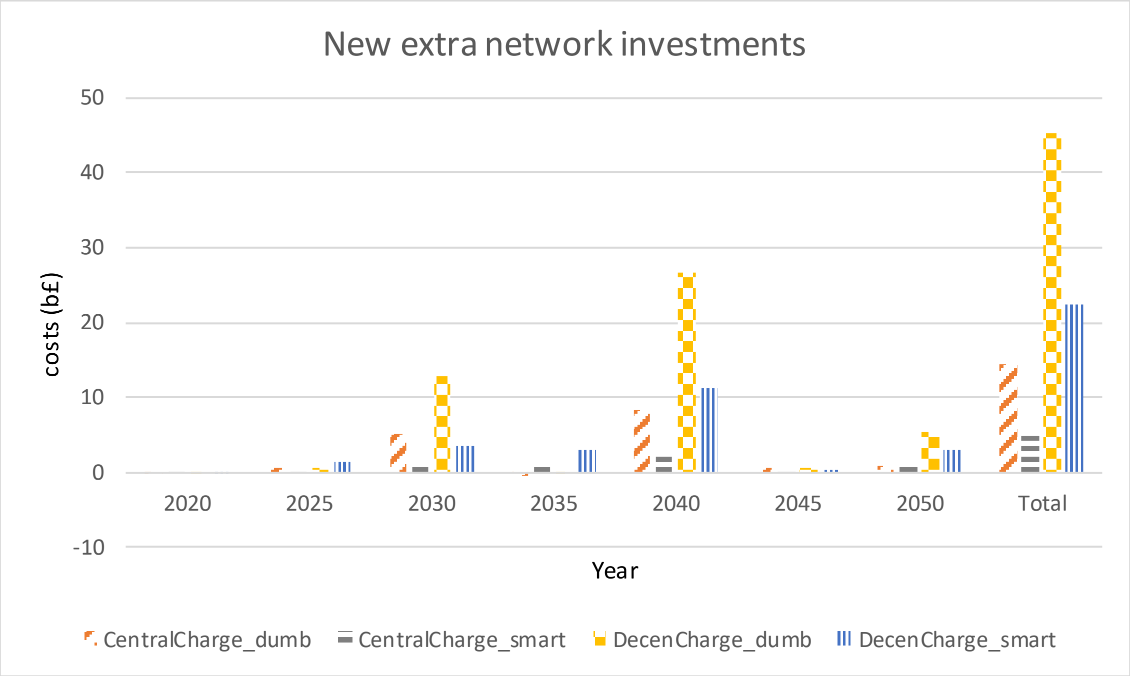

Figure 5. New extra network investments relative to the base scenario.

Figure 6 shows the fuel use changes for car transport. For the sake of brevity, only the scenarios: base, centralised-smart and decentralised-dumb are shown here. In the base scenario, the use of petrol and diesel stay 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 (Toyota, 2019)).

In the centralised ‘smart’ charge scenario (Figure 6.b) 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 importantly 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 efficiency of EVs, relative to conventional cars (in this study EVs are assumed is slightly over three times more efficient than conventional petrol cars, in terms of km travelled per unit of energy input). Energy use in the decentralised ‘dumb’ scenario is very similar to the centralised ‘smart’ one (see Figure 6.b and Figure 6.c), showing that the required electricity to fuel EVs is practically same independently of the charging point and the small differences between them relate to network loses.

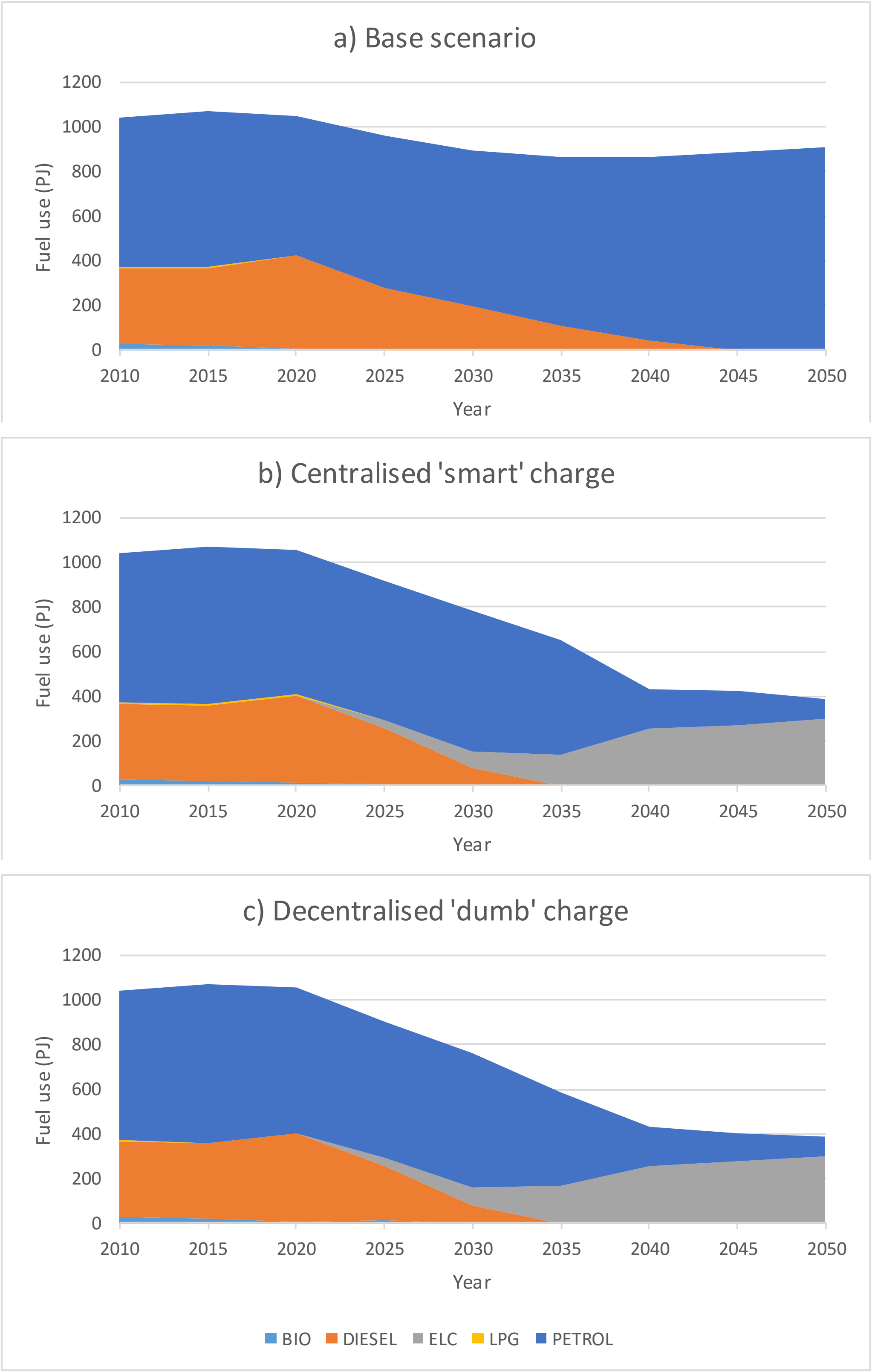

Figure 6. Car transport energy use per fuel type for a) base, b) centralised ‘smart’ charge and c) decentralised ‘dumb’ charge scenarios.

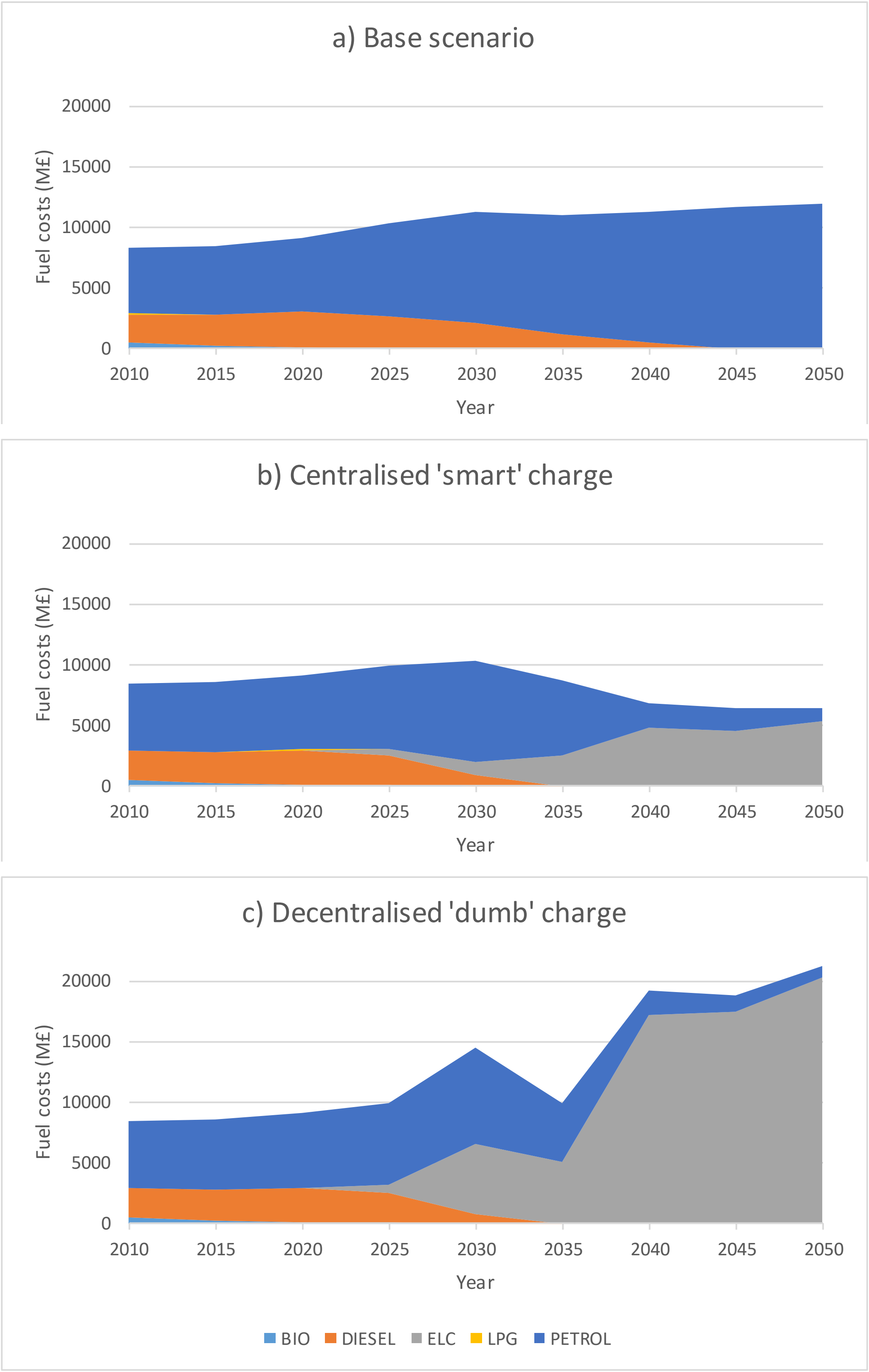

Figure 7. Car transport energy cost per fuel type for a) base, b) centralised 'smart' charge and c) decentralised 'dumb' charge scenarios.

Figure 7 shows the fuel costs for car transport under different scenarios. In the base scenario (Figure 7.a), the fuel costs increases steadily up to 2050. However, this contrasts with the reduction in total energy use shown in Figure 6.a, which suggests that the price of petrol increases at a higher rate than the decrease in energy units. In the case of centralised smart charge, fuel costs are reduced significantly. The total fuel costs in 2050 is 46.3% lower than in the base scenario which responds to the reduction on total energy use decreases due to the higher efficiency of EVs (see Figure 6.b). On the contrary, the decentralised 'dumb' charging scenario (Figure 7.c) presents a considerably greater fuel costs, which for 2050 are 78.6% higher than in the base scenario. Note that this scenario has similar fuel use than under the centralised 'smart' charging, so the increased costs relate to considerably higher prices, reflecting the large network investments required to accommodate the extra decentralised load at peak hour (see network investment in Figure 4).

Figure 8 shows the total sectoral emissions across the different scenarios. As expected, transport related emissions (TRA) decreased approximately 32% relative to the base scenario. However, the extra electricity generation required to fuel EVs has produced an increase of emissions in the power sector (ELC) in the range of 42 – 48%. All EV scenarios present a reduction in overall CO2 emissions relative to the base case, with the 'smart' charging scenarios presenting greater reductions (-7.5% in CentralCharge_smart and -6.5% in DecenCharge_smart) than the 'dumb' ones (-5.1% CentralCharge_dumb and -4.3% DecenCharge_dumb). The difference on emissions between 'smart' and 'dumb' scenarios is attributed to the electricity production in peak time, which is mostly supplied by more polluting technologies than during off-peak times.

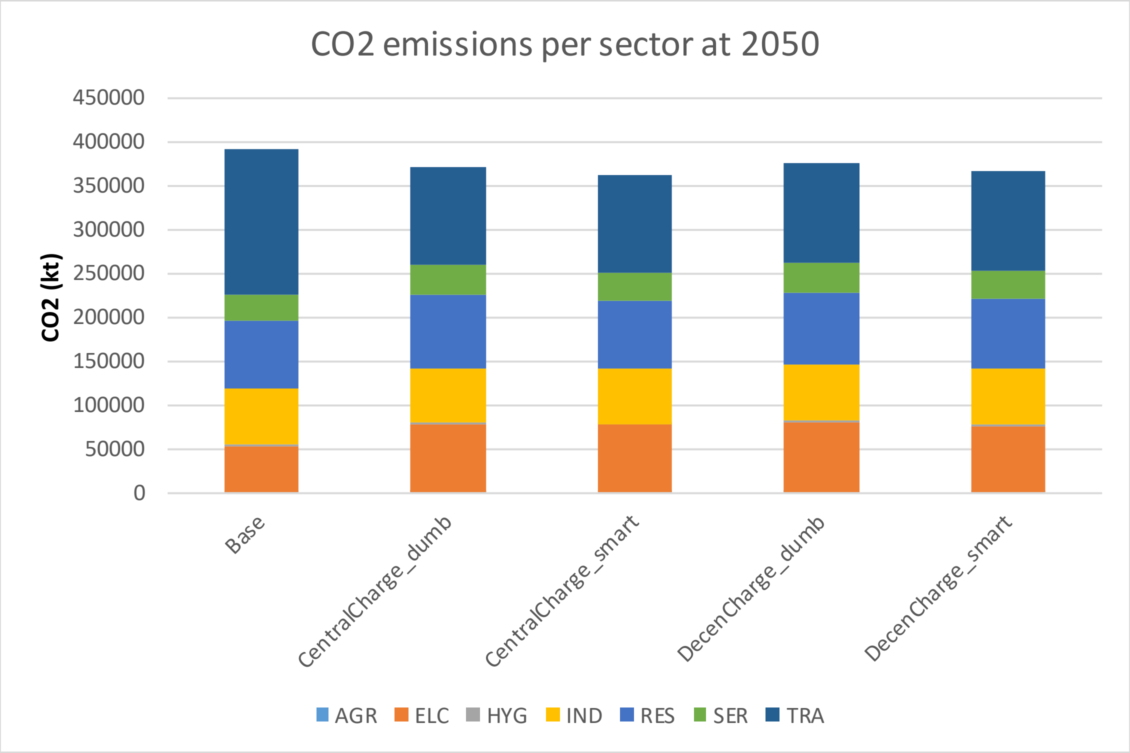

Figure 8. Comparison of CO2 emission production per sector at 2050.

4.1 Discussion of results

Analysing the results of this study, it is evident that the different charging scenarios show great difference across most outputs. Network investment costs is one example of this, with total cost ranging from b£4.9 to b£45.3. These outputs also remark on the importance 'smart' charging, with an approximate reduction of 50% on network investment costs, relative to the 'dumb' cases. Moreover, the location where the charging takes place can significantly affect network reinforcement costs, where the decentralised charging can be up to three times more expensive than the centralised charging. Note that the obtained network cost do not consider charging point costs, which could potentially change these differences between scenarios. These results could be used to inform policies that promote more centralised and/or 'smart' EV charging schemes, potentially reducing the need of expensive network investments.

Another interesting result is the timing of the network investments. Figure 5 shows how the investments in TIMES react to the increase points in EV demand. That is, the largest investments are made in 2030 (increase up to 20% EV penetration) and 2040 (increase up to 80% EV penetration). The timing of the investment is relevant for further economic analysis as the required network expansion is likely to be a complex project requiring several years to finance and implement, so the investment pathways shown in TIMES are likely to be impractical or unrealistic.

For energy use in car transport, the results show that there is no significant difference in fuel use between the considered EV scenarios (see Figure 6.b and Figure 6.c). This is an expected outcome as all scenarios implement the same EV penetration and the required input fuel is the practically same independently of the charging point (very minor differences due to network losses). On the contrary, energy costs show major differences across scenarios (see Figure 7) as the electricity marginal cost (a proxy for price) reflects on the network reinforcement costs. Therefore, the cost to charge their EVs will be considerably higher in those scenarios with higher network reinforcement needs.

The difference between these scenarios also show that the EV charging approach will have an important impact on overall energy costs for the final consumer. Not only for charging EVs but for all activities that require electricity. Hence, it is likely that households will not agree on EV policies and/or will not participate in the expected EV uptake if energy prices raise significantly, as in the case of the decentralised 'dumb' charging scenario. The potential impacts on energy prices is an important consideration for policy makers while designing effective EV policies.

The electrification of private transport produced important reductions on CO2 emissions for the sector (about 32%). However, most of this emissions were shifted to the power sector, due to the need of extra electricity generation to meet the new EV demand. Therefore, the final total CO2 emissions reduction were in the range of 4 – 7%. Note that the TIMES scenarios analysed does not include a CO2 emissions constraint, so the model decides on the most cost effective technology to produce electricity to meet the EV demand, which in this case are combined cycle gas turbines (CCGT) burning natural gas. These results show the importance of whole system approaches, to avoid the shift of emissions between sectors, eroding potential benefits of policies to tackle climate change.

4.2 Research limitations and future work

We believe that this study and the selected scenarios provide valuable insight on the potential impacts of the expected rollout of EVs. However, there are some opportunity areas and limitations of this study that should be taken into account. For instance, four 'extreme' EV charging scenarios have been considered, analysing 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. However, these 'extreme' scenarios give a range of outcomes that can provide valuable insight for policy makers and network operators.

The TIMES model is an important tool for energy policy analysis with several examples of its use worldwide (IEA-ETSAP, 2019). However, the energy network representation is limited in TIMES. In particular, UKTM is a single region model, so the modelled energy networks do not consider geographical location of generation and demand points and 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 (Pennock et al., 2016)) could be used for a more accurate approximation of network costs.

Nevertheless, we believe that these TIMES result give insight of the order of magnitude of such costs and to be able to compare the impacts 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.

As future work, we will plan to use other models in combination with TIMES to expand the results obtained here. For instance, power system models could be used to improve the cost estimation of network reinforcements. Also, macroeconomic models such as CGE (Scottish Government, 2016) can be used to provide insight on how network costs could be paid for and what impacts do they have in the wider economy, in terms of overall economic growth (GDP changes), job creation and wealth distribution across different consumer groups, which could provide further insight on who ultimately pays for the large scale rollout of EVs.

5. Conclusions

This study analysed four EV charging scenarios in the context of a large penetration of EVs. These four scenarios represent extreme cases of charging: smart vs dumb, and centralised vs decentralised. Using the UK TIMES model, we analysed the impacts of these scenarios in terms of network investment needs to accommodate the increasing EV demand, changes in fuel costs for the final consumer and changes in CO2 emissions.

The results obtained show the importance of the 'smartness' of EV charging in terms of network reinforcements and fuel costs, where 'dumb' charging (i.e. charging at peak times) represent approximately double the cost than under 'smart' charging (at off-peak times). The impact of the location of the charging was also assessed, and the decentralised charging (e.g. charging at home, at the end of the distribution network) presented higher overall costs, up to three times those of the centralised charging alternative (e.g. charging outside cities in a centralised location). Another interesting result of this analysis is that the decentralised 'smart' case is more costly than the centralised 'dumb' case, which suggest that the location of EV charging might be more important in reducing overall costs than the 'smartness' of charge. Also note that these differences in network investment costs are passed to the final consumers as an increase in energy marginal costs (energy prices). These outcomes are also important to take into account while designing energy tariffs and EV policies.

Looking into CO2 emissions, all EV scenarios presented a similar reduction in emissions for the transport sector of approximately 32% by 2050, relative to the base case without EV penetration. However, we observed a shift of sectoral emissions as the power sector, required to generate more energy to meet EV demand, increased their emissions in the range of 42 to 48%, relative to the base case. Note that the 'smart' charging scenarios produced lower emissions in the power sector as the more polluting power plants are normally used to generate power at peak times. Also, these results show the importance of a whole system approach to tackle climate change, where policies that target a particular sector (e.g. promoting EV uptake) need to be accompanied with other policies that ensure that there is no emission transfer to other sectors or 'outsourced' to other countries.

Even though the representation of the network in TIMES is limited, the study proposed in this paper provides some insight on the implications on network investments and energy costs of different types of EV charging options. We believe that these scenarios provide a range of outcomes that may help policymakers and network operators to plan and find solutions that do not overburden consumers and facilitate the uptake of EVs.

Acknowledgement

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