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Research paper

Electric vehicles and the energy generation mix in the UK: 2020–2050

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ABSTRACT

This study estimates CO2e emissions from road transport in the UK under the Future Energy Scenarios from the National Grid ESO through to 2050, including emissions from electricity generation for EVs and tailpipe emissions. In addition, it estimates emissions under a combination of the UK current electricity generation mix with the increase in EVs and the reduction in fossil fuel vehicles assumed under the different scenarios. The main finding is that road transport electrification can save CO2e emissions through 2050 even assuming no further decarbonisation of the power sector. All the Future Energy Scenarios with and without decarbonisation of the power sector and with and without bioenergy with carbon capture and storage see emissions decline. There are, however, important differences in the extent to which emissions decline and the only scenarios that achieve negative emissions from road transport are the scenarios that incorporate bioenergy with carbon capture and storage. This provides an opportunity for the UK government to not just reduce emissions from road transport, but to achieve net zero in road transport, and indeed, to yield negative emissions and compensate for other sectors where emissions are not possible to reduce. Some policy recommendations are also provided.

1. Introduction

Global CO2 concentrations are the highest they have been in at least the last 2 million years and global surface warming between 1970 and 2020 was faster than in any other 50-year period over the last 2000 years (Intergovernmental Panel on Climate Change, IPCC, 2021, SPM-9). These unprecedented changes are being driven by human activity (IPCC, 2021, SPM-5) and there will be significant consequences such as catastrophic sea level rise and adverse impacts of severe changes in climate if we do not act. On top of signing the Paris Agreement (United Nations, 2015), the UK has set an overall target of net-zero emissions by 2050, the world's first major economy to do so (Department for Business, Energy and Industrial Strategy, BEIS, 2020a).

Road transport was responsible for 78.4% of transport CO2 emissions globally in 2020 (International Energy Agency, 2021) and is therefore a key area to tackle. This means that traditional petrol and diesel vehicles will need to be phased out and instead alternative technologies will need to be adopted. The ban on the sale of new petrol and diesel cars and vans in the UK has been moved forward from an original target of 2040 to 2030 (Department for Transport, DfT, 2020; HM Government, 2020). Electric vehicles (EVs) are now seen as a crucial path towards decarbonisation to replace reliance on traditional fossil fuel powered vehicles, as they do not emit CO2 directly (Gómez Vilchez et al., 2019; He et al., 2019; Santos and Rembalski, 2021). However, EVs can only help to reduce CO2 emissions if (most of) the electricity they are powered with is generated in a clean manner (Liu and Santos, 2015; Woo et al., 2017; Cox et al., 2020; Gryparis et al., 2020; Gómez Vilchez and Jochem, 2020; Sobol and Dyjakon, 2020; Märtz et al., 2021; Logan et al., 2022).

The present study makes two important contributions: first, it calculates the likely emissions that will be generated by EVs under different rates of decarbonisation of the electricity generation mix in the UK, using the Future Energy Scenarios produced by National Grid ESO (2021a,b,c) and combines these calculated emissions with the expected decline in tailpipe emissions to find the cumulative total emissions from road transport; and, second, it combines the UK current electricity generation mix with the EV penetration scenarios from the Future Energy Scenarios to understand the potential for emissions savings from switching to EVs without any further decarbonisation of the power sector.

Estimating total CO2e emissions from road transport under different decarbonisation scenarios in the UK through 2050 is important, especially in light of the UK commitment to net-zero. Also important is to estimate total CO2e emissions from road transport in the UK through 2050 assuming the current electricity generation mix remains unchanged (i.e., higher production but same share of different sources) but EVs increase and fossil fuel vehicles decrease in line with the assumptions under the different

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scenarios. This is interesting for two reasons. The first reason is that it allows an informed assessment of the impacts of an increase in the number of EVs and a decrease in the number of fossil fuel vehicles on UK roads assuming no further decarbonisation of the power sector, which has already minimised the share of coal. The second reason is that it allows a comparison of the potential impacts of road transport electrification in line with the Future Energy Scenarios, including further decarbonisation of the power sector on the one hand, and the potential impacts of road transport electrification in line with the Future Energy Scenarios, but assuming no further decarbonisation of the power sector, on the other.

The paper proceeds as follows. Section 2 critically reviews previous work. Section 3 describes the model and the data. Section 4 presents and discusses the results, and Section 5 concludes and provides some policy recommendations.

2. Previous work

In 2019, transport was responsible for 27% of all source CO2e[1] net domestic emissions in the UK (DfT, 2021). Cars, taxis and vans accounted for 71% of domestic transport emissions (DfT, 2021). Decarbonising road transport in the UK is therefore crucial for both meeting the Paris Agreement targets and reaching net zero by 2050. There have been important advances in the power sector (Diesendorf and Elliston, 2018) and the time is now ripe to decarbonise transport.

Replacing vehicles that run on fossil fuels with vehicles that run on electricity will reduce emissions as long as the electricity used to charge vehicle batteries is not generated in fossil fuel power stations (Liu and Santos, 2015; Woo et al., 2017; Cox et al., 2020; Gryparis et al., 2020; Gómez Vilchez and Jochem, 2020; Sobol and Dyjakon, 2020; Märtz et al., 2021; Logan et al., 2022). This is not a trivial point. Worryingly, planned large investments in energy generation globally, which have a large share of coal power stations, commit the planet to emissions of around 300 GtCO2 (Pfeiffer et al., 2018, p. 1). This level of emissions from power stations is not compatible with the Paris Agreement targets. For example, to have a 50% probability of limiting global warming to 1.5 °C, the remaining carbon budget for the whole world from the beginning of 2020 was 500 $GtCO_2$ (IPCC, 2021, Table SPM.2, SPM-38).[2]

The picture in the UK is not too pessimistic. Coal, in particular, has drastically decreased its share in the UK electricity generation mix over the years, as can be seen in Fig. 1.

Further to the progress that has been made in terms of a cleaner energy generation mix, there are promising technologies, such as for example, fusion, which could be the "ultimate clean power solution, representing a low carbon, safe, continuous and effectively unlimited source of energy" (BEIS, 2021a, p. 4). Nuclear fusion energy, however, is decades away from being commercially viable, which means the technology will not be ready to help reach net zero by 2050 (Vaughan, 2020; Harrabin, 2022).

Even investment in proven technologies can take time. In April 2022, the UK government published the British Energy Security Strategy (HM Government, 2022), with ambitious plans to ramp up both nuclear generation and wind turbines (offshore and onshore), as well as low carbon hydrogen. The strategy received criticism as the commitments are so ambitious, they will require "government, business and industry … to focus relentlessly on delivery at a scale and pace as yet unseen" (Climate Change Committee, 2022). In addition, nuclear generation of the magnitude proposed in the strategy will require substantial "political and financial capital", and onshore wind will face "very restrictive planning rules" (Watson, 2022).

Carbon Capture and Storage (CCS) can help substantially on the road to net-zero. CCS are technologies that collect CO2 at emission sources or remove it directly or indirectly from the atmosphere, transport it and bury it (British Geological Survey, 2021; National Grid ESO, 2022). CCS can be combined with Bioenergy (BECCS), which is electricity produced by burning biomass (National Grid ESO, 2022). BECCS can provide negative emissions (National Grid ESO, 2022). Despite these promising prospects, few large-scale CCS facilities are in operation around the world (Budinis et al., 2018; Global CCS Institute, 2021) because lead-times are long (Global CCS Institute, 2021) and costs are high in the short and medium term (Budinis et al., 2018). In addition, there are issues linked to the long-term security of CO2 storage and containment, which need to be monitored and verified (Dean and Tucker, 2017; British Geological Survey, 2021), and other barriers such as residual emissions from CCS plants (Budinis et al., 2018). That said, some of the Future Energy Scenarios used in the present study allow for BECCS, as explained in Section 3.

Against this background, there has been research into EVs and the carbon intensity of the grid. Liu and Santos (2015), for example, find that PHEVs capable of driving long(er) distances using energy from the battery (i.e., on charge depleting mode) would increase CO2 emissions in China because of the high carbon intensity of the grid, which relies on coal. On the same lines, Woo et al. (2017) find that EVs would increase emissions in South Africa, Australia, India and China, all of which have over 60% share of coal in their electricity generation mix. They also find that EVs would decrease emissions in countries with a higher share of nuclear and/or renewables. Gómez Vilchez and Jochem (2020) focus on China, France, Germany, India, Japan and the United States and also find that the impact of EVs on emissions depends on the electricity generation mix. Even gas versus coal, both fossil fuels, entails a 50% difference for China and India in their study. Sobol and Dyjakon (2020) compare CO2 emissions from EVs and fossil fuel vehicles in Poland, and find that the emissions associated with the electricity produced to satisfy the demand for electricity by EVs can be higher than the direct emissions from tailpipes because the mix is carbon intensive. Gryparis et al. (2020) conduct a study for Europe and find that EVs will help reduce emissions, but this reduction would be faster were it not for the presence of fossil fuel-based electricity generation.

When decarbonisation of the power sector is taken into account, the prospects are better, as shown by Cox et al. (2020), Märtz et al. (2021) and Logan et al. (2022). Cox et al. (2020) compare different powertrains for Europe under a baseline scenario and a decarbonisation of the power sector scenario, and find that emission savings from EVs are, unsurprisingly, higher under decarbonisation. Märtz et al. (2021) combine future energy scenarios for China, Europe, Japan, the United States and India, with two alternative scenarios of EV market penetration, an ambitious one, and a slower one. They find that under either scenario future emissions associated to EVs decrease over time thanks to the decarbonisation of energy generation, although this varies greatly across countries. Focusing on the UK, Logan et al. (2022) use older National Grid ESO scenarios and assume different rates of EV

[1] A CO2 equivalent (CO2e) is a unit of measurement that is used to standardise the climate effects of various greenhouse gases, on the basis of their global warming potential.

[2] This budget is subject to an additional increase or decrease of 220 $GtCO_2$ or more, depending on variations in reductions in non-CO_2 emissions (IPCC, 2021, Table SPM.2, SPM-38).

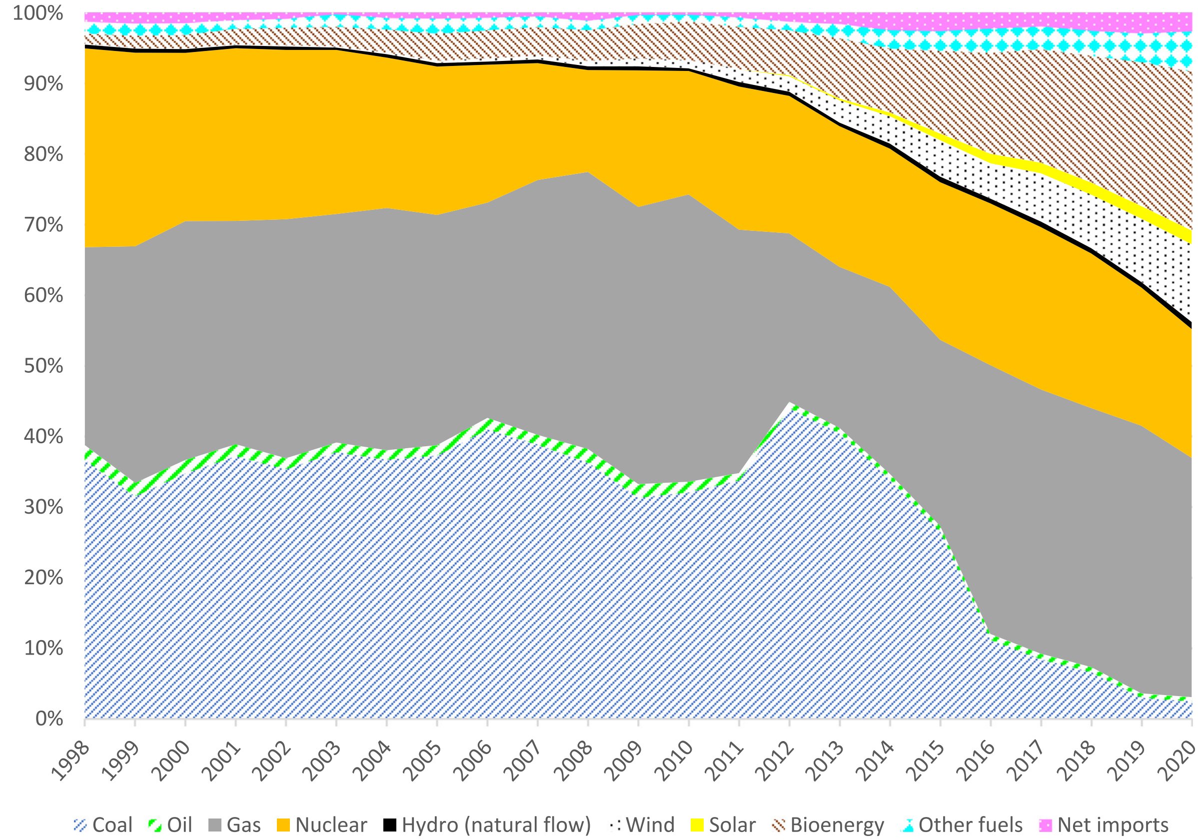

Fig. 1. Electricity generation mix in the UK 1998–2019.
Source: BEIS (2022).

uptake, and find that under all scenarios, emissions from road transport would decrease, and of course, that for scenarios with faster decarbonisation of the power sector and faster penetration of EVs, the reduction in emissions would be higher.

This paper estimates emissions from EVs under different Future Energy Scenarios for the UK and combines these with the expected decline in tailpipe emissions from fossil fuel vehicles through to 2050. It then takes a step back and estimates emissions from EVs assuming no further decarbonisation of the power sector takes place. This exercise helps assess the impacts of an increase in the number of EVs and a decrease in the number of fossil fuel vehicles assuming the electricity generation mix does not change, and also allows a comparison of the potential impacts with and without further reductions in the carbon intensity of electricity generation. The model and the data used to do this are discussed in the section that follows.

3. Model and data

The data used in the present study is data from the Future Energy Scenarios produced by National Grid ESO (2021b) combined with additional data that was requested from National Grid ESO and with some official data published by the UK government, as explained in the sections that follow.

The four scenarios are Leading the Way, Consumer Transformation, System Transformation, and Steady Progression (National Grid ESO, 2021a,b,c). Table 1 summarises the main assumptions under each scenario.

The Future Energy Scenarios outline four pathways that the UK could follow in the area of energy generation and energy consumption. These scenarios are not forecasts or predictions; instead, they represent a range of possible paths that are feasible (National Grid ESO, 2021a). In reality, the UK may end up following none, or combining some elements of one with elements of another, or other, scenarios. Not all the scenarios meet both the Sixth Carbon Budget requirements, which call for a 78% reduction in UK emissions between 1990 and 2035 (Climate Change Committee, 2020), and the carbon neutrality by 2050 target the UK has committed to BEIS (2020a). Steady Progression is the least ambitious scenario, and it does not meet the Sixth Carbon Budget targets or net-zero by 2050 (National Grid ESO, 2021a). Leading the Way, Consumer Transformation and System Transformation do achieve net-zero by 2050 (National Grid ESO, 2021a). Leading the Way and Consumer Transformation also meet the Sixth Carbon Budget (National Grid ESO, 2021a).

The main data sets used in this study were the power sector carbon intensity in the UK through 2050, the demand for electricity by EVs in the UK through 2050, and tailpipe CO2e emissions from petrol, diesel, hybrid, and plug-in hybrid vehicles in the UK through 2050.

The power sector carbon intensity was available from Table SV.27 from National Grid ESO (2021b). The demand for electricity by EVs was available from Table ED5 from National Grid ESO (2021b). Tailpipe CO2e emissions from petrol, diesel, hybrid, and plug-in hybrid vehicles were available from Table NZ.5 from National Grid ESO (2021b). The data was, however, combined

Table 1
Main assumptions of the Future Energy Scenarios.
Source: National Grid ESO (2021a,c).

Main assumptions of the Future Energy Scenarios
Leading the Way: There is a high level of investment in decarbonisation technologies and, as a result, there is rapid decarbonisation. All assumptions regarding decarbonisation are the earliest credible dates. There is a very high carbon tax, which creates clarity for zero carbon technologies by early 2020s. In addition, there are many energy efficiency improvements, which reduce the demand for energy. Industrial and commercial energy efficiency improves by at least 20% by 2030 because it decarbonises early through electrification. In the residential sector, consumers adopt smaller or more portable appliances, which are more efficient. These include lighting, wet appliances and white goods. Insulation in homes increases and there is a sharp roll-out of smart homes and grids, which include the removal of gas for cooking and gas boilers. Oil and liquefied petroleum gas (LPG) heating systems are banned. Hydrogen is eventually used for heating in both the residential and commercial sectors. Hydrogen is also used in high temperature energy intensive industrial sectors. There is a widespread national rollout of charging infrastructure and home smart charging devices for EVs. There is a rapid electrification of road transport, which improves energy efficiency in transport overall, as electric vehicles are far more energy efficient than petrol and diesel vehicles. This rapid electrification is the result of both consumer pull and policy support. The levels of adoption of Vehicle-to-Grid[a] are high. Heavy good vehicles (HGVs) begin to use hydrogen from the mid-2030s. No natural gas is used to produce hydrogen, which instead is produced, carbon-free, solely from electrolysis[b] powered by renewable electricity. Consumers actively reduce their energy consumption. From the mid-2020s, there is high uptake of public transport and active travel, such as walking and cycling. The ban on sales of new petrol and diesel cars and vans becomes effective in 2030, and the ban on sales of new plug-in hybrid electric vehicles (PHEVs), in 2032.
Consumer Transformation This scenario uses a high level of electrification for heating and other energy demands, including in the industrial, commercial and transport sectors. There is a high carbon tax, which creates clarity for zero carbon technologies by mid 2020s. Consumers are concerned and engaged in decarbonisation. Industrial and commercial energy efficiency improves by at least 20% by 2030, thanks to electrification. In the residential sector, consumers adopt smaller or more portable appliances, which are more efficient. These include lighting, wet appliances and white goods. There is a national insulation programme for homes. Improvements in energy efficiency of homes are widespread, assisted by new smart technologies. High electrification leads to low demand for gas. A sustainable hydrogen economy fails to materialise, but there are medium/low levels of hydrogen produced via electrolysis, used in transport, industrial and commercial sectors, and some residential and commercial heat. Consumer pull accelerates EV adoption. Consumers are highly engaged in smart charging and Vehicle-to-Grid, especially from the 2040s. Charging predominately happens at home. There is more consumer demand for both autonomous vehicles and public transport. Buses are predominantly electric and a larger proportion of HGVs are electric than in other scenarios. The ban on sales of new petrol and diesel cars and vans becomes effective in 2030, and the ban on sales of new PHEVs, in 2035. The uptake of hydrogen by HGVs begins to increase by the mid-2030s, and there is a similar increase in electric HGVs.
System Transformation: Consumers experience less disruption than in Consumer Transformation because most of the changes in the energy system take place on the supply side. There is a very high carbon tax, which creates clarity for zero carbon technologies by early 2020s. This scenario assumes a high use of hydrogen for heating, and for the industrial, commercial and transport sectors. A self-sustaining hydrogen economy develops at a national scale. Industrial and commercial energy efficiency improves by 20% by 2030. The price of gas is low to support hydrogen production from natural gas. There is good progress in electrical efficiency, as new standards for new appliances come into place. In the residential sector, consumers adopt smaller or more portable appliances, which are more efficient. These include lighting, wet appliances and white goods. There is also an ambitious national insulation programme. Cars are electric or hybrid but there are more hydrogen cars after 2030. The levels of adoption of Vehicle-to-Grid are medium due to concerns over battery degradation. HGVs start to decarbonise from the 2030s, and most switch to hydrogen in the 2040s, along with some buses. Increase in public transport patronage is lower than in Leading the Way and Consumer Transformation because consumers are less willing to switch from private transport. The ban on sales of new petrol and diesel cars becomes effective in 2032, and the ban on sales of new PHEVs and new petrol and diesel vans, in 2035.
Steady Progression: Decarbonisation happens at a much slower pace compared to the other scenarios. There is a low carbon tax and low fuel prices. Decarbonisation policy decisions are delayed or not taken at all. The scenario misses the clean growth strategy target to improve business and industry energy efficiency by 20% by 2030, although heat and industrial processes become more efficient and slowly decarbonise. Consumers buy similar appliances to today. There is improvement in home insulation but significant reliance on natural gas, which remains very cheap. Energy efficiency programmes remain focused on addressing fuel poverty. There is very little use of hydrogen. There is low growth in public transport due to a lack of consumer willingness to mode shift. Natural gas becomes the main fuel for buses and HGVs from the 2020s, as barriers to electric or hydrogen vehicles are not overcome. Consumer resistance and other barriers means the uptake of electric cars is slower. There is low consumer engagement in smart charging and Vehicle-to-Grid adoption levels are low. Charging at home is limited by a lack of viable solutions for those without off-street parking. The ban on sales of new petrol and diesel cars becomes effective in 2035, and the ban on sales of new PHEVs and new petrol and diesel vans, in 2040. By the 2040s some buses are electrified.

[a]Vehicle-to-Grid is a technology that allows energy to be returned from the battery of an electric vehicle to the power grid.
[b]Electrolysis is the process of using electricity to split water into hydrogen and oxygen.

with emissions from rail. In order to separate CO2e emissions from road transport and rail transport, National Grid ESO was contacted, and they provided the breakdown by email. This is displayed in Table A.1 in the Appendix.

With the data described above, potential total CO2e emissions from road transport in the UK were computed through 2050. These include tailpipe emissions and emissions from electricity generation to satisfy the demand for electricity by EVs.

The potential CO2e emissions from electricity generation to satisfy the demand from EVs in the UK through 2050 were computed under each of the scenarios. To do this, the carbon intensity from electricity production from Table SV.27 from National Grid ESO (2021b) was multiplied by the demand for electricity by EVs in the UK through 2050 from Table ED5 from National Grid ESO (2021b). SV.27 includes two separate datasets, one without BECCS and one with BECCS. Both scenarios are used and presented, creating two differing projected CO2e emissions from EVs.

National Grid ESO (2021b) has carbon intensity expressed in CO2, not CO2e. CO2e includes other greenhouse gases alongside CO2 and converts these into an equivalent amount of CO2 based upon them having the same global-warming potential (Eurostat, 2017). BEIS publishes the conversion factor from CO2 to CO2e every year in their ''Greenhouse gas reporting: conversion factors'' series, with the latest one being the one corresponding to the year 2021 (BEIS, 2021b).

Eq. (1) was used to calculate CO2e emissions from electricity generation to satisfy the demand for electricity from EVs in the UK through 2050:

$$E_t = D_t \times I_t \qquad (1)$$

where E_t denotes total CO2e emissions from electricity generation to satisfy the demand for electricity from EVs in year t, with $t = 2020, 2021, \ldots, 2050$; D_t denotes demand for electricity from EVs, including PHEVs, in year t; and I_t denotes CO2e intensity of electricity generation, in million tonnes of CO2e (MtCO2e) per kWh, in year t.

I_t was estimated using Eq. (2):

$$I_t = I_t^{CO2} \times f \tag{2}$$

where I_t^{CO2} denotes CO2 intensity (as opposed to CO2e intensity) of electricity generation and f denotes a factor, which was assumed to be constant. The factor used was 1.01, which was rounded to 2 decimal places from the computed factor of 1.01033 from the spreadsheet "UK electricity" from the Greenhouse Gas Reporting Conversion Factors 2021 tables (BEIS, 2021b).

This conversion factor of 1.01 was chosen because the conversion factor is stable over time. For example, in 2017 it was 1.00777, in 2018 it was 1.00800, in 2019 it was 1.00797 and in 2020 it was 1.00908 (BEIS, 2017, 2018, 2019, 2020b). The main change in the generation mix in the UK is that CO2 emissions are decreasing because there are more renewables and less fossil fuel-based electricity generation. CO2 emissions are going down and obviously CO2e emissions are going down too, but the ratio between them (CO2e/CO2) is not changing significantly as demonstrated above. Therefore, for this study, the conversion factor 1.01 was used for all years, 2020 through to 2050.

Eqs. (1) and (2) were used for all four scenarios, excluding BECCS and including BECCS.

Potential total CO2e emissions from road transport in the UK were computed through 2050 by adding the tailpipe emissions and the emissions from electricity generation to satisfy the demand for electricity by EVs excluding BECCS, and including BECCS. This gave two sets of results for CO2e emissions from road transport, one excluding BECCS, and one including BECCS.

Eq. (3) summarises what was done:

$$RT_t = E_t + TP_t \tag{3}$$

where RT_t denotes total road transport emissions, in CO2e, in year t, with $t = 2020, 2021, \ldots, 2050$; E_t denotes total CO2e emissions from electricity generation to satisfy the demand for electricity from EVs in year t, and TP_t denotes total CO2e emissions from tailpipes of all petrol, diesel, hybrid, and plug-in hybrid vehicles in year t. Eq. (3) was used for all four scenarios, excluding BECCS and including BECCS.

As well as estimating total CO2e emissions from road transport under the four scenarios in the UK through 2050, total CO2e emissions from road transport in the UK through 2050 were also estimated assuming that the increase of EVs and decrease of fossil fuel vehicles proceed according to the assumptions under each scenario but in combination with the current electricity generation mix (i.e., higher production but same share of different sources). To calculate this, the carbon intensity of electricity production for 2020 was chosen as the "current" intensity and was kept constant through to 2050. This would be the case if there were no further decarbonisation of the electricity sector in the UK. In other words, Eq. (1) was used, but I_t was kept constant assuming $t = 2020$.

Eqs. (1) and (2), were adapted, as follows:

$$E_t = D_t \times I_{2020} \tag{1a}$$

where E_t and D_t are as before, but I_{2020} denotes CO2e intensity of electricity generation, in million tonnes of CO2 per kWh, in 2020.

I_{2020} was estimated, using Eq. (2a):

$$I_{2020} = I_{2020}^{CO2} \times f \tag{2a}$$

where I_t^{CO2} denotes CO2 intensity (as opposed to CO2e intensity) of electricity generation in 2020, and f is the same factor as before, i.e., 1.01.

The calculations in this case exclude BECCS, as the CO2 intensity is now assumed to be the 2020 CO2 intensity through to 2050, and there is no BECCS in 2020.

Like before, potential total CO2e emissions from road transport in the UK were computed through 2050 by adding tailpipe emissions and the emissions from electricity generation to satisfy the demand for electricity by EVs. In this exercise, however, tailpipe emissions and EV penetration from the Future Energy Scenarios were combined with the 2020 electricity generation mix.

The projections computed for the Future Energy Scenarios, all of which assume decarbonisation, were then compared with the projections which combine the Future Energy Scenarios for EV penetration and fossil fuel vehicle phase-out with the 2020 electricity generation mix.

4. Findings and discussion

4.1. CO2e emissions from electricity demand from EVs in the UK through 2050

Increasing the number of EVs on UK roads will inevitably imply an increase in demand for electricity, which will need to be satisfied. The potential CO2e emissions from electricity generation to satisfy the electricity demand from EVs in the UK through 2050 were computed under each scenario, excluding and including BECCS, as explained in Section 3. The results are presented in Tables A.2 and A.3 in the Appendix and in Figs. 2 and 3.

Fig. 2 shows the CO2e emissions that would result from an increase in electricity production to satisfy the demand from EVs assuming no BECCS under any scenario at any point. Needless to say, without BECCS, there are no negative CO2e emissions. In all cases emissions increase and then decrease, thanks to the decarbonisation of the power sector. The different trends are shaped by the speed of decarbonisation, especially the share of renewables, shown in Fig. A.1, and nuclear, shown in Fig. A.2, and also by the number of EVs on the road under each scenario, shown in Fig. A.3 in the Appendix.

Fig. 3 shows the CO2e emissions that would result from an increase in electricity production to satisfy the demand from EVs assuming that BECCS were taken up in the late 2020s under the Leading the Way, Consumer Transformation and System Transformation scenarios. The year in which BECCS kicks in and the speed with which it grows varies across the three scenarios, as shown in Fig. A.4 in the Appendix. What matters for this analysis, however, is that CO2e emissions from this increased electricity production initially grow very slowly and then decrease quickly and become negative under all scenarios, except for the Steady Progression scenario, which has slower decarbonisation and does not include BECCS at any point. This is why the trend for the Steady Progression scenario in Fig. 3 is identical to that in Fig. 2. BECCS is fundamental in making emissions negative, and the reason why the Leading the Way, Consumer Transformation and System Transformation scenarios see negative CO2e emissions in spite of increased electricity production to satisfy the demand from EVs.

The total cumulative CO2e emissions from electricity production to satisfy the demand from EVs under each scenario are presented in Table 2. As it can be seen on the table, Steady Progression has higher cumulative emissions than the other scenarios, and the scenarios that include BECCS are the only ones that achieve negative cumulative emissions.

These projections of CO2e emissions originating in electricity generation to satisfy the demand for electricity from EVs can be compared with the projections of CO2e emissions from vehicle tailpipes, as discussed in the section that follows.

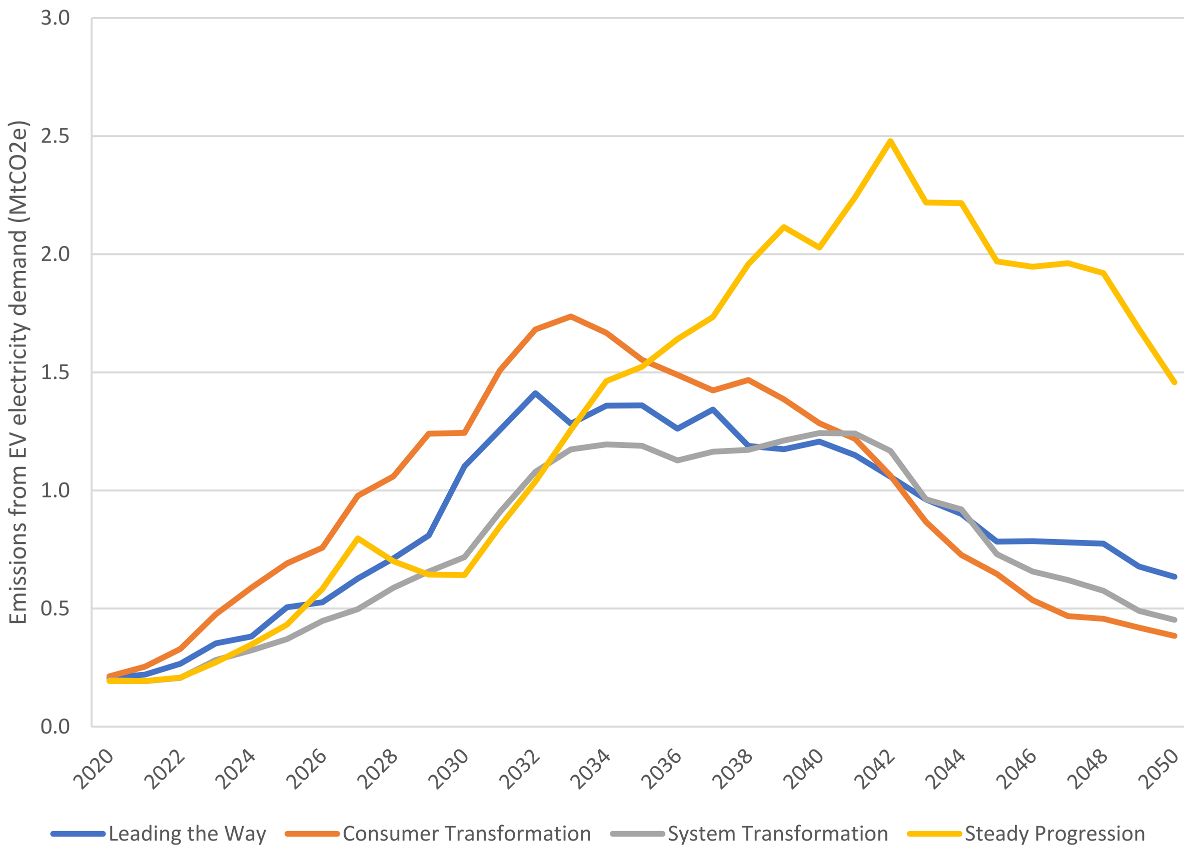

Fig. 2. Emissions from electricity generation for EVs (MtCO2e) excluding BECCS, 2020–2050.
Source: Table A.2, itself produced on the basis of Tables ED5 and SV27 from National Grid ESO (2021b).

Table 2
Total cumulative emissions from electricity generation for EVs (MtCO2e), 2020–2050.
Source: Tables A.2 and A.3.

Scenario	Excluding BECCS	Including BECCS
Leading the Way	27.1	−57.4
Consumer Transformation	29.8	−69.6
System Transformation	23.8	−58.6
Steady Progression	40.7	40.7

4.2. Total CO2e emissions from road transport through 2050

As EVs increase their share of vehicles on the road, fossil fuel propelled vehicles decrease theirs under all scenarios. The total CO2e emissions from road transport were simply computed by adding tailpipe emissions from Table A.1 and emissions from electricity generation to satisfy the demand for electricity from EVs through 2050 under all scenarios, excluding BECCS and including BECCS, from Tables A.2 and A.3, respectively. The results are presented in Tables A.4 and A.5 in the Appendix and in Fig. 4. The Steady Progression scenario does not incorporate any potential to include BECCS and hence is shown as just one dashed line (excluding BECCS).

Fig. 4 demonstrates, as expected, that when BECCS is included, all scenarios, except for Steady Progression, achieve net negative emissions by 2047, with System Transformation and Leading the Way doing so in 2046. Although only the three scenarios that incorporate BECCS reach net-zero for road transport by 2050, all scenarios see an overall decrease in emissions because reduced tailpipe emissions far exceed any emissions from electricity generation to power EVs. The question that emerges then is whether reduced tailpipe emissions would still exceed emissions from electricity generation to power EVs if no further decarbonisation of the power sector were to take place. This is discussed in the section that follows.

4.3. Total CO2e emissions from road transport through 2050 with the 2020 electricity generation mix

The total CO2e emissions from road transport through 2050 were estimated assuming that the increase in EVs and decrease in fossil fuel vehicles proceed according to the assumptions under each scenario but in combination with the current electricity generation mix.

As explained in Section 3, to calculate the emissions from electricity for EVs, the carbon intensity of electricity production was held constant at the 2020 value through to 2050. This obviously excludes BECCS, as there is no BECCS in 2020. The results are presented in Table A.6 in the Appendix.

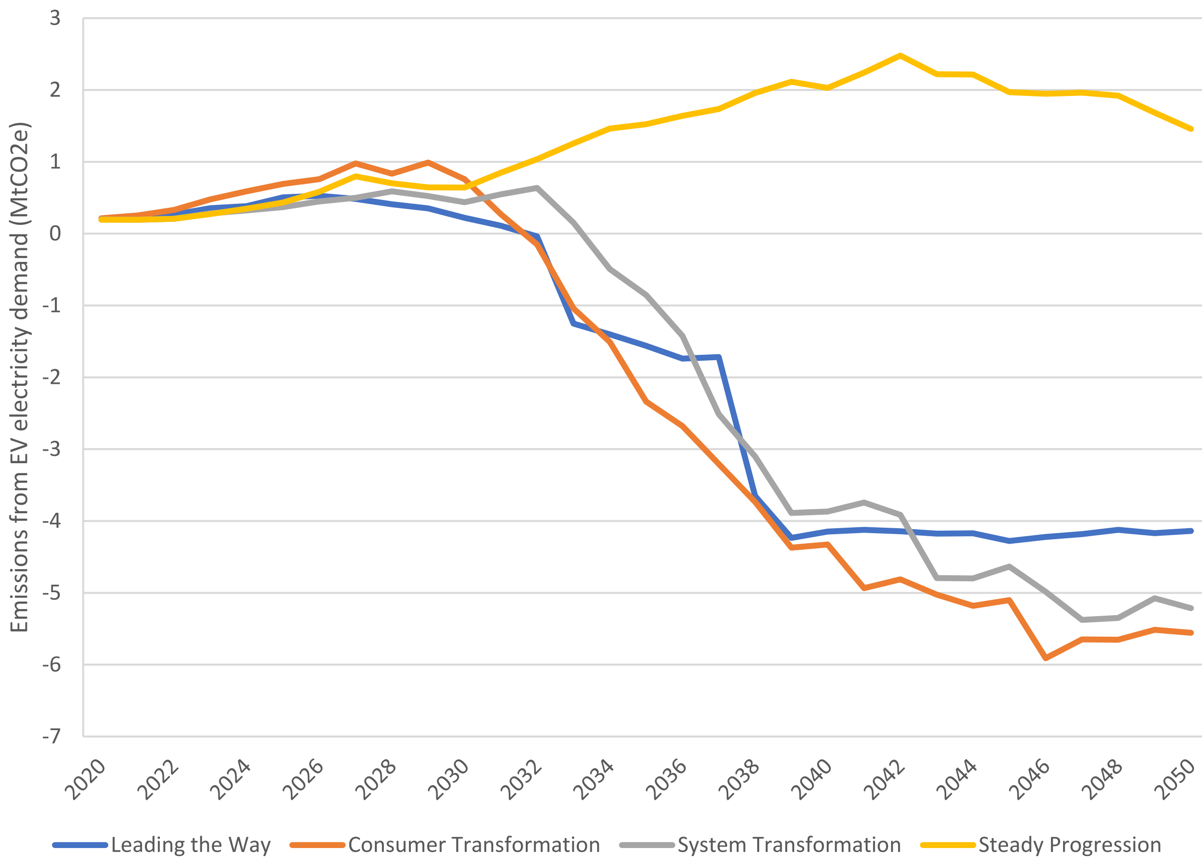

Fig. 3. Emissions from electricity generation for EVs (MtCO2e) including BECCS, 2020–2050.
Source: Table A.3, itself produced on the basis of Tables ED5 and SV27 from National Grid ESO (2021b).

Potential total CO2e emissions from road transport were then computed through 2050 by adding the tailpipe emissions from Table A.1 and the emissions from electricity generation to satisfy the demand for electricity by EVs from Table A.6. The results are presented in Table A.7 in the Appendix. A comparison of all the results is presented in Fig. 5.

Fig. 5 shows that EVs save emissions even assuming no further decarbonisation of the power sector. Increasing the number of EVs on the road in the UK will increase the demand for electricity and therefore emissions. However, the savings in tailpipe emissions exceed any increase in emissions from electricity generation for EVs under all scenarios and also under the assumption that the power sector is not decarbonised any further.

Table 3
Total cumulative emissions from road transport[a] (MtCO2e), 2020–2050.
Source: Tables A.4, A.5, and A.7.

MtCO2e	Scenario
1269.0	Leading the Way with Decarbonisation (including BECCS)
1309.2	Consumer Transformation with Decarbonisation (including BECCS)
1353.5	Leading the Way with Decarbonisation (excluding BECCS)
1408.6	Consumer Transformation with Decarbonisation (excluding BECCS)
1451.7	System Transformation with Decarbonisation (including BECCS)
1534.1	System Transformation with Decarbonisation (excluding BECCS)
1630.4	Leading the Way - 2020 Electricity Generation Mix
1687.4	Consumer Transformation - 2020 Electricity Generation Mix
1692.1	Steady Progression with Decarbonisation - always excludes BECCS
1766.8	System Transformation - 2020 Electricity Generation Mix
1874.4	Steady Progression - 2020 Electricity Generation Mix

[a]Emissions from road transport include tailpipe emissions and emissions from electricity generation to satisfy the electricity demand from EVs.

4.4. Net zero road transport and the power sector

The results presented in Sections 4.1 to 4.3 are in line with the results obtained for other countries and regions of the world, such as those from Liu and Santos (2015), Woo et al. (2017), Cox et al. (2020), Gryparis et al. (2020), Gómez Vilchez and Jochem (2020) and Märtz et al. (2021). They are also in line with the results from Logan et al. (2022) for the UK.

The analysis presented also shows that road transport electrification in the UK can generate substantial emission savings even with the current electricity generation mix. Emissions decline in all cases, but there are important differences in magnitude, as can be seen in Table 3. The total cumulative emissions from road transport under all the scenarios considered vary from 1269 to 1874 MtCO2e for the period 2020–2050. The Leading the Way (including BECCS) scenario yields the lowest emissions and the Steady Progression scenario combined with the 2020 electricity generation mix scenario yields the highest emissions.

The UK has committed to overall net zero emissions by 2050 (BEIS, 2020a). Only the three scenarios that incorporate BECCS reach net zero for road transport by 2050, which shows that (a)

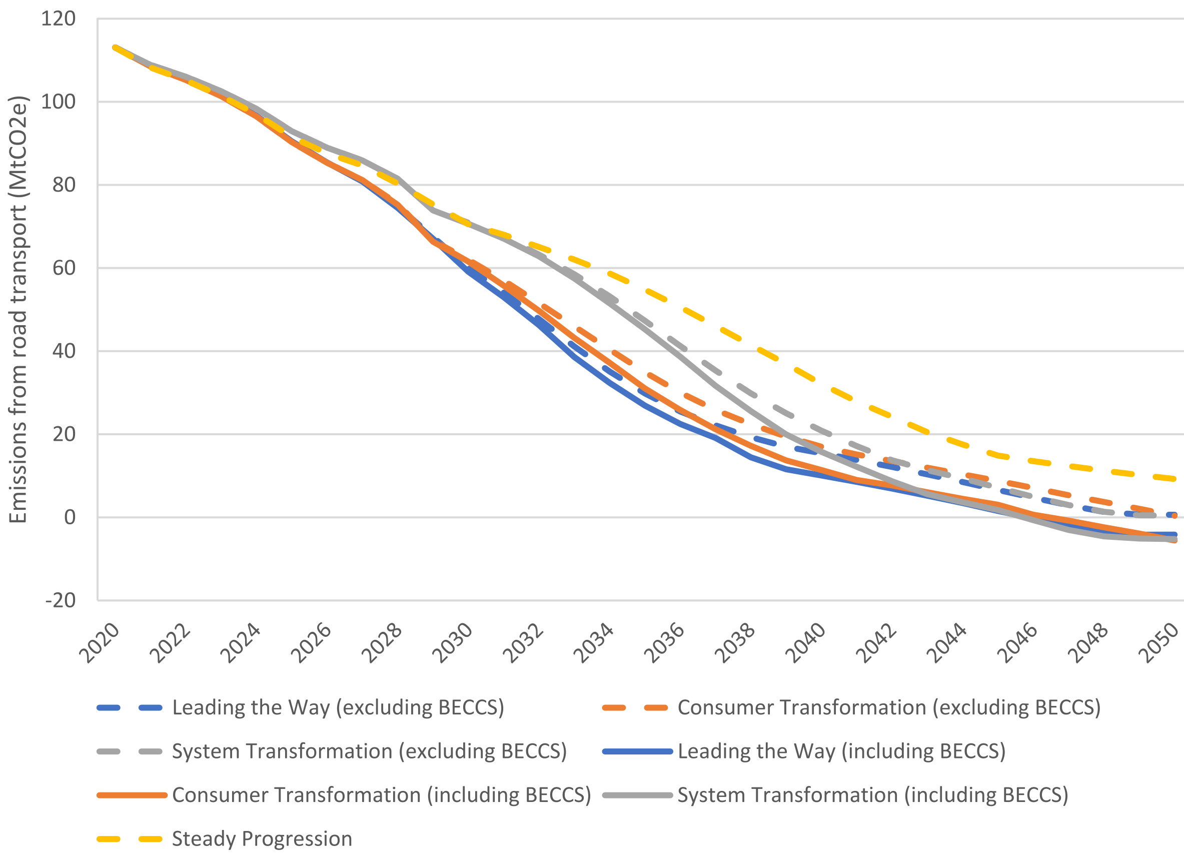

Fig. 4. Emissions from road transport[a] (MtCO2e), 2020–2050.
[a]Emissions from road transport include tailpipe emissions and emissions from electricity generation to satisfy the electricity demand from EVs.
Source: Tables A.4 and A.5.

it is possible to achieve net zero by 2050 in road transport, (b) BECCS is essential, and (c) road transport can make up for other sectors where emissions are not possible to reduce. The policy recommendations that emerge from these findings are discussed in Section 5.

5. Conclusion and policy recommendations

This paper has estimated CO2e emissions from electricity generation for EVs in the UK under the Future Energy Scenarios from the National Grid ESO through to 2050. These emissions were then combined with the expected decline in tailpipe emissions, also under the Future Energy Scenarios, to find the cumulative total emissions from road transport. In addition, CO2e emissions from road transport were estimated assuming the current electricity generation mix stays constant through to 2050, but the number of EVs increases and the number of fossil fuel vehicles decreases in line with the different scenarios' assumptions. This was done to understand the potential for emissions savings from road transport electrification without any further decarbonisation of the power sector.

The main finding is that road transport electrification can save CO2e emissions through 2050 even under the 2020 electricity generation mix. All the Future Energy Scenarios with and without decarbonisation of the power sector and with and without BECCS see emissions decline. There are, however, important differences in the extent to which emissions decline and the only scenarios that achieve negative emissions from road transport are the scenarios that incorporate BECCS. This provides an opportunity for the UK government to not just reduce emissions from road transport, but to achieve net zero in road transport, and indeed, to yield negative emissions and compensate for other sectors where emissions are not possible to reduce.

Not achieving negative emissions in road transport by the late 2040s would be a missed opportunity given that this is indeed feasible, provided BECCS is adopted widely. The main policy recommendation is therefore that the government ensures that BECCS is financially viable on a mass scale. The second policy recommendation is that the ban on the sale of new petrol and diesel cars and vans currently planned for 2030 does indeed go ahead, and that new PHEVs are banned from 2032, as contemplated under the Leading the Way scenario, which yields the highest emissions savings. The third policy recommendation is that government support is provided so that HGVs can begin to use hydrogen from the mid-2030s, and hydrogen is produced from electrolysis powered by renewable electricity, again in line with the Leading the Way scenario. Other obvious essential interventions, also in line with the Leading the Way scenario, include the support of charging infrastructure and home smart charging devices for EVs, the investment in public transport and active travel (walking and cycling) infrastructure and the discouragement of car use, potentially via financial incentives.

These recommendations should not be read to imply that the Leading the Way scenario needs to be targeted and implemented, but rather, that steps taken on those lines should deliver substantial decarbonisation of road transport, yielding negative emissions

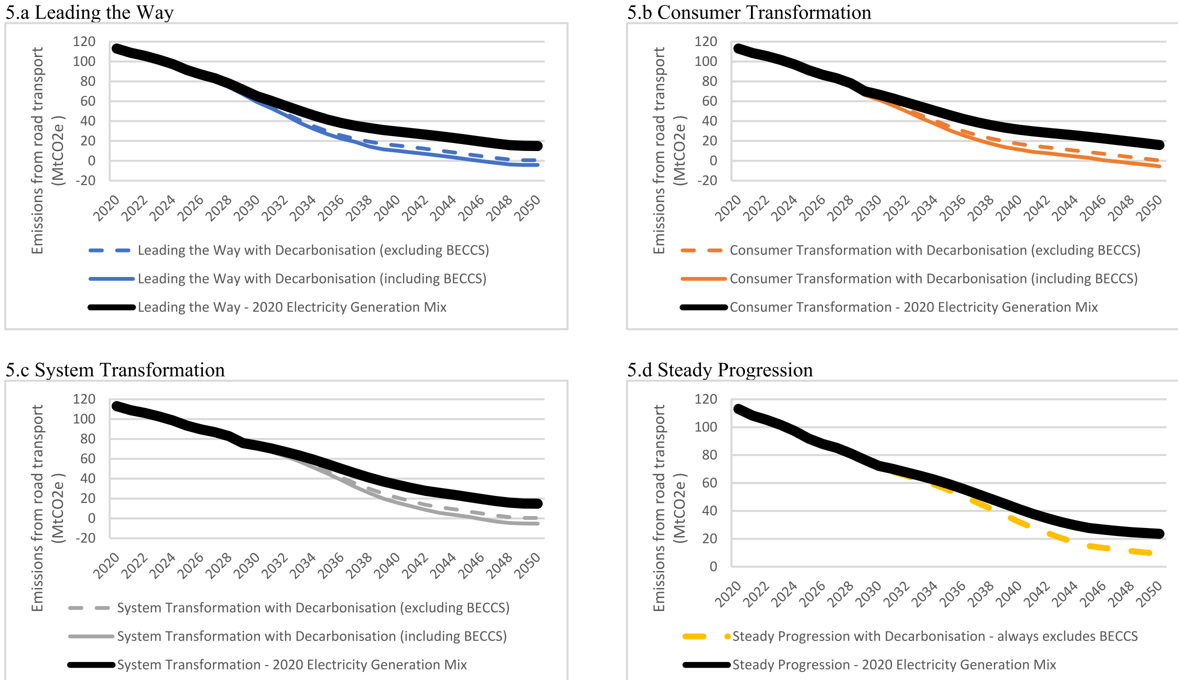

Fig. 5. Comparison of emissions from road transport[a] (MtCO2e) under the Future Energy Scenarios and under the Future Energy Scenarios for tailpipes and EVs combined with the 2020 electricity generation mix, 2020–2050.
[a]Emissions from road transport include tailpipe emissions and emissions from electricity generation to satisfy the electricity demand from EVs.
Source: Tables A.4, A.5 and A.7.

by the late 2040s. The Future Energy Scenarios are theoretical constructs that are more likely to materialise in some hybrid form rather than in their pure form. The key points to take away are that BECCS has an essential role to play, and that sooner is better than later in terms of electrification of road transport because it delivers higher savings faster.

One shortcoming of the present study is that it does not include CO2e emissions from EV manufacturing and disposal, or from battery manufacturing and disposal. Including these would allow for the whole lifecycle emissions from EVs to be estimated. Hall and Lutsey (2018) and Cox et al. (2020) compare lifecycle emissions of EVs and conventional tailpipe vehicles in Europe, and Gómez Vilchez and Jochem (2020) do the same for China, France, Germany, India, Japan and the United States. These ideas could be extended to consider the effect of the Future Energy Scenarios from National Grid ESO (2022a) on EV lifecycle emissions, with a focus on the UK.

The effect of the recent policy changes such as the highlighted new British Energy Security Strategy (HM Government, 2022) due to the crisis in Ukraine will also need to be assessed on these future projections once the situation stabilises. Decarbonisation may now happen at a faster rate than it would have before, as there is some urgency to reduce the UK's dependence on oil and gas imports. Consumers may also be more inclined to move towards EVs, in response to higher petrol and diesel costs. An external shock like the Russian invasion to Ukraine can accelerate behavioural and policy change. On the one hand, it is causing instability, inflation, weaker economic growth, falling real incomes and an increase in poverty across the UK, Europe and further afield, but on the other, it is strengthening political and public determination from governments, the private sector, and consumers to cut or at least reduce dependence on fossil fuels. This new determination can be used to maximum advantage in the fight against climate change, and in particular, in the efforts to achieve negative emissions in road transport.

Declaration of competing interest

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

Data availability

All the data used in this paper is freely available from various websites, as highlighted throughout the paper. The data provided by e-mail to the authors not available on any website is presented in the paper.

Acknowledgments

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Appendix

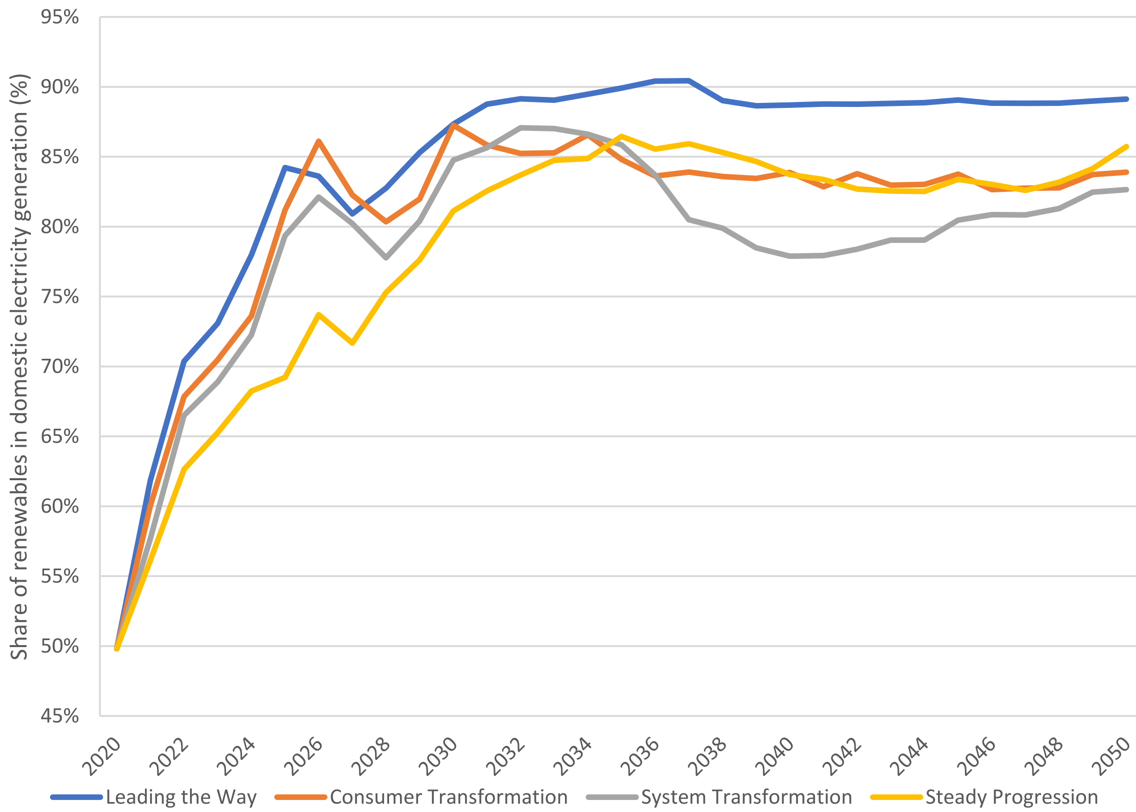

Fig. A.1. Share of renewables in domestic electricity generation.
Source: Table SV.25 from National Grid ESO (2021b).

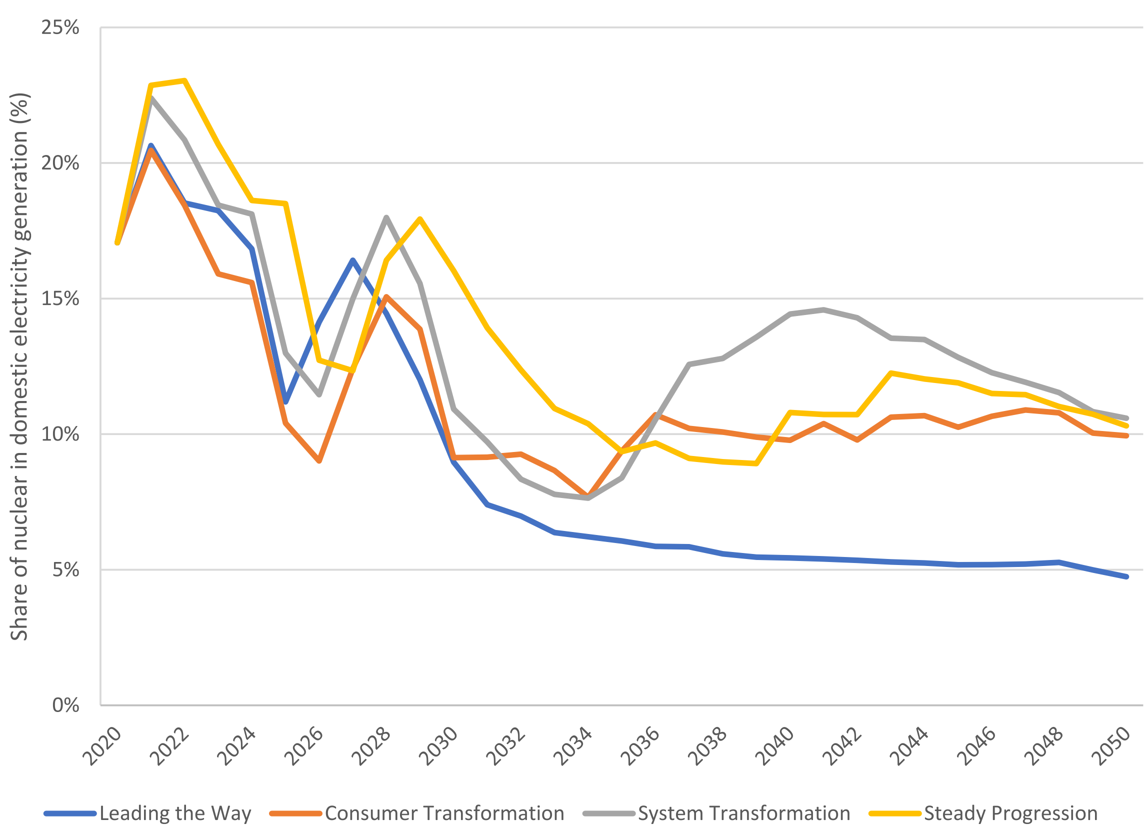

Fig. A.2. Share of nuclear in domestic electricity generation.
Source: Table SV.25 from National Grid ESO (2021b).

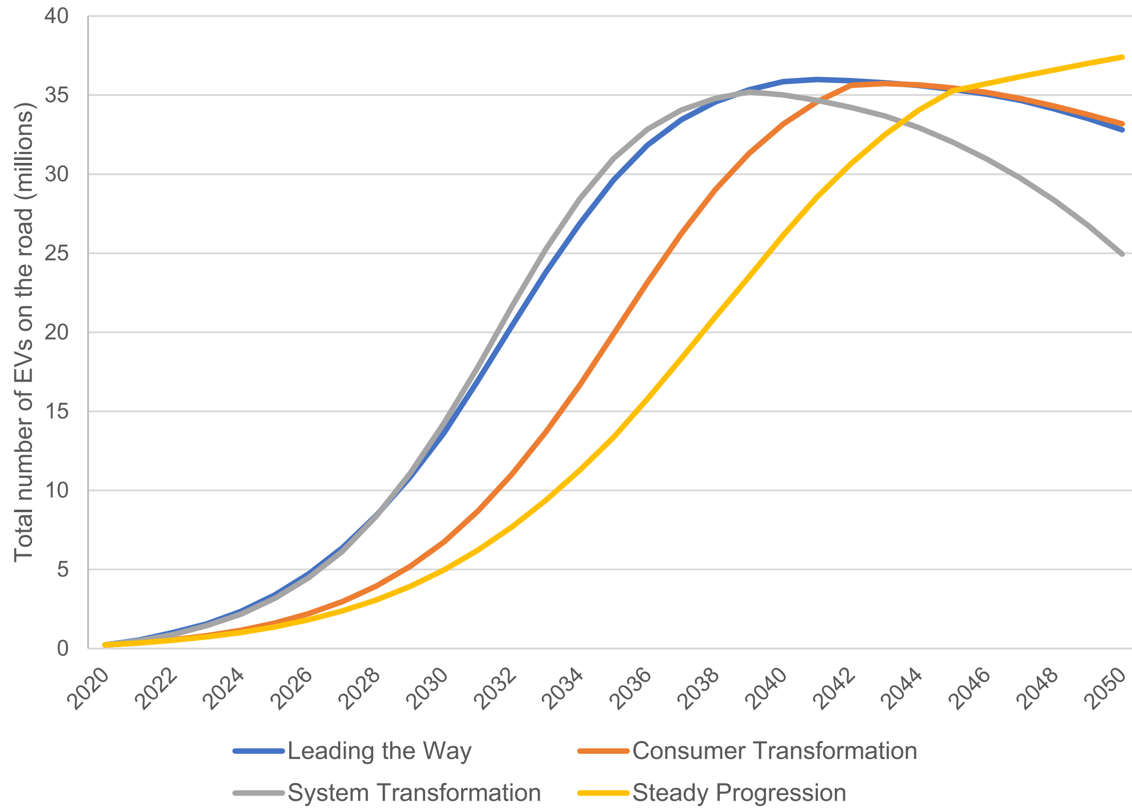

Fig. A.3. Total number of EVs on the road (millions), including cars, vans and HGVs.
Source: Tables CV.35, CV36 and CV.37 from National Grid ESO (2021b).

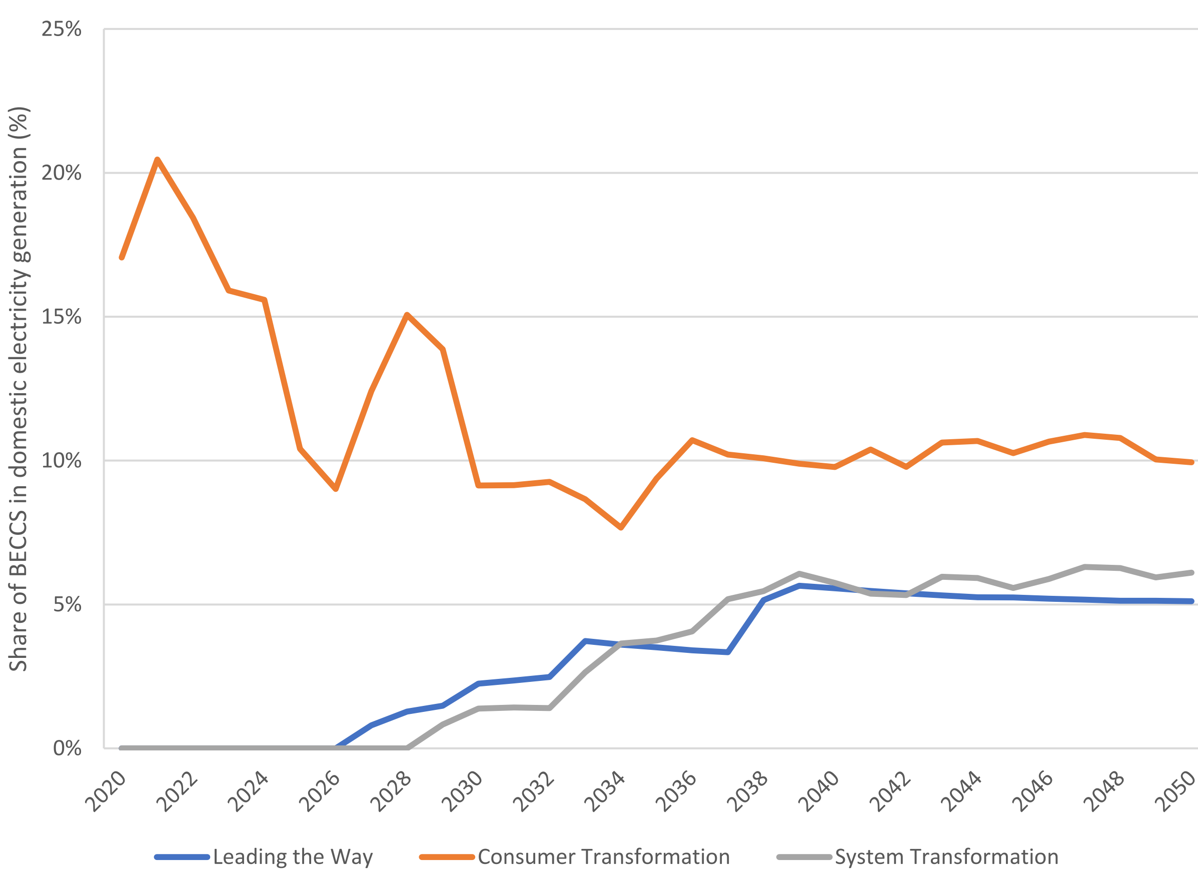

Fig. A.4. Share of BECCS in domestic electricity generation.
Source: Table SV.25 from National Grid ESO (2021b).

Table A.1
Future Energy Scenarios segregated rail and road tailpipe emissions.
Source: Data provided via e-mail by National Grid ESO.

Total emissions (MtCO2e)	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way	116	111	108	103	98	92	87	82	76
Consumer Transformation	116	111	107	103	98	92	87	82	76
System Transformation	116	111	108	105	100	95	90	87	83
Steady Progression	116	111	108	104	99	94	89	86	82

Rail emissions (MtCO2e)	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way	3	3	2	2	2	2	2	2	1
Consumer Transformation	3	3	3	2	2	2	2	2	2
System Transformation	3	3	3	2	2	2	2	2	2
Steady Progression	3	3	3	3	3	3	3	2	2

Road Tailpipe emissions (MtCO2e)	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way	113	108	105	101	96	90	85	80	74
Consumer Transformation	113	108	105	101	96	90	85	80	74
System Transformation	113	109	106	102	98	93	89	85	81
Steady Progression	113	108	105	101	97	91	87	84	80

Total emissions (MtCO2e)	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way	68	60	54	47	40	34	29	24	21
Consumer Transformation	67	62	57	51	45	40	34	29	25
System Transformation	75	72	68	63	58	53	47	41	35
Steady Progression	77	72	69	66	63	59	55	51	46

Rail emissions (MtCO2e)	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way	1	1	1	1	1	0	0	0	0
Consumer Transformation	2	1	1	1	1	1	1	1	0
System Transformation	2	1	1	1	1	1	1	1	0
Steady Progression	2	2	2	2	2	2	2	2	2

Road Tailpipe emissions (MtCO2e)	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way	67	59	53	46	40	34	28	24	21
Consumer Transformation	65	61	56	50	44	39	33	29	24
System Transformation	73	70	67	62	57	52	46	40	34
Steady Progression	75	70	67	64	61	57	53	49	44

Total emissions (MtCO2e)	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way	18	16	14	13	11	9	8	6	4
Consumer Transformation	21	18	16	14	12	11	10	8	7
System Transformation	29	24	20	16	13	10	8	6	4
Steady Progression	41	36	32	27	23	20	17	14	13

Rail emissions (MtCO2e)	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way	0	0	0	0	0	0	0	0	0
Consumer Transformation	0	0	0	0	0	0	0	0	0
System Transformation	0	0	0	0	0	0	0	0	0
Steady Progression	2	2	2	2	2	1	1	1	1

Road Tailpipe emissions (MtCO2e)	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way	18	16	14	13	11	9	8	6	4
Consumer Transformation	21	18	16	14	12	11	10	8	7
System Transformation	29	24	20	16	13	10	8	6	4
Steady Progression	40	35	30	26	22	18	15	13	12

Total emissions (MtCO2e)	2047	2048	2049	2050
Leading the Way	2	1	0	0
Consumer Transformation	5	3	2	0
System Transformation	2	1	0	0
Steady Progression	12	10	10	9

Rail emissions (MtCO2e)	2047	2048	2049	2050
Leading the Way	0	0	0	0
Consumer Transformation	0	0	0	0
System Transformation	0	0	0	0
Steady Progression	1	1	1	1

Road Tailpipe emissions (MtCO2e)	2047	2048	2049	2050	Cumulative total
Leading the Way	2	1	0	0	1326
Consumer Transformation	5	3	2	0	1379
System Transformation	2	1	0	0	1510
Steady Progression	10	9	9	8	1651

Table A.2
Emissions from electricity generation for EVs (MtCO2e) excluding BECCS.
Source: Tables ED5 and SV.27 from National Grid ESO (2021b).

	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.7
Consumer Transformation	0.2	0.3	0.3	0.5	0.6	0.7	0.8	1.0	1.1
System Transformation	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6
Steady Progression	0.2	0.2	0.2	0.3	0.3	0.4	0.6	0.8	0.7
	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way	0.8	1.1	1.3	1.4	1.3	1.4	1.4	1.3	1.3
Consumer Transformation	1.2	1.2	1.5	1.7	1.7	1.7	1.6	1.5	1.4
System Transformation	0.7	0.7	0.9	1.1	1.2	1.2	1.2	1.1	1.2
Steady Progression	0.6	0.6	0.8	1.0	1.3	1.5	1.5	1.6	1.7
	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way	1.2	1.2	1.2	1.1	1.1	1.0	0.9	0.8	0.8
Consumer Transformation	1.5	1.4	1.3	1.2	1.1	0.9	0.7	0.6	0.5
System Transformation	1.2	1.2	1.2	1.2	1.2	1.0	0.9	0.7	0.7
Steady Progression	2.0	2.1	2.0	2.2	2.5	2.2	2.2	2.0	1.9

	2047	2048	2049	2050	Cumulative total
Leading the Way	0.8	0.8	0.7	0.6	27.1
Consumer Transformation	0.5	0.5	0.4	0.4	29.8
System Transformation	0.6	0.6	0.5	0.5	23.8
Steady Progression	2.0	1.9	1.7	1.5	40.7

Table A.3
Emissions from electricity generation for EVs (MtCO2e) including BECCS.
Source: Tables ED5 and SV.27 from National Grid ESO (2021b).

	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.4
Consumer Transformation	0.2	0.3	0.3	0.5	0.6	0.7	0.8	1.0	0.8
System Transformation	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6
Steady Progression[a]	0.2	0.2	0.2	0.3	0.3	0.4	0.6	0.8	0.7
	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way	0.4	0.2	0.1	0.0	−1.3	−1.4	−1.6	−1.7	−1.7
Consumer Transformation	1.0	0.8	0.3	−0.2	−1.0	−1.5	−2.3	−2.7	−3.2
System Transformation	0.5	0.4	0.5	0.6	0.2	−0.5	−0.9	−1.4	−2.5
Steady Progression[a]	0.6	0.6	0.8	1.0	1.3	1.5	1.5	1.6	1.7
	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way	−3.7	−4.2	−4.1	−4.1	−4.1	−4.2	−4.2	−4.3	−4.2
Consumer Transformation	−3.7	−4.4	−4.3	−4.9	−4.8	−5.0	−5.2	−5.1	−5.9
System Transformation	−3.1	−3.9	−3.9	−3.7	−3.9	−4.8	−4.8	−4.6	−5.0
Steady Progression[a]	2.0	2.1	2.0	2.2	2.5	2.2	2.2	2.0	1.9

	2047	2048	2049	2050	Cumulative total
Leading the Way	−4.2	−4.1	−4.2	−4.1	−57.4
Consumer Transformation	−5.6	−5.7	−5.5	−5.6	−69.6
System Transformation	−5.4	−5.4	−5.1	−5.2	−58.6
Steady Progression[a]	2.0	1.9	1.7	1.5	40.7

[a]Steady Progression is the only scenario where BECCS is never included.

Table A.4
Total CO2e emissions from road transport (including tailpipe emissions and emissions from electricity generation for EVs) (MtCO2e) excluding BECCS.
Source: Tables A.1 and A.2.

	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way	113.1	108.7	105.5	101.5	96.6	90.5	85.4	81.0	74.8
Consumer Transformation	113.1	108.5	105.2	101.3	96.5	90.3	85.3	81.2	75.4
System Transformation	113.1	108.9	106.0	102.5	98.3	92.9	89.0	85.9	81.5
Steady Progression	113.1	108.3	105.1	101.4	97.0	91.5	87.6	84.7	80.3
	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way	67.5	60.0	54.1	47.7	41.1	35.1	29.8	25.5	22.2
Consumer Transformation	66.6	62.0	57.0	51.6	46.0	40.4	34.9	30.0	25.8
System Transformation	74.0	70.9	67.4	63.2	58.5	53.2	47.3	41.2	35.3
Steady Progression	75.3	70.5	68.0	65.1	62.0	58.7	54.8	50.6	46.0
	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way	19.3	17.0	15.4	13.8	12.2	10.4	8.5	6.6	4.7
Consumer Transformation	22.4	19.5	17.0	15.2	13.6	11.9	10.4	8.8	7.1
System Transformation	29.8	25.1	20.9	17.2	13.8	11.3	9.4	7.1	5.0
Steady Progression	41.5	36.9	32.1	27.9	24.2	20.5	17.5	14.9	13.5

	2047	2048	2049	2050	Cumulative total
Leading the Way	2.9	1.3	0.7	0.6	1353.5
Consumer Transformation	5.3	3.7	2.1	0.4	1408.6
System Transformation	3.0	1.3	0.5	0.5	1534.1
Steady Progression	12.4	11.2	10.2	9.2	1692.1

Table A.5
Total CO2e emissions from road transport (including tailpipe emissions and emissions from electricity generation for EVs) (MtCO2e) including BECCS.
Source: Tables A.1 and A.3.

	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way	113.1	108.7	105.5	101.5	96.6	90.5	85.4	80.8	74.5
Consumer Transformation	113.1	108.5	105.2	101.3	96.5	90.3	85.3	81.2	75.2
System Transformation	113.1	108.9	106.0	102.5	98.3	92.9	89.0	85.9	81.5
Steady Progression[a]	113.1	108.3	105.1	101.4	97.0	91.5	87.6	84.7	80.3
	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way	67.0	59.1	53.0	46.3	38.6	32.4	26.9	22.5	19.1
Consumer Transformation	66.3	61.5	55.8	49.7	43.2	37.2	31.0	25.9	21.2
System Transformation	73.9	70.6	67.1	62.8	57.5	51.5	45.3	38.7	31.7
Steady Progression[a]	75.3	70.5	68.0	65.1	62.0	58.7	54.8	50.6	46.0
	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way	14.5	11.6	10.1	8.5	7.0	5.2	3.5	1.5	−0.3
Consumer Transformation	17.2	13.7	11.4	9.0	7.7	6.1	4.5	3.0	0.6
System Transformation	25.6	20.0	15.8	12.2	8.7	5.6	3.6	1.8	−0.7
Steady Progression[a]	41.5	36.9	32.1	27.9	24.2	20.5	17.5	14.9	13.5

	2047	2048	2049	2050	Cumulative total
Leading the Way	−2.0	−3.6	−4.2	−4.1	1269.0
Consumer Transformation	−0.8	−2.4	−3.9	−5.6	1309.2
System Transformation	−3.0	−4.6	−5.1	−5.2	1451.7
Steady Progression[a]	12.4	11.2	10.2	9.2	1692.1

[a]Steady Progression is the only scenario where BECCS is never included.

Table A.6
Emissions from electricity generation for increased EVs (MtCO2e) under the Future Energy Scenarios combined with the 2020 electricity generation mix[a].
Source: Tables ED5 and SV.27 from National Grid ESO (2021b).

	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way - 2020 Electricity Mix	0.2	0.3	0.5	0.8	1.1	1.5	2.1	2.8	3.7
Consumer Transformation - 2020 Electricity Mix	0.2	0.4	0.6	0.8	1.2	1.6	2.2	2.9	3.7
System Transformation - 2020 Electricity Mix	0.2	0.3	0.4	0.5	0.7	0.9	1.2	1.5	1.9
Steady Progression - 2020 Electricity Mix	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.3	1.6
	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way - 2020 Electricity Mix	4.8	6.1	7.6	9.2	10.7	12.1	13.2	14.0	14.5
Consumer Transformation - 2020 Electricity Mix	4.7	5.9	7.3	8.8	10.3	11.6	12.8	13.8	14.4
System Transformation - 2020 Electricity Mix	2.5	3.1	4.0	4.9	6.0	7.3	8.6	9.9	11.2
Steady Progression - 2020 Electricity Mix	1.9	2.4	2.9	3.5	4.2	5.0	5.9	6.9	8.0
	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way - 2020 Electricity Mix	14.9	15.2	15.3	15.4	15.4	15.4	15.4	15.4	15.4
Consumer Transformation - 2020 Electricity Mix	14.9	15.3	15.6	15.7	15.8	15.9	16.0	16.0	16.0
System Transformation - 2020 Electricity Mix	12.4	13.4	14.1	14.8	15.2	15.3	15.4	15.3	15.3
Steady Progression - 2020 Electricity Mix	9.1	10.2	11.2	12.2	13.0	13.7	14.3	14.8	15.1

	2047	2048	2049	2050	Cumulative total
Leading the Way - 2020 Electricity Mix	15.4	15.3	15.1	14.9	304.0
Consumer Transformation - 2020 Electricity Mix	16.1	16.0	16.0	15.9	308.6
System Transformation - 2020 Electricity Mix	15.2	15.1	15.0	14.8	256.5
Steady Progression - 2020 Electricity Mix	15.3	15.4	15.6	15.8	223.0

[a]The 2020 electricity generation mix excludes BECCS.

Table A.7
Total CO2e emissions from road transport[a] (MtCO2e) under the Future Energy Scenarios for EVs and fossil fuel vehicles combined with the 2020 electricity generation mix[b].
Source: Tables A.1 and A.6.

	2020	2021	2022	2023	2024	2025	2026	2027	2028
Leading the Way - 2020 Electricity Mix	113.1	108.8	105.7	101.9	97.4	91.5	87.0	83.2	77.8
Consumer Transformation - 2020 Electricity Mix	113.1	108.6	105.5	101.7	97.1	91.2	86.7	83.1	78.1
System Transformation - 2020 Electricity Mix	113.1	109.0	106.2	102.8	98.7	93.5	89.7	86.9	82.8
Steady Progression - 2020 Electricity Mix	113.0	108.3	105.3	101.6	97.3	91.9	88.0	85.1	81.2
	2029	2030	2031	2032	2033	2034	2035	2036	2037
Leading the Way - 2020 Electricity Mix	71.5	65.1	60.5	55.5	50.6	45.9	41.6	38.2	35.4
Consumer Transformation - 2020 Electricity Mix	70.1	66.7	62.8	58.7	54.5	50.3	46.2	42.3	38.8
System Transformation - 2020 Electricity Mix	75.8	73.4	70.5	67.1	63.4	59.3	54.7	50.0	45.4
Steady Progression - 2020 Electricity Mix	76.6	72.3	70.1	67.6	65.0	62.3	59.2	55.8	52.3
	2038	2039	2040	2041	2042	2043	2044	2045	2046
Leading the Way - 2020 Electricity Mix	33.1	31.1	29.5	28.0	26.5	24.8	23.1	21.2	19.4
Consumer Transformation - 2020 Electricity Mix	35.9	33.4	31.3	29.7	28.3	27.0	25.6	24.1	22.6
System Transformation - 2020 Electricity Mix	41.1	37.2	33.8	30.7	27.8	25.7	23.8	21.7	19.6
Steady Progression - 2020 Electricity Mix	48.6	45.0	41.3	37.8	34.7	32.0	29.7	27.7	26.6

	2047	2048	2049	2050	Cumulative total
Leading the Way - 2020 Electricity Mix	17.5	15.8	15.1	14.9	1630.5
Consumer Transformation - 2020 Electricity Mix	20.9	19.3	17.6	15.9	1687.4
System Transformation - 2020 Electricity Mix	17.5	15.9	15.0	14.8	1766.8
Steady Progression - 2020 Electricity Mix	25.6	24.8	24.1	23.6	1874.4

[a]Emissions from road transport include tailpipe emissions and emissions from electricity generation to satisfy the electricity demand from EVs.
[b]The 2020 electricity generation mix excludes BECCS.

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