Phasing in electric vehicles: Does policy focusing on operating emission achieve Net Zero emissions reduction objectives?

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Abstract

Battery electric vehicles (BEVs) are being integrated into the UK transport network to reduce operating emissions (OEs) as BEVs produce zero emission at point of use. True OEs depend upon fuel source emissions, and ‘cradle-to-grave’ life cycle emissions. This paper investigates method comparisons of a simple operation emissions model (OPEM) against a life cycle analysis (LCA) (Transport Energy and Air Pollution Model (TEAM-UK)) approach to inform on the UK’s target to achieve net zero emissions. Emission comparisons from internal combustion engine vehicles (ICEVs) and BEVs between 2017 and 2050 using TEAM-UK (estimating both OEs and full LCA) and the OPEM (OEs only) across three vehicle scenarios were analysed: (S1) 100% ICEVs, (S2) new ICEVs banned from 2040, and (S3) new ICEVs banned from 2030.

Both model outputs varied between scenarios. The OPEM predicted 19% more emissions in S1 (OEs only comparison). Differences between methods in S2 and S3 were minimal (<0.1% and <3% respectively). Comparing the LCA with its own OE estimate indicates OEs remain at approximately 40% of total emissions suggesting they are a strong candidate for monitoring and policy targeting. These comparisons would imply the simpler OE approach is robust for a precautionary approach to assessing changes in OEs for policy implementation impact assessments of ultra-low emission vehicle initiatives.

Development of future emission policies should consider both LCA and OPEMs, as although LCAs give more complete results, OPEMs can provide rapid, low data requirement, useful policy guidance. A stringent shift towards earlier BEV adoption is recommended, however, to approach net zero emissions a mode shift away from private cars is required.

1. Introduction

Reducing tailpipe emissions from road vehicles has become dominant in European Union (EU) policy. Under Regulation (EU) 2019/631, new vehicles from 2021 should produce less than 95 gCO_2 km^{-1}, which corresponds to fuel consumption of 4.1 l/100 km of petrol or 3.6 l/100 km of diesel (European Commission, 2018). The UK laws are currently EU aligned, however this may change after Brexit, although this is currently unknown. Manufacturers of internal combustion engine vehicles (ICEVs) have continually improved petrol and diesel engine efficiency and lower emissions per unit of fuel. However, these factors alone will be unable to reduce transport greenhouse gas (GHG) emissions (Faria et al., 2013) as road transport is the only UK sector where emissions have continued to increase, comprising of ~21% of the UK's total GHG emissions in 2017 (ONS, 2019). The UK has set the ambitious target of net zero emissions by 2050, however to achieve this target, in 2020, the UK Government banned the sale of all new petrol and diesel cars (and vans and hybrids) by 2035. This has left room in the market for alternatives such as battery electric vehicles (BEVs) integration which are often seen as 'zero emission' at their point of use.

The objective of this paper is to analyse whether the UK is likely to meet its net zero emissions target through two different methods of assessing carbon dioxide (CO_2) emissions from ICEVs and BEVs. To do this, we compare emission projections from the Transport Energy and Air Pollution Model (TEAM-UK), a life cycle analysis (LCA) model focusing on the CO_2 emissions produced from the vehicle and its operation (Brand et al, 2019b), and a self-developed operating emission model (OPEM). These methods were chosen as although EU policy tends to focus on the operating emission levels of vehicles, this has led policymakers to introduce new policy based only on the analysis of vehicle emissions. This in turn ignores vehicle production, maintenance and scrappage, infrastructure provision and fuel requirements to support these modes of transport which all contribute emissions (Chester and Horvath, 2009). Our study compares LCA and operating emissions (OEs) of ICEVs and BEVs, for two different target years (2040 and 2030 – five years before and after the new phasing out ban) to better understand whether policy based upon narrow target parameter values will have the desired effect on reducing overall transport emissions.

This newly introduced vehicle ban applies to the purchase of new vehicles and does not take into consideration ICEVs that are currently in use or that will be purchased before this ban. For example, cars have an average life expectancy of ~13.9 years before scrappaging, therefore any vehicle purchased in 2035 could remain on the roads until ~2049. This will result in the UK's net zero emission target under the Paris Agreement, being difficult to achieve. Therefore, by comparing the results of OEs and from a full LCA, policymakers will be able to better understand the projected levels of emissions that could be emitted during this interim period. This will allow additional policies to be implemented such as including ultra-low emission zones (ULEZ), priority bus lane access for BEVs or other methods to encourage the use of low carbon public transport.

BEVs are often perceived to be a net zero emission technology as they do not produce tailpipe emissions, however this is dependent on how electricity is used to fuel these vehicles. By switching to more low carbon electricity generation, there is the potential to reduce OEs from BEVs, and fall in line with UK and EU policy (Richardson, 2013). In the UK, the share of renewables has been increasing with 48.8% of electricity generated from renewables and nuclear resources (BEIS, 2019a) with a large mix of generating sources which has diversified the electricity mix, reducing energy insecurity. Although, these changes are expected to significantly contribute towards the net zero target, greater levels of low carbon renewables, nuclear and fossil/biomass with carbon capture and storage (CCS) are still required. Therefore, the energy generation source should not be targeted singularly, the production and end-use phases, including scrappage, of BEVs and associated emissions need to be considered when trying to reduce transport emissions on a large scale. This is why we have considered two methodologies within this study. UK policy currently focuses on improving internal combustion engine efficiency to reduce vehicle OEs but does not consider the other phases of the vehicle life cycle. Therefore, by comparing OEs with expected LCA emissions produced we can hope to achieve a better understanding of total transport emissions as the UK emission target moves towards net zero: this is the focus of this paper.

1.1 Life cycle emissions model versus operating emissions model

Through the (so-called) 'dieselgate' emissions scandal, an increasing divergence, or 'gap' between 'real world' and 'official' energy use and air pollutant emissions of road vehicles was highlighted. Crucially, the 'official' CO_2 vehicle emission ratings have been shown to be misleading for European passenger cars (Brand, 2016; Ligterink et al., 2016; Ligterink and Eijk, 2015; Tietge et al., 2017) and commercial vehicles (Zacharof et al., 2016). 'Real world' emissions have been shown to be almost a third higher than their official values and standards operating in the EU (Brand, 2016; Ligterink and Eijk, 2015; Tietge et al., 2017). The likely cause of the divergence between 'official' and 'real world' emissions is often linked to shortcomings from the European type-approval process for light-duty vehicles (Tietge et al., 2017) and actual driving conditions and practices. Furthermore, there has been increasing evidence that fuel consumption improvements originate from test-orientated optimisations and practices as opposed to operating fuel saving technologies (Fontaras et al., 2017b; Fontaras and Dilara, 2012). Therefore, when estimating the OEs from vehicles, differences between 'real' world and 'official' emissions need to be considered to give an overall idea of emissions produced. It was estimated that the difference between European passenger cars in 2013-2014 was ~32% higher (40 $gCO_2\ km^{-1}$) compared to the official certification (Fontaras et al., 2017a).

This divergence in 'real' world and 'official' emissions have resulted in many researchers conducting LCA of the total emissions produced from road transport. An LCA model is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle from construction, operation and scrappage, considering both direct and indirect CO_2 emissions produced throughout the entire process (Rebitzer et al., 2004). An LCA is particularly useful for transport, given the myriad of interrelated effects that can be influenced by vehicle production and use. However, due to the lack of long term measurements and monitoring only a few LCAs have the ability to provide an overall picture of emissions as a lot of estimations are required to give an overall picture of emission levels (Egede et al., 2015). Furthermore, the design of the vehicles can influence greatly the environmental impact of other stages within the life cycle. For example, if the design of a vehicle is determined by the fuel consumption and emissions per kilometre driven when the vehicle is in use, then this may not influence the GHG cost of construction or the reusability of materials within the end-of-life phase (Rebitzer et al., 2004).

Decision making bodies, including the UK Government, are only recently beginning to look at LCAs for critical inputs related to transport fuels (Chester and Horvath, 2009). LCA models need to consider both direct and indirect processes and services required to operate the vehicle. This includes raw material extraction, manufacture, construction, operation, maintenance, scrappage, infrastructure and fuels (Chester and Horvath, 2009; Hawkins et al., 2013; Helms et al., 2010). To provide an accurate parameterisation for an LCA it is important to consider averages across the UK, for example, fuel consumption or the vehicle weight which can vary widely between two vehicles and locations, producing different results and interpretations of the data (Messagie, 2014). It is therefore essential to consider these influences on the LCA when looking at the end results. The TEAM-UK model takes this LCA approach whilst also considering lifestyle choices and socio-cultural factors from the individuals using different transport methods, which are often overlooked and not generally included in transport modelling. Only a few attempts have been made to integrate these insights into systems models of future transport energy demand and supply (Creutzig et al., 2018). Current research shows that a full LCA cannot be implemented in many locations around the world due to data access restrictions. Therefore, both methodologies need to be analysed to better understand why future policy makers need to consider both LCA and OPEMs when introducing future policies to reduce transport emissions.

Although an OPEM is a more simplistic model than a LCA model, estimating the level of direct and indirect CO_2 emissions produced solely during the operation phase of a vehicle’s life cycle is also important. Estimating the change in CO_2 emissions associated with changes in the electricity system becomes a topical issue due to different methodologies used to determine the emission rates as this has significant consequences (Hawkes, 2014).

2. Methodology

The future UK transport emissions produced by ICEVs and BEVs from 2017 to 2050 were simulated using the TEAM-UK model and the OPEM model based on the UK

Government's Department for Business, Energy and Industrial Strategy (BEIS) projections of vehicle type and numbers, distance driven and electricity generation mix. 2017 was chosen as a starting year for both models as this was the latest historical data set available whilst 2050 was the final year analysed, as although both models were able to make data projections past this, policy is likely to change as the UK transitions to net zero by 2050.

LCA outputs include OE estimates within their value. Here, we utilise this to consider the representativeness of an OPEM approach to the overall carbon dioxide emissions produced over an LCA for both ICEVs and BEVs. Production and scrappage emissions are known to be different between ICEV and BEVs, and with the changes in vehicle fleet composition, consistency in the percentage of total emissions that OEs represent will indicate whether OPEMs are good candidates for simple, representative policy impact assessments.

2.1 TEAM-UK model

TEAM-UK is an LCA tool that can be used to assess and develop transport policy scenarios through a range of technological, fiscal, regulatory and behavioural change policy interventions to meet climate change, energy security and air pollution goals (Brand et al., 2019b). TEAM-UK provides annual projections of transport supply and demand for all passengers and freight modes of transport and calculates the corresponding energy use, life cycle emissions and environmental impacts year-by-year to a set target (up to 2100; however, this is dependent upon the policy being investigated). For the purposes of this study, we are focusing on the emissions produced from cars alone, as cars produce the highest level of emissions from transport. The TEAM-UK model combines four linked models of the transport-energy system to analyse the impact of different policy already instigated and future policy to reduce transport emissions (Brand and Anable, 2019). The four models that make up TEAM-UK comprise: the transport demand model (TDM), the vehicle stock model (VSM), the direct energy use and emissions model (DEEM) and the life cycle and environmental impacts model (LCEIM).

The TDM comprises a partial econometric model and a simulation model that calculates the overall level of transport activity and modal shares for passenger and freight movements. As future demands for transport are highly uncertain, the TDM develops a set of plausible developments for transport demand as a function of scenario variables which includes fluctuations and changes in demographics, population size, household income, fuel costs and costs of future technologies during the time frame analysed. In this case, due to these fluctuations analysis was concentrated between 2017 and 2050. A previous example was to calculate the vehicle manufacture, maintenance and scrappage, in which two main steps occurred (Brand et al., 2019b). Firstly, each vehicle type is analysed in terms of mass of materials required to manufacture the vehicle and for maintenance (Brand et al., 2019b). The model uses 15 materials that are all modelled for each vehicle type. The material decomposition, emissions, primary energy use and land use changes that are embedded within each kilogram of material are estimated for up to 25 emissions categories including embedded CO_2 (Brand et al., 2019b). After this, the energy use and emissions for the processes involved in manufacturing, maintenance and disposal are derived by multiplying each process category with process emissions factors (Brand et al., 2019b).

The VSM tracks the changes in the demand for vehicles, scrapping of old vehicles and the purchasing of new vehicles based on the current population by vehicle type, size, technology and age which may have had technological advances through new or improved propulsion technology. This part of the model is highly disaggregated and involves segmented discrete choice modelling of over 1,200 alternative ‘vehicle technologies’: i.e. 1200+ different combinations of vehicle type (car, bus etc), size/category (small car class A/B, etc), main fuel (gasoline, electricity, etc.), hybridisation (ICEV, HEV, PHEV, etc) and vintage (linked to EURO bands). In this paper the focus is on average ICEVs and BEVs. To ensure consistency from year-to-year, TEAM-UK allocated all manufacturing emissions to the year of first registration (Brand et al., 2019b). This means the VSM works in tandem with the TDM model as the vehicle demand estimated in the TDM directly influences the development of prices in the VSM within the same year. The development of prices in the VSM then influences the demand in the TDM the following year. This allows a near equilibrium between supply and demand. Furthermore, for ICEVs, the fuel supply and vehicle manufacture stages account for ~20% of the total lifetime GHG emissions, whereas the vehicle maintenance and disposal account for a much smaller share of GHG emissions. The first year of registration was used for analysis to ensure independent modelling of individual years was possible and allowed direct evaluation of new technologies within each year (Brand et al., 2019b). Furthermore, the model takes into consideration the number of trips and the trip length. As income elasticities can represent the dependence of transport demand growth, input data includes additional demographics such as income and GDP per capita. Furthermore as TEAM-UK is a policy based model, other factors including pre-use tax, fuel prices, road tax, pricing, speed limits and driver behaviour also need to be taken into consideration to give a representative overview for the UK (Brand et al., 2019b).

Using the outputs of the TDM and the VSM, the DEEM calculates the direct emissions (also referred to as the ‘tailpipe’ emissions, ‘source’ or ‘end use’) and energy consumption due to the different vehicle technologies that comprise of the vehicle fleet. DEEM has the ability to project various types of direct emissions including CO_2 and methane, as well as non-direct emissions such as carbon monoxide, sulphur dioxide, nitrogen oxides, non-methane volatile organic compounds and particulate matter.

The LCEIM in TEAM-UK uses a hybrid approach that combines process chain and input-output analyses to derive aggregated values for the entire process chain. For the purposes of this analysis, focus is placed on LCEIM which has two main functions. Firstly, it provides an energy and emissions life cycle inventory due to the manufacture, maintenance and disposal of vehicles as well as infrastructure contributions (i.e. embedded emissions). The inventory also provides energy use and emissions over the fuel production cycles for the different fuels used by different vehicle technologies. Secondly, the LCIEM estimates the environmental impacts of the overall levels of emissions by providing a series of impact indicators such as global warming potential and the monetary valuation associated with the damage caused by these levels of emissions.

Figure 1 demonstrates the input and output flow of the LCEIM process used in the TEAM-UK model. The blue lines indicate how the different models feed into each other whilst the red lines indicate the model inputs and outputs. The model outputs (red solid line boxes) then need to be fed into the next model to get results. The purple dashed boxes indicate the inputs needed to calculate the OEs for both models.

Figure 1: The model inputs and emission outputs for the Life Cycle and Environmental Impacts Model used within the TEAM-UK Model and the operation emissions model. The purple boxes indicate the inputs needed to calculate the operating emissions for both models (Adapted from Brand et al,. 2019b).

2.2 OPerating Emission Model

An OPEM was used to calculate the CO_2 emissions produced from the mix of electrical and fossil fuels vehicles operation in the UK considering the distance driven and the fuel used and the emissions from electricity generation. To keep consistency between the model's future projections electricity carbon intensity data were also obtained from BEIS (Brand et al., 2019b).

The OPEM is a simple model requiring data for each year from 2017 to 2050: the projected number of vehicles, projected distance travelled, electricity generation carbon intensity and technological improvements each year. The model outputs the CO_2 OEs for each year. To ensure consistency between the models the carbon intensity of electricity generation was also obtained from BEIS which can be seen in **Appendix B.** Battery charge and recharge efficiency, motor efficiency and the energy required to travel one kilometre data was all collated from the following sources and kept consistent between the models (Brand et al., 2019b; Ellingsen et al., 2014). The model does not include emissions produced through the construction of infrastructure and disposal of vehicles.

2.2.1 Battery electric vehicle emission projections

To estimate the level of CO_2 emissions produced for 100% BEVs, **Equation 1** was used.

Equation 1

$$EVs = \left(\left(\left((D * V) * (CI * E)\right) * F\right) + (B * D * V)\right)$$

Where, D = average distance travelled per vehicle (km), V = estimated number of vehicles for the year, CI = carbon intensity of electricity generation (gCO_2 kWh^{-1}), E = energy efficiency (kWh km^{-1}) and F = the correctional factor for energy production inefficiencies and B is the electric vehicle battery emissions. Data units are then converted to $MtCO_2$.

To account for discrepancies, a correctional factor for energy production (F) was given a value of 1.18 to account for inefficiencies, distribution and network losses (BEIS, 2019b). Power conservation is expected to improve through advances in BEV technology and average annual distance travelled per vehicle is expected to decrease over time, however limited information quantifying this is currently available. This has resulted in current and future years being run with the same correctional factor, therefore energy required by BEVs in 2050 may be overestimated.

BEVs will need at least one replacement battery through its usable life, therefore to incorporate battery manufacture and lifetime carbon intensity, B was given a value of 30 gCO_2 km^{-1} travelled (Ellingsen et al., 2014). Similarly, through technological improvements of BEVs, this value is expected to decrease, however for the purposes of this study it has remained constant throughout as the changes should be minimal over the time frame.

In addition, the energy efficiency (E) used (kWh km^{-1}) produced was estimated by averaging the three vehicle sizes from the TEAM-UK model. This was done by taking the average values of the kWh km^{-1} from the three vehicle types and averaging them. This gave an average value of 0.21 kWh km^{-1}.

The proportion of BEVs used in the consumer market for **Scenarios 2 and 3** were projected to result in a realistic emission from this factor. This meant that the integration rate sees an increase at the respective year ban point. Our approach to this assumes that as the ICEV ban rate nears, consumers will begin switching to BEVs. As the ban applies to new vehicles only there is not a defined step change in integration rate as proportional market share of BEVs will only become the majority vehicle type after current ICEVs have come to the end of their life span. The yearly proportion of BEV integration can be found in **Appendix A.**

2.2.2 Internal combustion engine vehicle emission projections

To estimate the level of emissions for ICEVs, **Equation 2** was used. This method considered the differences with the proportions of current petrol and diesel vehicles used to give a more representative result. The relevant values can be seen in **Appendix A**.

Equation 2

$$CFVs = (D * (V * P_t) * K) + (D * (V * P_t) * K)$$

Where, P = vehicle type proportion (i.e. diesel or petrol), t = parameter value that changes depending on vehicle type (i.e. diesel or petrol) and K = estimated CO_2 per kilometre travelled. Data units are then converted to $MtCO_2$.

For the UK, the value for emission per kilometre (K) was adjusted to take into consideration vehicle technology improvements. Although, under the EU Regulation (EC) No 443/2009 new vehicles must not produce an average of more than 95 gCO_2 km^{-1} from and including 2020, the average value used will be higher than this due to different vehicle ages that are already on the roads. For the purposes of this equation, the average large, medium and small vehicle gCO_2 km^{-1} travelled were derived endogenously in TEAM-UK, through DEEM. DEEM takes into consideration UK specific traffic conditions (mean speeds and route segment including urban, rural or motorways) and vehicle fleet compositions (Brand et al., 2012). This gave an average value of 157 gCO_2 km^{-1} for 2017.

The UK has seen 1% reduction in tailpipe emissions each year, mainly driven by efficiency improvements therefore, the gCO_2 km^{-1} was decreased by 1%each year to 112.7 gCO_2 km^{-1} by 2050. This is an ambitious target for the UK unless this coincides with substantial behavioural changes including eco-driving features within new vehicles.

2.3 Data consistency between models

This comparison was made for three different vehicle mix scenarios. For the purposes of this research, PHEVs and HEVs were not included in analysis as they combined both fuel types. The first considered 100% ICEVs, the second included a ICEV ban from 2040, and the third included a ICEV ban from 2030, ten years ahead of the UK target, to determine the impact this could have on cumulative emissions. The introduction of BEVs in 2030 was used to better understand the impact of having a more stringent target as in some other countries. The rate of BEV integrated into the transport network can be seen in **Appendix A**, with the same integration values used for both models.

The total number of vehicles and projected km travelled remained constant between both models. These values were modelled using TEAM-UK, which included baseline projections based on national and regional databases (Brand et al., 2017, 2012; Brand and Anable, 2019). Within the TEAM OPEM, the projected number of vehicles, small medium and large vehicles were combined to give an overview of total vehicles **(Appendix B)**, with the average increase in ICEVs by 25.5% and distance travelled decreasing by 9.3% within the time frame. Over time, travel patterns can change considerably with individuals opting to avoid travel and shifting towards more sustainable travel modes. This change reflects the assumption that cars are banned or priced out of city/town centres (Brand et al., 2020). In addition, input values for total number of vehicles increased by 11% with new car sales estimated as a function of endogenously derived household car ownership and car scrappage, with the latter modelled as a function of average life expectancy. This was calculated through a S-shaped (modified Weibull) scrappage probability curve (Brand et al., 2020; Zachariadis et al., 2001). Through these estimates, based on existing age distributions, average car age was assumed to stay at 6.3 years (Brand et al., 2020). Total car ownership also takes into consideration household income, average vehicle costs, household location (either urban or rural) and car saturation rates for multiple car ownership (Brand et al., 2020).

For BEVs, both models used the same predictions for the carbon intensity of electricity generation. This considered national electricity generation mix, transmission and distribution losses (around 10%) and imports from other countries (mainly France and the Netherlands). Base data was taken from 2015 giving an electricity supply mix of 39% from gas-fired power stations, 17% from coal, 19% from nuclear, 21% from wind and 4% from hydropower and solar power. This resulted in the carbon intensity of electricity generation starting at 363 gCO_2 kWh^{-1} end-use (including transmissions and distribution losses) in 2015. Both models used the same energy mix predictions up to 2050 which were based on the electricity generation mixes from BEIS's energy and emission projections per year **(Appendix B).**

3. Results

The results are split into three sections. **Section 3.1** compares the operating CO_2 emissions for ICEVs between for both models. **Section 3.2** considers the emissions for new sales of ICEVs banned from 2030 and from ICEVs banned from 2040, whilst taking into consideration the cumulative emissions of these vehicles. **Section 3.3** compares the LCA emissions from the TEAM-UK model and compares these results with their OE to explain whether UK should focus on OE of LCA when designing policy. Similarly, the benefits to other countries of an OPEM approach where LCA data requirements are not met are highlighted.

Results also highlight whether projections fall into line with the UK's emissions targets. In 1990, emissions from cars were 72.3 $MtCO_2$ (DfT, 2018a), therefore, to reflect the UK's previous emissions target of a 80% reduction in emissions from the 1990 baseline, car emissions would need to be below 14.5 $MtCO_2$ (DfT, 2018a). Furthermore, to take into consideration the UK's net zero emission target, a more stringent target of a 95% emission reduction in transport emissions from the 1990 levels will also be highlighted. This is the equivalent of 3.6 $MtCO_2$ of car emissions (DfT, 2018a).

3.1 Emissions from internal combustion engine vehicles

Figure 2 demonstrates the projected level of CO_2 OEs from ICEVs between 2017 and 2050 using both TEAM-UK and OPEM.

Figure 2: Projected carbon dioxide emissions produced from the operating emissions model (OPEM) and the operating emissions disaggregated from TEAM-UK per year for the UK between 2017 and 2050. The red line indicates 80% reduction in emissions from the UK's 1990 baseline emissions to meet Paris Agreement targets. The purple line indicates a more stringent target of 95% reduction in emissions from of the UK's 1990 baseline emissions.

In 2017, emissions produced are similar at 64.3 $MtCO_2$ for the OPEM and 66.4 $MtCO_2$ for the TEAM-UK. By 2050, there is an emissions gap of 15.6 $MtCO_2$ between the two models, with TEAM-UK projecting emissions to be lower than OPEM at 36.9 $MtCO_2$.

Results indicate that for the OPEM model, in 2050 emissions were 38.0 $MtCO_2$ higher than the 80% target and 48.9 $MtCO_2$ higher than the 95% target. For the TEAM-UK, in 2050 emissions were 22.4 $MtCO_2$ higher than the 80% target and 33.3 $MtCO_2$ higher than the 95% target. Therefore, for the UK to meet their previous emission target or their new emission targets, ICEV technological advances alone cannot be relied upon even with technological advances for ICEVs, emissions from both models remain higher than the 80% and 95% emission targets and more rigorous actions need to be taken.

3.2 Operating emissions: OPEM Vs TEAM-UK

Figure 3 demonstrates the OE calculated by the TEAM-UK and OPEM model for the mix of BEV and ICEVs based on the sale of new ICEVs banned from 2030 and from 2040. The graph shows the time series of emissions between 2017 and 2050.

Figure 3: Projected carbon dioxide operating emissions from both the OPEM and the operating emissions disaggregated from the TEAM-UK model between 2017 and 2050. The red line indicates 80% reduction in emissions from of the UK's 1990 baseline to meet Paris Agreement targets. The purple line indicates a more stringent target of a 95% reduction in emissions from the UK's 1990 baseline emissions.

Results indicate that the OE for both OPEM and TEAM-UK have similar emission values in 2017. OPEM had vehicle emissions starting at 63.7 $MtCO_2$ for both the 2030 and 2040 new ICEV ban dates whereas TEAM-UK had car emissions starting 1.3 $MtCO_2$ higher at 66.4 $MtCO_2$ for both 2030 and 2040 ICEV ban.

By 2050, emissions produced from TEAM-UK were lower for the 2030 new ICEV ban date scenario, producing 18.9 $MtCO_2$ in 2050 compared to 34.6 $MtCO_2$ from the OPEM. Similarly, under the 2040 new ICEV ban scenario, emissions under TEAM-UK were lower at 28.2 $MtCO_2$ in 2050 compared with 37.8 $MtCO_2$ from the OPEM. Results indicate that projections from both models fail to meet both the 80% and 95% emission targets from OEs by 2050.

3.2.1 Cumulative operating emissions

The projected cumulative emissions of the fourth and fifth carbon budgets for both the OPEM and TEAM-UK models for three scenarios: new ICEVs banned from 2030, new ICEVs banned from 2040 and 100% ICEVs, are shown in **Table 1.** In addition, although the sixth carbon budget will not be announced until late 2020, emission projections have been made for it and cumulatively for 2017-2050. ICEVs were used for comparison to illustrate that although emissions from the BEV:ICEV mix remain higher than both emission targets, cumulative emissions will remain lower.

Table 1: Projected third, fourth, fifth and sixth emissions from carbon budgets and total cumulative operating emission projections for the OPEM and TEAM-UK Models.

Results indicate that for both models under the three carbon budgets emissions decreased. Introducing BEVs into the transport mix in 2030 resulted in the lowest levels of cumulative emissions for both models. Cumulative emissions highlighted that for all of the Committee on Climate Change's (CCC) carbon budgets and total cumulative emissions, results indicate the ICEVs produce the highest level of emissions.

The current third, fourth and fifth carbon budgets are expected to see a decrease in emissions by 92%, 76% and 88% respectively from the previous budget. By estimating the percentage decrease from the carbon budgets in **Table 1**, it can be determined whether the decrease in emission levels will be enough to meet the CCCs targets from BEVs and ICEVs, incorporating the integration in 2030 and 2040. Results indicate that under both the 2030 and 2040 BEV policy scenarios and for ICEVs alone, neither model predicts that car emissions will meet the CCC's equivalent percentage reduction requirements. It should be noted that the differences in the model predictions highlight that under different budget predictions whether the UK meets its targets may differ between models and between policy scenarios. Policymakers should therefore take a precautionary approach when using emission prediction models as trusting a more complex approach may indicate targets being met when this could be sensitive to data input. As the sixth carbon budget has not yet been determined we cannot say whether this will be met however with consideration of the previous budgets, our outputs may suggest that policy and meeting set targets needs to be more stringent in future.

3.3 TEAM-UK: Operating emissions versus life cycle analysis

The analysis of OE falls in line with UK and EU policy in their attempt to reduce transport emissions. Using TEAM-UK, a comparison of the OE for ICEVs, BEVs integrated in 2030 and BEVs integrated in 2040 between 2017 and 2050 was compared to an LCA. This would give better understanding differences between OE (that policy tends to focus on) and other life cycle emissions that are produced. It is important to recognise that LCA emissions outputs include OE estimates. This can be seen in **Figure 4**.

Figure 4: Comparison of operating emissions and an LCA of ICEVs, ICEV purchase ban from 2030 and a ICEV ban from 2040 using the TEAM-UK model between 2017 and 2050 for the UK. The red line indicates 80% reduction in emissions from the UK's 1990 baseline emissions to meet Paris Agreement targets. The purple dashed line indicates a more stringent target of 95% reduction in emissions from the UK's 1990 baseline emissions.

LCA emissions in 2017 were 96.1 $MtCO_2$ under all three vehicle scenarios. In 2050 for ICEVs, total LCA emissions were 44% higher at 66.3 $MtCO_2$ compared to 36.9 $MtCO_2$ of OE, indicating OEs represent 40% of total emissions. Under the 2040 scenario, LCA emissions were 52% higher at 58.7 $MtCO_2$ in 2050 than the OE at 28.2 $MtCO_2$, indicating OEs represent 39% of total emissions in this scenario. Finally, under the 2030 scenario, LCA emissions were 60.5% higher at 47.9 $MtCO_2$ in 2050 than the OE at 18.9 $MtCO_2$, with OEs representing 42% of total emissions.

Results indicate that the total LCA emissions and OE both decreased over the time frame. This indicates that although LCAs may give a more realistic overview of the total emissions produced, OPEMs are just as useful as if OE decrease, then the overall emission values for vehicles also decreases.

3.3.1 TEAM-UK cumulative LCA emissions

Table 2 demonstrates the cumulative emissions produced from an LCA using TEAM-UK for the three different vehicle types under the fourth, fifth, sixth carbon budgets as well as cumulatively between 2017 and 2050.

Table 2: Projected LCA cumulative emissions under the fourth, fifth and sixth carbon budgets and total cumulative operating emission projections between 2017 and 2050 using TEAM-UK.

Cumulative LCA emissions and for each carbon budget were lowest for the ICEV ban in 2030. The highest cumulative emissions were for ICEVs, which were 10% higher than for a ICEV ban in 2030 and 2% higher than a ICEV ban for 2040.

In comparison to **Table 1**, as expected, cumulative LCA emissions were higher than the cumulative OE under all vehicle scenarios using TEAM-UK. Furthermore, through analysis of the percentage reduction, in line with the CCC’s carbon budget reduction, it can be concluded that none of these scenarios will meet these targets.

4. Discussion

Results from both the OPEM and TEAM-UK models have indicated that tailpipe emissions from ICEVs, whilst considering technological improvements, will not allow the UK to meet their previous emission reduction target of 80% of emissions from the 1990 baseline or their new net zero emissions targets (approximately 95% of emissions based on the 1990 baseline). More needs to be done to ensure emission targets are met successfully. With the introduction of UK policy to ban the sale of new ICEVs in 2040, or even ten years prior in 2030, emission levels will also struggle to meet targets. A revision of policy is recommended not just on vehicle sales bans but in regard to the energy provision sources, enabling a more rapid development of cleaner energy sources will be the biggest source of emissions reductions when switching to BEVs. Additionally, although an LCA is unable to answer every question related to the wider implications of adopting BEVs into the transport mix, it does play a critical role within the decision making process by providing insight into overall LCA impacts. LCA results indicate that emissions for 100% ICEVs would be 44% higher, 52% higher when new ICEVs were banned in 2040 and 60.5% higher when ICEVs were banned in 2030, by the year 2050 compared to OEs. Comparing the break-down of the LCA with its own OE estimate indicates OEs remain approximately 40% of total emissions, suggesting they are a viable candidate for emissions monitoring and policy targeting. These comparisons would suggest the simpler OE approach is robust and representative of overall emission changes for rapidly assessing policy impact of implementation of ultra-low emission vehicle types.

LCAs are generally limited in use with comparisons to other countries hindered due to data restrictions. TEAM-UK is highly parameterised for the UK and has attempted to endogenise methods and data, including over 1200 vehicle type technology choices. However, the data requirements of this level of parameterisation are not available in all countries, especially developing ones. Therefore, a more simplistic model such as the OPEM, that considers fewer variables with a more focussed approach, can be used to compare a broader range of countries. The OPEM allows for easy substitution of other vehicle types, like BEVs, directly into the model, with different BEV percentages, number of vehicles and distances travelled easy to adjust; it can therefore be easily manipulated for international comparisons (Logan et al., 2021, 2020b).

The TEAM-UK model is UK wide and is not spatially explicit for UK regions in terms of electricity generation mix, vehicle numbers or miles travelled. This will not enable the different policy target of Scotland to be examined as the Scottish Government planning to phase out the need for new petrol and diesel cars (and vans) by 2032 (Nieuwenhuis et al., 2020). For this, a variation of the model was developed for Scotland called Scottish Transport Energy and Air pollution Model (STEAM) (Brand et al., 2019a). However, a variation of the model has not yet been developed for England, Northern Ireland or Wales and so cannot be compared to the TEAM-UK model. Furthermore, this analysis will require additional data inputs as the electricity generation mix is currently connected throughout the UK via interconnectors with other parts of Europe. Interconnectivity needs to be more robustly considered as regional scale decreases.

The OPEM is a simple model and easy to manipulate and comparable to the OEs disaggregated from the TEAM-UK model, however the OPEM emissions and energy expenditure of converting and maintaining the nationwide structures to accommodate new BEVs are not accounted for, primarily because there are no current estimates for work on this scale. However, the energy and infrastructure networks need to be maintained and are not a one off so capital expenditure and operating expenditure carbon emissions are included. Therefore, energy and emission projections from the current model will be lower than if the new infrastructure is included. As a result of this, other alternative models were considered for comparison including the Long-range Energy Alternatives Planning System (LEAP) which is a software tool for energy policy analysis and climate change mitigation assessment (Heaps, 2008). Over the past decade this model has been used for multiple countries including Pakistan, China, Colombia, Korea and Taiwan (Cai et al., 2013; Huang et al., 2011; Paez et al., 2017; Perwez et al., 2015; Shabbir and Ahmad, 2010; Shin et al., 2005). Similar to TEAM-UK it has taken a national approach and can be applied to cities and regions. In addition, the model gives a more realistic overview of GHG emissions taking into consideration industrial processes, solid waste, land use change and forestry. Therefore, increased data will be required to run the model effectively. However, like TEAM-UK, LEAP requires an extensive data set for analysis.

Whilst the OPEM is easier to use when comparing countries, it does quantitively underrepresent the true costs and subsequent total emission targets being met. Consistent values of number of vehicles were used for analysis for both models. Weighting the OPEM by small, medium and large vehicles against their respective group average efficiency could result in more valid numbers as opposed to an average for all vehicles. However, this data might not be available for all countries and to ensure an easy comparison an average was used. Although there are other similar models to OPEM used within Europe, such as the EMEP/EEA air pollutant emission model, it does not include energy consumption (Arndt et al., 2020). Therefore, to ensure consistency between the data used within TEAM-UK, the OPEM was used.

Furthermore, when analysing the emissions produced using an OPEM, something often overlooked is where the vehicle is manufactured, as this type of model focuses primarily on the vehicles within the country. Therefore, policymakers need to use all the tools available, whether it is an LCA or an OPEM to assess whether projections meet their legislative requirements at all levels or whether their only primary focus is on emissions produced in their own country. For example, the LCA here does not consider where the vehicles are initially manufactured as number of vehicles in the UK, often BEVs, are imported from other countries including China and Germany; in addition, due to the global supply chains for vehicle manufacture with components from multiple countries this is hard to police and maintain accurate accounting. This lack of global responsibility will make it considerably more difficult to meet the Paris Agreement targets if neither country, i.e. the country exporting the vehicle or the country importing the vehicle, takes responsibility for the associated emissions. Therefore, if the UK is to meet their net zero emission targets from transport, there is also a need to remain accountable for the emission produced when importing BEVs to meet demand. However, when looking at the problem globally the LCA emissions are important, so the user of the model data is important as political and scientific needs are different. To maintain alignment with international laws and treaties relating to climate change, current LCAs may need to be expanded to consider cross border import and export of emissions to provide a more holistic model that will inform international aspects of emissions rules and laws to a greater extent.

4.1 Electricity Generation Mix

Over time, this transition to BEVs will likely increase energy demand, however how this electricity is generated may not necessarily follow the same electricity generation mix used within this study. In this study, we used National Grid data and model projections, which are based on existing and planned generating capacity and the lifetime of each facility, along with future required additions. As the National Grid are the primary owner and operator of a majority of electricity transitions within the UK these are therefore believed to be the most realistic future projections. However, like most energy projection models, projecting future demand will likely ‘smooth out’ fluctuations in energy production from different technologies during periods of fluctuation, i.e. weather variability for wind and solar. Although the specificities in fine temporal scale energy fluctuations are out with the scope of our study, we acknowledge that the energy generation input data is the most influential aspect of emission projections. Furthermore, by using annually projected data, this should reduce fluctuations over the time frame. Beyond creating a dynamic energy source model, which would be difficult to parametrise with current data, we believe we have informed these models with the best available data but acknowledge this assumption.

Future energy networks aim to reduce the impact of energy demand increases by a system wide planning approach. This often relies upon having stored energy available for deployment when demand increases or spreading demand throughout the day to flatten the peak of demand with demand management incentives such as variable pricing. Bahamonde-Birke (2020a) highlights that the time of day in which BEVs are being charged can significantly impact the emission levels produced due to how electricity is being generated. For example, a Chevrolet Colt can emit 37 gCO_2km^{-1} when ‘fuelled’ from renewable resources, or as much as 190 gCO_2km^{-1} when generated from lignite (Plötz et al., 2018). This is important to consider as current charging patterns of BEVs occur during the evenings when electricity generation is high and renewable electricity generation remains lower, highlighting that electricity to support demand is mostly from non-renewable resources (Anderson et al., 2018; Schill and Gerbaulet, 2015). Although out with the scope of this study, there is also the potential for BEVs to be used to help with fluctuating energy stores to help cope with the broader energy network demands as long as the network infrastructure is developed with this consideration in mind.

Ensuring adequate measures, such as the introduction of smart meters, has allowed a more coordinated timing of widespread charging of BEVs. This in turn has the potential to reduce demand on the grid and ensure charging does not negatively impact on peak demand times. In the UK, BEV charging regulations are continually changing with the Automated and Electric Vehicles Act 2018 stating in section 15 that infrastructure installed for the purposed of charging BEVs are to have *'smart functionality'*(DfT, 2018b). This allows charging points to receive, understand and respond to signals sent by energy system participants (i.e. energy companies, National Grid etc) to balance energy supply and demand (DfT, 2018b). This therefore means operators will be required to modify their charging infrastructure to ensure 'smart' functionality (DfT, 2018b). Therefore, smart charging can be used to minimise emissions, cost and peak demand. As technology advances, smart charging will likely become the norm, marginal emissions for BEVs are likely to fall below average. These issues need to be addressed if the UK is to meet the set targets as individuals will either use the current public charging facilities or those possibly located at their place of work.

Due to data availability constraints, energy generation values within this study are used at the annual scale. This limitation does not describe the fine scale fluctuations of daily energy usage that demand management incentives seek to mitigate. The results from this study therefore may represent underestimations of grid capacity requirements with widespread BEV implementation. Storage through battery farms or hydrogen storage may therefore be needed to ensure that the cleaner energy generated by nuclear or renewable sources during non-peak times is best utilised. This is often a critique of renewable energy, with this current intermittency issue dealt with using dispatchable gas powered electricity to balance the load or by paying for the temporary shutdown of windfarms, neither of which is a sustainable route in the future. Whilst this strategy is possible at the larger grid scale, the demands on the network as it transitions will further be enabled by possible financial incentives for individuals to charge their vehicles during certain times of the day to make system wide planning more attainable. This means that future energy networks require a dual axis approach, with encouragement of BEVs supported by appropriate grid managements approaches to manage the peak demand curves which will overall decrease BEV emission impact. In addition, there is the potential for BEVs to be used to help cope with the broader energy network demands as long as the network infrastructure is developed with this consideration in mind.

In addition, the National Grid has stated that implementing PHEVs and replacing all ICEVs will present a serious challenge of electricity generation (Aaradhya Towner and Thomson, 2019; National Grid, 2019). For example, electricity required during peak times could result in an additional 50% of the current peak of 61 GW (~17 times the total power output of Hinkley Point C Nuclear power station at 3,620 MW) (Aaradhya Towner and Thomson, 2019; National Grid, 2019). This, coupled with the closure of coal power stations in 2025, could result in the UK importing electricity from several countries, which may not necessarily generate their electricity from sustainable resources. These emissions will also need to be considered in the UK's total emissions and not simply ignored or assumed that the country which has exported the electricity will take them into consideration.

4.2 Future UK policy recommendations

The results of this paper discuss an outright ban of new petrol and diesel vehicles (and vans and hybrids) from 2035 onwards with our analysis emphasising an earlier ban of ICEVs is required if the UK is going to meet net zero. Results here indicate that even with an earlier ban of ICEVs, emission targets will not be met, therefore other low carbon alternatives will need to be considered if the UK is to successfully meet its targets. Recent work by the UK Energy Research Centre confirms this (Brand, 2020; Brand et al., 2020). Many countries have already integrated incentives to encourage the modal shift to BEVs including the introduction of subsidies and tax incentives in the early stage of BEV integration and beyond and industrial investment for sustained development of BEV (Wang et al., 2017). Incentives like this have seen large expansion and uptake in BEVs in Norway, however a study by Lévay et al., (2017) concluded that in other European countries (including the UK, France, Germany, Hungary, Italy, Netherlands and Poland), the majority of BEVs are still more expensive than ICEVs alternatives based on the total cost of ownership and deterred purchase. Their results highlighted that registration and circulation tax exemption in Norway and the Netherlands favours big BEVs, while de facto lump-sum subsidies in France and UK (20–27% of purchase price with a maximum cap) favour small BEVs. Therefore, taxation of ICEVs and older vehicles will need to be more aggressive to act as a push management measure, with other pull measures introduced like park and ride schemes and priority to use bus lanes for car sharing (Logan et al., 2020d). Furthermore, scrappage schemes for ICEVs and higher fuel duty as oil products become cheaper should also be considered to push individuals away from ICEVs. If introduced in conjunction with other pull measures such as lower VAT on electricity prices for BEV users and road tax, individuals may be further incentivised to transition to low carbon transport. In the absence of a mature second-hand resale or recycling market for BEVs, uptake is even further decreased as individuals do not want to pay a higher initial price even if savings are likely to occur during the vehicles lifetime (Berkeley et al., 2018). Research in the USA further highlighted that consumers had difficulties calculating the electricity costs and where and when to charge their vehicles to maximise savings and efficiency. By reducing this doubt there is the potential to encourage update.

Even with these incentives in place, a shift to BEVs will not be enough to meet emission reduction targets, therefore encouraging either active travel or low carbon public transport will be necessary. Several studies have highlighted that emission levels per person per kilometre travelled are significantly lower when travelling by buses and trains than by the average BEV (Logan et al., 2020a, 2020c). Therefore, future policy should actively encourage a transition to low carbon public transport with incorporated “pull” measures through subsidised fares, reliable and more frequent services, to encourage individuals to choose public transport instead of individual vehicles, reducing overall transport emissions (Logan et al., 2020a, 2020c). A further demand management measure is the introduction of access charges for vehicles which do not meet emissions standards, for example, one solution in London is that high emitting vehicles accessing ultra-low emission zones (ULEZ) are charged daily and fined if rules are broken (Cavallaro et al., 2018). In addition to this, the availability of the Oyster card for public transport including trains and buses and fixed and subsidised fares, black cabs and shared bike schemes and Uber-type services have helped to make ICEVs the least favourable travel method in London (Logan et al., 2020a, 2020c).

The decarbonisation of the electricity mix plays a crucial role in the total OEs produced from BEVs, PHEVs and HEVs and will be necessary to meet emission targets. Although tailpipe emissions will be unaffected by the deployment of technologies such as CCS, this can be used to help decarbonise the electricity used to fuel these vehicles lowering their overall environmental impact (Kyle and Kim, 2011). CCS technologies will help reduce emissions from the generating process, which will help the UK meet their target of net zero emissions.

Although the CCC have proposed several methods to allow the UK to achieve net zero it is still believed the UK will fall short of their ambitious target unless more is done (CCC, 2019). Therefore, as our results suggested under both the TEAM-UK LCA and from the OPEM, bringing the BEV integration date ahead by ten years, will lower the cumulative emissions although net zero will still not be met. Moreover, the 2040 target is considered relatively weak compared to other countries with the Netherlands, Denmark, Ireland, Austria, Slovenia, Israel, India and China all aiming for a ICEV ban by 2030 (Brand and Anable, 2019; Eyre and Killip, 2019; Saele and Petersen, 2018; Zeniewski, 2017).

The current 2035 policy also poses potential issues within the UK, with Scotland setting a more stringent target for banning the sale of ICEVs by 2032 (Aaradhya Towner and Thomson, 2019). This could result in localised conflict of regulation, with individuals from Scotland travelling to England to purchase ICEVs, resulting in Scotland not meeting their national targets as part of their efforts to meet the Paris Agreement targets due to the availability of ICEVs under another nation’s regulations. Furthermore, in the UK’s ‘Road to Zero’ strategy (DfT, 2018c), several clear opportunities to decrease the level of emissions from transport are missed. The strategy also does not address future policy issues such as whether the UK government intends to remain part of the EU framework for emission standards having left the EU. Furthermore, the strategy fails to discuss new charging infrastructure needed to be implemented for BEVs. Although the strategy has commented that all new homes will have mandatory charging facilities it fails to mention what will happen for current homes and homes that cannot have charging facilities such as blocks of flats (DfT, 2018c). These challenges will need to be addressed if there is to be successful, widespread and accessible access of BEVs.

4.2.1. Emission trading scheme

Where it is not possible for the UK to meet their net zero emission reduction targets, an Emission Trading Scheme (ETS) may allow the UK to mitigate GHG emissions with flexibility, cost savings and effectiveness within the transport sector (Jiang et al., 2016; Tang et al., 2020, 2017). This scheme works through a 'cap and trade' system as a policy instrument for pollution quantity control coupled with a defined, tradable unit. For example, it provides a country with a permit to emit a pre-determined level of a pollutant for a pre-determined duration of time (Zelljadt and Mehling, 2021). ETS have become an important instrument for Governments from regional to international level to achieve GHG emission reduction targets (Zelljadt and Mehling, 2021).

In the case of the EU, from 2021 onwards, the cap is in phase 4, with countries expected to reduce their emissions cap by 2.2% (compared to their 2008-2012 baseline) (Icap, 2021). Although the UK was previously covered by the EU ETS, from 2021 onwards the UK is no longer considered (Icap, 2021). Under phase 4, the EU ETS covers a number of sectors and gases including: CO_2 from electricity and heat generation, energy intensive industry (i.e. oil refineries, metals, cement etc), commercial aviation within the European Economic Area (until December 2023), nitrous oxide and perfluorocarbons. As the power producing sector is included within the ETS, the increased demand for electricity does not increase the total permissible GHG emissions but leads to higher CO_2 permit prices (Holtsmark and Skonhoft, 2014).

If the emission cap on the ETS is fixed and binding, the CO_2 emissions from the increased number of BEVs would be considered zero (Holtsmark and Skonhoft, 2014). This is because the total CO_2 emissions of the electric network are hard-capped, which means that every kilometre travelled by a BEV does not result in higher allowable CO_2 emissions (Bahamonde-Birke, 2020b). However, if the increased level of electricity consumed by the growing number of BEVs (as well as other electric transport types) is prevented from translating into additional permitted carbon emissions for the economy, this becomes harder and more expensive to reduce the cap to accommodate emissions produced (Andor et al., 2020). The transport sector in the EU represents ~25% of the total CO_2 emissions covered by the EU ETS, with the EU ETS covering 42% of those emissions (Hintermann, 2017). Therefore, the transport sector is likely to see an increase of ~60% of emissions accounted for under the cap (Bahamonde-Birke, 2020a). This is likely to be higher if ICEVs are replaced with vehicles that have a higher level of marginal emissions (Bahamonde-Birke, 2020a).

This type of scheme remains relatively new therefore it is difficult to determine how effective this scheme is at reducing emissions compared with other policies (i.e. increase vehicle tax for higher emitting ICEVs). A review of the ETS scheme in New Zealand suggested that ETS only had a minor impact on the country's emissions due to the low allowance prices, and did not encourage enough behavioural changes to reduce emissions (Zelljadt and Mehling, 2021). The New Zealand Productivity Commission stated that the emissions component of fuel prices was NZ$0.05 per litre for petrol and ~2.5% of the pump price whereas it remains at NZ$20 per tonne (New Zealand Productivity Commission, 2018). Bahamonde-Birke (2020b) comments that if a country were to compensate all CO_2 emissions associated with lignite power plants, it could be argued that in this specific country this technology exhibits a better ecological performance than energy from gas, diesel or coal. However, this is incorrect as it is not the technology that causes the better ecological footprint but the regulation. Therefore, in the case of New Zealand, regulation with significantly higher ETS prices would be required to increase behavioural changes for the emission reduction to be attributed to ETS.

Furthermore, under the EU ETS, ICEVs are not currently considered, therefore as the phase 4 comes to an end in 2030, it is likely that this cap will expand to cover more CO_2 emitting sources. In the UK the CCC has stated that agreeing and communicating a replacement for the ETS will be critical to ensure that the right level of disincentives for the purchase of petrol and diesel vehicles have been implemented (Wills, 2020). This is important to consider as if all vehicle types (both ICEVs and BEVs) are to compensate their CO_2 emissions, the cost of a CO_2 emissions permit would drastically increase and increase pressure on this system (Hintermann, 2017). Therefore, whatever technology emits the lower emission value would be preferred as this would result in cheaper CO_2 permits and put less pressure on the system (Bahamonde-Birke, 2020b). Furthermore, focusing on who is responsible for the transport emissions in terms of where the vehicles are from or where they are travelling to, should also be considered in future policy.

5. Conclusions

This study aimed to demonstrate whether policy focusing on OEs would allow the UK to achieve their net zero emission objectives by 2050. Using two different methodologies, projected OEs and LCA emissions for ICEVs and BEVs between 2017 and 2050 were estimated. Results indicate that although focusing on reducing OEs is beneficial for reducing total emissions, results from an LCA allows policymakers to consider projected cumulative emissions for the future from a whole system perspective and avoid claiming successful target meeting based on OEs alone. However, LCAs are often not applicable due to data deficiencies and therefore operation-level based simple models have greater utility in international comparisons and at consumer levels. Additionally, our results suggest empirical evidence for consistent scaling factors between emission estimate methods across vehicle mix scenarios. Overall, both methodologies have value when assessing future emission projections, with choice being data available, scale and question details dependant.

However, if the UK wants to produce net zero emissions by 2050 the full LCA should be considered because if the UK switches towards BEVs, the additional infrastructure required will create emissions. Therefore, if the overall emissions are greater than before widespread integration then further focus needs to be placed on encouraging individuals away from ICEVs and onto public transport. As a result, the OE based targets and policies will not reach net zero.

This study further indicated that a considerable reduction in carbon emissions needs to be made if the UK wants to meet their net zero emissions and Paris Agreement targets. Therefore, a more ambitious change needs to be made to the decarbonisation of energy generation and the phasing out of ICEVs brought forward to 2030, as suggested by the CCC.

Although this will reduce private vehicle emissions, transport remains the largest emitting GHG sector, therefore the UK Government needs to encourage the use of sustainable public transport including electric and hydrogen buses and trains over ICEVs. This will require the insights of an LCA approach to give an overview of public transport emissions compared to ICEVs. By encouraging the uptake of use of buses and trains and introducing push and pull measures to encourage sustainable travel uptake, total emissions per individual will be reduced.

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