Transportation Research Part D 85 (2020) 102350

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Electric and hydrogen buses: Shifting from conventionally fuelled cars in the UK

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ARTICLE INFO

Keywords:
Buses
Electric buses
Hydrogen buses
Carbon dioxide emissions

ABSTRACT

For the UK to meet their national target of net zero emissions as part of the central Paris Agreement target, further emphasis needs to be placed on decarbonizing public transport and moving away from personal transport (conventionally fuelled vehicles (CFVs) and electric vehicles (EVs)). Electric buses (EBs) and hydrogen buses (HBs) have the potential to fulfil requirements if powered from low carbon renewable energy sources.

A comparison of carbon dioxide (CO_2) emissions produced from conventionally fuelled buses (CFB), EBs and HBs between 2017 and 2050 under four National Grid electricity scenarios was conducted. In addition, emissions per person at different vehicle capacity levels (100%, 75%, 50% and 25%) were projected for CFBs, HBs, EBs and personal transport assuming a maximum of 80 passengers per bus and four per personal vehicle.

Results indicated that CFVs produced 30 $gCO_2\ km^{-1}$ per person compared to 16.3 $gCO_2\ km^{-1}$ per person by CFBs by 2050. At 100% capacity, under the two-degree scenario, CFB emissions were 36 times higher than EBs, 9 times higher than HBs and 12 times higher than EVs in 2050. Cumulative emissions under all electricity scenarios remained lower for EBs and HBs.

Policy makers need to focus on encouraging a modal shift from personal transport towards sustainable public transport, primarily EBs as the lowest level emitting vehicle type. Simple electrification of personal vehicles will not meet the required targets. Simultaneously, CFBs need to be replaced with EBs and HBs if the UK is going to meet emission targets.

1. Introduction

Transport is the leading contributor of greenhouse gas (GHG) emissions in the UK, closely followed by energy generation, both of which will contribute to irreversible climate damage over the next decade if changes are not made. To reduce emissions, the UK has begun introducing electric buses (EBs), and more recently hydrogen buses (HBs), into the transport network. Both EBs and HBs offer key advantages over conventionally fuelled buses (CFBs) and other conventionally fuelled vehicles (CFVs), as they do not produce emissions directly from operation since their emissions are produced upstream (Correa et al., 2017; Mekhilef et al., 2012). This means their true environmental impact is dependent upon non-tailpipe emissions from fuel/energy production. Reducing non-tailpipe emissions, i.e. energy network emissions, is a central objective of the 2015 Paris Agreement. The Paris Agreement has set a target to limit global warming to less than 2 °C above pre-industrial temperatures and to pursue efforts to limit the temperature increase to 1.5

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https://doi.org/10.1016/j.trd.2020.102350

°C above pre-industrial temperatures within this century (Pietzcker et al., 2014). In addition, GHG emissions will need to reach optimum levels and decline as fast as possible to meet these targets (Pietzcker et al., 2014). From a transport perspective, future energy sources should be predominantly electric, produced from various power station types, or hydrogen power. The objective of this paper is to analyse bus emissions, compared with private vehicles, through four different energy scenarios from the UK National Grid. This will allow predictions to be drawn to determine the extent to which a move away from CFVs and electric vehicles (EVs) towards EBs and HBs can contribute to the UK's national target of net zero emissions by 2050 to meet Paris Agreement targets.

In previous years, large focus has been placed on managing demand and promoting co-modality, however this only supports a partial solution to reducing transport GHG emissions. By assuming the maximum capacity of an average bus is 80 and a small CFV is four, as least 20 CFVs could be taken off the road if buses were fully utilized, significantly reducing road transport emissions and congestion. Furthermore, although the UK aims to ban the sale of CFVs (and vans as well as hybrid vehicles) from 2035 onwards, with EVs likely to fill this gap in the transport network (The UK Government, 2020), there will remain a need to encourage the use of public transport. Due to the role and influence that electric powered transport could have on UK energy systems and future - GHG emissions, projecting future energy use has become an important topic in research, business and policy making. If increased use of public transport is achieved by 2050 there is a reduced need for the number of small EVs on the road which can help decrease transport emissions as well as partially mitigate increases in power generation, congestion, safety and reduction of CFV and EV infrastructure. Therefore, increased use of public transport is an important part of any comprehensive strategy to mitigate GHG emissions from the transport sector and achieve the net zero target.

EBs are operated by a lithium ion battery charged by electricity (Charters, 2016). However, if the electricity is generated from fossil fuels, the environmental benefits will be diminished (Correa et al., 2017; Mekhilef et al., 2012). HBs are powered by fuel cells converting hydrogen (H_2) into electrical energy, emitting water vapor as a by-product (Charters, 2016). H_2 is produced using electricity to split water into oxygen and H_2 or chemically by reforming methane into H_2 with carbon monoxide as a bi-product. Furthermore, the use of H_2 as a fuel for buses with a fuel cell propulsion system will allow the replacement of mineral oils, offering an opportunity for a sustainable alternative (Emonts et al., 2017). Transitioning to a H_2 energy system would likely rely on H_2 from the reforming of natural gas or electrolysis powered by the National Grid incorporating a mix including fossil-powered plants. Similarly, to EBs, if H_2 is generated from fossil fuels, there would be no advantage of switching from CFBs unless the carbon emissions can be isolated indefinitely either as an inert chemical or in a geological repository. HBs use more electrical energy due to the energy required to convert electricity to H_2 and back to electricity with the potential for loss in storage; therefore, it is expected they will produce a higher level of operating emissions than battery powered EBs (Shinnar, 2003). If HB and EBs are fuelled from renewables, they could be especially advantageous within city centres where there is typically heavy traffic and as a result air quality can be poor due to emissions from CFVs and CFBs (Correa et al., 2017; Lajunen and Lipman, 2016; Lajunen and Tammi, 2019).

As part of the shift to decarbonised transport, small scale integration of HBs and EBs has begun in the UK into the public transport network. EBs are currently more popular than HBs, primarily because the infrastructure is more easily implemented as shown, for example, in London, Birmingham and Manchester. In London, two bus routes will become exclusively electric by 2020 as the London-wide bus fleet becomes the largest electric fleet in Europe. The route 43 bus service runs a total of 14.5 km between Archway and the London Bridge stations, and route 134 runs between North Finchley and Warren Street station (a total of 14.7 km), both serve thousands of travellers every day. Both routes will shift to electric double decker utilising some of the 200 existing EBs currently in place and with an additional 78 being brought into service by the end of 2020; this will help to ensure that all buses in London will be Euro VI emission standard by October 2020. These routes will contribute to London's ultra low emission zones, which are expected to reduce nitrogen oxide emissions by 84% (Greater London Authority, 2020). Euro VI is the latest standard targeted by new diesel engines, reducing nitrogen oxide emissions by up to 95% compared to the previous generation of buses. By 2037 all 9,200 buses across London are expected to be zero emissions (Greater London Authority, 2020). This targeting of 2037 for a major commuter city is part of the UKs targeting of reduced emissions and is informed by discussion of comparisons of different integration points of EVs. In 2014, ten single decker HBs were introduced in Aberdeen through two European funded projects (Fuel Cells Bulletin, 2012) as a small-scale trial. Single decker HBs have also been operating in London and Brighton. Due to its success it was announced in 2019, in London, that 20 double decker HBs will be integrated from 2020 onwards. These HBs will feature amenities to encourage public transport use such as USB charging facilities onboard and a smoother, quieter journey along three routes from west London to Wembley which served over 10 million passenger journeys in 2018. Although EBs and HBs are being integrated into the bus network, it remains at a small scale country wide.

Bus usage in the UK has differed over time decreasing from 5.3 million passenger journeys in 1986/87 to 2.8 million passenger journeys in 2016/17 with all four nations seeing a decline in use. However, within London bus usage has increased from 1.2 million passenger journeys in 1986 to 2.3 million passenger journeys in 2015/16 (DfT, 2017). Increase bus usage within London has been driven by policy, price and convenience with the introduction of online apps making travel easier and the Oyster card that can also allow for integrated travel between public transport and caps the daily cost allowing individuals to travel for hours at a cheaper rate. Therefore, the UK could benefit from the introduction of a UK wide travel card to encourage new users.

Previous studies have highlighted the role of public and consumer attitudes of alternative fuelled vehicles with perception remaining positive and a key role in the successful deployment of new technologies (Bögel et al., 2018). H_2 safety did not play a significant role as many experts believed that it would (O'Garra et al., 2005). The main deterrent to user acceptance of H_2 vehicles is the lack of prior knowledge, however as knowledge improves then public acceptance of H_2 vehicles could improve (Lipman et al., 2018; O'Garra et al., 2005; Yetano Roche et al., 2010). It is clear that public acceptance of both EBs and HBs, which will be enhanced by public education and direct experience, will be imperative for widescale expansion and scale-up across the UK. Additionally, most new buses in London are hybrid buses or low emission (Euro VI). While these changes are advertised most of the public are largely unaware except that they are quieter in traffic. Notwithstanding the anticipated benefits of improved knowledge about EBs and HBs, it must be acknowledged that bus use has remained relatively low in comparison to other transport types. This is partly because buses have historically been considered a low status mode of transport (Beirão and Sarsfield Cabral, 2007; Ellaway et al., 2003; Fitt, 2018; Goodman et al., 2014; Green et al., 2014; Griskevicius et al., 2010; Musselwhite and Haddad, 2010; Sadalla and Krull, 1995; Stokes and Hallett, 1992). In addition, buses are seen to lack the convenience, mobility, freedom, control and privacy that personal CFVs hold; these are perceptions that will need to be overcome if bus use is going to increase (Clayton et al., 2017; Miller, 2001; Sheller, 2004). Successful transport networks have benefitted from several schemes and policies aimed at shifting consumers towards utilising the network that's available. In London, bus use has been primarily driven by investment including the Oyster card, bus lanes and gates and frequent night services. These have coincided with de-incentivisation methods against personal transport such as the introduction of congestion zones and high parking fees in both residential and business areas raising the costs of car ownership. The combination of all these factors has driven a successful bus service in London and these approaches will need to be incorporated in the rest of the UK to encourage bus use.

Encouraging this shift away from CFVs and EVs towards public transport poses challenges. In 2018, only 4% of individuals in the UK travelled by bus annually (National Travel Survey, 2019) with most commuters outside London favouring personal vehicles (83%). Public and active travel in total represented 15% of travel in 2018 showing a great disparity in travel choice. The drivers of this disparity are not considered in this study, however regional, practical and socio-economic factors are thought to be the primary causes. Urry (2016) believed that private vehicles not only provided status to their owners including representing their career achievements, but also *'speed, home, safety, sexual success, freedom, family, masculinity and genetic breeding'*. This in turn could encourage an individual to purchase a vehicle for use instead of using public transport; indeed, previous UK tax regimes encouraged the provision of company cars as an in-kind benefit, creating a status structure. The introduction of travel demand management (TDM) initiatives, with push and pull measures, aims to establish and enable the appropriate use of critical transport infrastructure, -encompassing the desire to optimize transportation systems for all users (Mahmood et al., 2009). It is recognized however that the impact of TDM initiatives can be dependent upon the context and particularities of each individuals' motivation for using CFVs (Redman et al., 2013). Measures to encourage switching to public transport should optimize the price, environmental, social and cost benefits of use (Redman et al., 2013). By encouraging public transport use that supports the needs of the individual, coupled with the integration of alternative fuels such as electric and $H_{2,}$ greater decarbonization, energy security and urban air quality improvements could occur (Offer et al., 2010).

Although no single technology can make transportation carbon neutral (Mathiesen et al., 2015), this paper will focus on the environmental operating emissions of EBs and HBs. These results will be compared to CFBs and the emissions per person from buses compared with CFVs and EVs to demonstrate the importance of switching to public transport to reduce emissions, which is necessary if the UK wants to meet its national targets. This will be calculated through the projected CO_2 emissions produced from varying the electricity generation mix to supply EB and HB from 2017 to 2050. To do this, the paper will focus on the potential GHG emissions produced from the electricity supply mix through four electricity generation scenarios modelled by the UK National Grid (National Grid, 2018). The National Grid generates these scenarios to provide a continually updated reference point for environmental, network and use analyses. It reflects the annual returns from various stakeholders including production, sale and end-use of electricity generation with consideration of uncertainties. These scenarios can therefore be used to quantify likely societal energy use, which when related to emissions is of great importance in transport emission modelling. The first scenario, 'two-degree', estimates the level of intensity of carbon produced for the UK to meet the two-degree Paris Agreement targets. Secondly, the 'steady progression' scenario provides a more realistic transition towards electric transport as a business as usual approach ensuring low costs for consumers. Thirdly, 'community renewables' predicts what could happen if consumers and businesses began to install small-scale renewable generation in their homes, offices and neighbourhoods , though is reliant on high economic growth. Finally, 'consumer evolution' predicts the carbon intensity in a high economic growth scenario with money available to spend.

In addition, for HB, emissions produced from steam methane reforming and coal regenerating with and without carbon capture and storage (CCS) were also examined (though for 2018 only due to data certainty limitations). Using these scenarios, this paper will address potential changes in emissions if the UK switches from CFVs and CFBs to EB and HB, using the National Grid scenarios and H_2 generation scenarios. This enables conclusions to be drawn on whether and under which scenarios the UK can meet net zero emissions by 2050 and the targets set in the Paris Agreement.

1.1. Electricity generation in the UK

Transitioning towards electricity generated from sustainable sources is essential for the UK to meet its net zero emissions target (Sithole et al., 2016). The transition to electric power for EBs and HBs will further increase the demand for low-carbon electricity generation (Eriksson and Gray, 2017). For a successful low-carbon future, the UK should consider moving away from a centralized approach and consider a more internally complex and diverse energy system, which will simultaneously improve energy security (Eriksson and Gray, 2017).

In previous years, the UK electricity sector has been dominated by a few energy types, primarily fossil fuels, with a record low of UK electricity generation from fossil fuels in 2019 (Evans, 2020). However, with the UK's carbon emission goals, energy generation is transitioning towards renewables for a low carbon economy. In 2015, the UK Government announced its intentions to end all unabated coal generation in the UK by 2025 (BEIS, 2018).

As part of the 2009 EU Renewable Energy Directive (2009/28/EC), the UK is required to generate 15% of its energy from renewable sources by 2020, with a revised target in the EU Renewable Energy Directive (2018/2001/EU) of 32% by 2030. The UK

Table 1
Projected UK electricity generation mix based on current policy between 2017 and 2035 for the UK (Source: BEIS, 2019a; BEIS 2019b; World Nuclear Association, 2011).

Electricity Generation Type	The UK Electricity Generation Mix (TWh) (%)				
	2017	2020	2025	2030	2035
Coal	21.4 **(6.6)**	1 **(0)**	0 **(0)**	0 **(0)**	0 **(0)**
Coal and natural gas CCS	0 **(0)**	0 **(0)**	0 **(0)**	0 **(0)**	0 **(0)**
Oil	1.5 **(0.5)**	0 **(0)**	0 **(0)**	0 **(0)**	0 **(0)**
Natural gas	134.2 **(41.5)**	100.5 **(34)**	73.5 **(26)**	74.8 **(25)**	51.6 **(17)**
Nuclear	64.0 **(19.8)**	59.2 **(20)**	40.5 **(14)**	63.7 **(21)**	57.6 **(19)**
Other Thermal	4.8 **(1.5)**	0 **(0)**	0 **(0)**	0 **(0)**	0 **(0)**
Renewables	94.5 **(29.3)**	134.7 **(45)**	170.4 **(59)**	159.4 **(53)**	182.9 **(61)**
Storage	2.9 **(0.9)**	3.2 **(1)**	3.6 **(1)**	5.0 **(2)**	7.8 **(3)**
Total electricity supplied (gross)	**323.2 (100)**	**298.6 (100)**	**288.0 (100)**	**303.0 (100)**	**300.0 (100)**
Carbon Intensity of Electricity Generation	315.2	237.1	214.6	203.5	173.9

aims to surpass this by sourcing 40% of electricity from low carbon technologies by 2020 (Sithole et al., 2016; The UK Governement, 2009). In 2018, the UK's energy generation consisted of 33.0% renewables,with 39.5% from gas, 5.1% from coal and 19.5% from nuclear (BEIS, 2019c).

Table 1 demonstrates the projected electricity generation mix between 2017 and 2035 using existing policies (BEIS, 2019a; BEIS 2019b). Due to possible policy changes to ensure the UK meet their emission targets, published projections do not go beyond 2035. It is unknown how ambitious these projections are. Over the next 18 years, the UK Government aims to have reduced coal use from 2% (in 2019) of electricity generation to 0%, aligning within the 2025 target, whilst simultaneously doubling renewable energy generation. The carbon intensity of electricity generations for these projections was calculated using the mean tonnes CO_2e GWh^{-1} from the World Nuclear Association (2011).

Within the electricity sector, emissions need to be reduced by 92% by 2035 if the UK wants to meet their targets (DECC, 2015). Furthermore, the carbon intensity of power generation will need to be reduced from 0.5 tCO_2 MWh^{-1} to 0.045 tCO_2 MWh^{-1} by 2035 (Heuberger et al., 2017). To achieve this target, future investments into new infrastructure for low carbon electricity generation need to be introduced by policy and potential government financial backing. Furthermore, for successful future energy system planning, electricity security, carbon emission reductions and costs must be balanced and any interaction between these factors considered (Heuberger et al., 2017). By taking this into consideration, it is therefore imperative that the electricity sector is decarbonized as soon as possible as these emissions need to be considered by policy makers whose objective is to meet the net zero targets.

1.2. Hydrogen generation

To use H_2 for fuel, significant infrastructure improvements are needed as currently there are low numbers of H_2 vehicles in use within the UK (Southall and Khare, 2016). The UK currently faces the ‘chicken and egg problem’ as although commercial H_2 vehicles exist, future development is dependent upon the widespread fuelling infrastructure to enable sales of H_2 vehicles (Kriston et al., 2010). To solve this problem, the UK produced a roadmap for the introduction of H_2 vehicles which involves full H_2 coverage through the installation of refuelling stations along main roads and cities by 2030 (Southall and Khare, 2016). Re-fuelling stations for bus use have already been introduced in some cities across the UK, including Aberdeen which can fuel up to 700 bar for cars and 350 bar refuelling pressure for vans, trucks and buses. However, if bus use of H_2 continues to increase and spread across the UK, re-fuelling stations will need to be built at intervals either in the form of ‘micro-generators’ with steam methane reform (SMR) gas fed by pipelines or by producing H_2 from renewables on site (Bellaby et al., 2016). In addition, as most petrol and diesel refuelling stations' in the UK take trucks, buses and cars, the addition or change to H_2 within these facilities should result in minimal impact as most of the infrastructure is already in place. For the purposes of this study, emission projections have been primarily focused on H_2 generated by electrolysis. However, H_2 generated through steam methane reforming (SMR) and through coal gasification SMR have also been analysed for 2018 only.

H_2 can be generated from an extensive range of sources and materials, including fossil fuels, biomass and industrial chemical by-products. Currently to generate H_2, 48% is from natural gas, 30% from petroleum, 18% from coal gasification, 3.9% from electrolysis and 0.1% from other processes (Kalamaras and Efstathiou, 2013). Fuel cell vehicles use H_2, which is stored within the vehicle, to power an electric motor, generating electricity by combining H_2 and oxygen in a fuel cell. Converting H_2 into electricity generally produces water and heat as by-products and they are considered zero emission vehicles. True emissions will depend on a method to produce H_2 which will determine the total environmental impact (Dicks et al., 2004); it is these source emissions that are considered here.

Electrolysis involves H_2 being generated as water is dissociated into H_2 and oxygen by applying electric current directly to the source. H_2 is obtained at 20 °C, at a 30-bar pressure level and at a 90% purity level. For this to be a true low carbon process, electricity needs to be generated from renewable or nuclear energy sources (Patyk et al., 2013; Suleman et al., 2015). For this method to be more widely used, electricity consumption must be reduced by improving the process efficiency (Patyk et al., 2013). It should also be noted that H_2 is easily stored and can be produced at low electricity demand periods, in contrast to charging vehicle batteries on demand.

SMR is one of the most widespread and least expensive methods of H_2 generation (Ogden et al., 2000). SMR occurs by steam and natural gas reacting at a high temperature between 500 and 900 °C, at pressures of between 20 and 35 atms and a steam to carbon ratio of 2.5:3 to yield carbon monoxide and H_2 (Ritter and Ebner, 2007; Voldsund et al., 2016). This process often involves a low-cost nickel-based catalyst to speed up the process (Voldsund et al., 2016). To increase chemical process efficiencies a second reaction called the Water-Gas Shift reaction is initiated which recovers additional H_2. These processes produce CO and CO_2 respectively which are among some of the most harmful emissions so switching to H_2 generation purely from this method may not be the most efficient emissions reducing policy.

The same methodology used to produce H_2 using SMR can also be used to produce H_2 from other fuels, such as oil and coal. Approximately 99% of the H_2 produced and consumed within industry is generated by natural gas reforming (Hosseini and Wahid, 2016; Mohammadfam and Zarei, 2015; Ozalp, 2008) producing high levels of CO_2 as by-products (National Academy of Engineering, 2004). A lifecycle of H_2 production from SMR using natural gas determined that this method of production is considered the least environmentally friendly method of H_2 generation due to abiotic depletion and global warming potential (Suleman et al., 2015). As this method produces CO_2, incorporating CCS can help reduce emissions by permanently storing these emissions in geological formations deep underground. Furthermore, the UK is one of the best suitable locations for CCS implementation as there are suitable carbon sinks (depleted oil and gas reservoirs and aquifers) with appropriate offshore infrastructure (BEIS, 2019d). This could allow emissions to be reduced as the UK transitions towards a low carbon economy (BEIS, 2019a) and H_2 production is being piloted in the ACORN project. The ACORN project aims to create a CCS system at minimal costs for capture, transport and storage by 2023 at the St Fergus Gas Terminal in the North East of Scotland (Alcalde et al., 2019). ACORN is a major H_2 and CCS hub which will reuse infrastructure, particularly existing oil and gas pipelines which are now redundant, prior to decommissioning, to minimize environmental and financial costs (Cooper and Hammond, 2018). ACORN is expected to capture 200,000 tons of CO_2 per year (Pale Blue Dot, 2017).

By analysing the operating emissions of EBs and HBs and comparing these to CFBs, results will highlight the importance of switching to sustainable public transport to reduce emissions if the UK wants to meet their net zero targets, as long as the energy selected for new transport systems is generated sustainably. Furthermore, by comparing all bus emissions with CFVs, results will emphasize the critical need for public transport in the UK. Results from this study can allow policy makers to help drive future TDM initiatives to encourage public transport use and deter individuals away from CFVs.

2. Methodology

To predict the CO_2 emissions produced by three differently fuelled buses in the UK, data was obtained from a range of local authority, regional and national databases including the UK Government and National Grid (BEIS, 2017; National Grid, 2018). These projections are the best available energy usage and network supply data currently available for the study period of between 2017 and 2050 as they include current and planned generating capacity and its economic life.

To ensure consistency between the different fuel type models, the number of buses and distance travelled remained constant (**Appendix A**). These projections were obtained from the Transport Energy Air Pollution Model for the UK (TEAM-UK) model, with the number of mini buses, urban buses (buses primarily used within urban areas that have a capacity of 80) and coaches combined to give a total number of buses in the UK (Brand and Anable, 2019; Brand et al., 2019; Brand et al., 2020). Over the time frame of between 2017 to 2050, the number of buses is projected to increase by 19% from 141,365 in 2017 to 168,836 in 2050. Urban bus distance was used for all buses as the median bus category for distance as its represented a precautionary approach (and therefore overestimation) compared to a simple all buses by all expected distance approach. There is a slight decrease projected in the total distance travelled by each bus by 4% from 40,791 km to 39,224 km in 2050.

This is since distance projections are based upon the need to fulfil demand, which in turn is estimated partly based upon the projected decrease in population size, resulting in a decrease in the need for public transport. The predicted population changes are provided by present household numbers in the base version of the TEAM-UK model (Brand et al., 2019). The TEAM-UK model is based upon current trends and policies that are implemented across the UK meaning trends in bus usage can increase and decrease retrospectively as policies are implemented in the model. Expanding and learning from policies in areas that have seen increases in public transport use, such as London, would further increase the emissions decrease seen across the country. This paper does not directly consider the embedded carbon costs of vehicles including the decommissioning of CFVs and the construction of vehicles. CFVs and EVs estimates were compared against EBs and HBs predictions using four of the National Grid electricity generation mix scenarios, ‘two-degree’, ‘steady progression’, ‘community renewables’ and ‘consumer volution’ (**Appendix B**).

2.1. Estimating total bus emissions and gCO_2 km^{-1}

To estimate the total CO_2 emissions produced for CFBs in the UK, Eq. (1) was used:

$$\text{Emissions}_{CFB} = \text{B} * \text{D} * \text{C} \tag{1}$$

where B is the total number of buses, D is the distance travelled (km) and C represents the carbon intensity (gCO_2 km^{-1}) of fuel type. Data units are converted to present in $MtCO_2$.

For this equation, the average values for fossil fuelled busses (CFBs) in the UK were used starting at 1,304 gCO_2 km^{-1} and decreased by 5 gCO_2 km^{-1} per annum to 1,139 gCO_2 km^{-1} to take into consideration annual technological improvements.

2.1.1. Capacity emissions per person for EBs, HBs, CFBs and CFVs

Eq. (2) estimates the $gCO_2\ km^{-1}$ per person and is then weighted depending on the number of individuals travelling. At full capacity double decker buses can hold 80 individuals on board and it was assumed that cars had four individuals on board at full capacity. Eq. (2) was used to calculate the emissions per person for HBs, EBs and CFBs and CFVs to determine the level of emissions at four vehicle capacity levels (full capacity (100%), 75% capacity, 50% capacity and 25% capacity). This enables conclusions to be drawn on at what point public transport can be considered a lower emission alternative to CFVs.

$$\text{Emissions}_{\text{Per Person}} = \left(\frac{\text{EC}}{\left(N * \left(\frac{\text{A}}{N}\right)\right)}\right) \tag{2}$$

where EC = total emissions per bus, N = total number of seats and A = number of seats occupied. Data units are converted to present in $MtCO_2$.

2.2. Electric bus emissions

To estimate the total level of emissions produced from a full fleet of EBs, Eq. (3) was used:

$$\text{Emissions}_{\text{EB}} = ((\text{B} * \text{D}) * (\text{G} * \text{F})) * \text{CI} \tag{3}$$

where G is the annual vehicle energy consumption ($kWh\ km^{-1}$), F = is the energy supply inefficiency and CI = the carbon intensity of electricity generation ($gCO_2\ kWh^{-1}$). Data units are converted to present in $MtCO_2$.

F was given a value of 1.18 to account for inefficiency in battery charge discharge, transmission disruptions and losses. Power efficiency and conservation are both expected to improve through EV technology improvements, however limited information quantifying this is currently available. This has resulted in current and future years being run with a conversion cost factor of 1.18, therefore energy required, and emissions produced by EBs up to 2050 may be overestimated. The annual average vehicle energy consumption (G) for EBs was given a value of 1.2 $kWh\ km^{-1}$ (Vepsäläinen et al., 2019). Although there are likely technological improvements between 2017 and 2050, this value was kept constant as these will be minimal as this depends upon vehicle uptake.

2.3. Hydrogen bus emissions

To calculate the total energy required to fuel all HBs, the conversion and inefficiency (I) of hydrogen generation via electricity generation needs to be taken into consideration. To do this, Eq. (4) was used:

$$\text{I} = \left(\frac{\text{R}}{\text{E}}\right) \tag{4}$$

where R = grid energy requirement (kWh) E = electricity generated from 1 GJ of H_2 electrolysis ($kWh\ GJ^{-1}$).

As no National Grid estimation of hydrogen carbon intensity were found during the literature search, the calculation of hydrogen carbon intensity was based on work by Fernández-Dacosta et al. (2019) who focussed on using photovoltaic sources to generate hydrogen. For every 1 GJ of H_2 to be produced, 479 kWh of electricity needs to be generated (R) from the energy source (specific sources or general market can be used in the estimation). The 1 GJ of H_2 was converted to kWh by dividing this by 3,600 giving 277.78 kWh equivalent (i.e. the value used as E in Eq. (4)) and therefore an inefficiency value of 1.72. It is assumed that the energy required during the hydrogen generation would be the same regardless of source. Therefore, these estimations do not include life cycle emissions from the generation source as in reality energy would come for the wider energy market which fluctuates across the years.

Using this value and to estimate the total volume of emissions from a HB between 2017 and 2050, using different methods to generate H_2, including natural gas SMR and coal gassification SMR with and without CCS, Eq. (5) was used:

$$\text{Emissions}_{\text{HB}} = (((\text{B} * \text{D}) * (\text{G} * \text{P})) * \text{I}) * \text{CI} \tag{5}$$

where P is the inverse of the hydrogen fuel cell efficiency. Data units are converted to present in $MtCO_2$.

When converting H_2 to electricity, 20% of energy is lost during this process due to thermodynamic conversion efficiency. Therefore only 80% of H_2 energy in a fuel cell can be used. Therefore, the inverse value needs to be included in the equation giving a value of 1.25.

The annual vehicle energy consumption for HBs was given a value of 1.8 $kWh\ Km^{-1}$ (Graurs et al., 2015). Although there are likely technological improvements between 2017 and 2050, this value was kept constant.

For HBs, the carbon intensity of electricity generation used under the four National Grid scenarios was used. In addition, the carbon intensity of different H_2 generation methods with and without CCS was obtained from Brukner et al., (2008) and the CCC (2018). The values used for analysis were the highest values within the estimate to gauge the highest level of emissions that could be produced from H_2 production. The carbon intensity of these methods can be seen in Table 2.

Table 2
The carbon intensity of producing hydrogen through SMR using natural gas and SMR using coal gasification with and without carbon capture and storage ($gCO_2\ kWh^{-1}$) in 2018 (Source: Brukner et al., 2008; CCC, 2018).

Technology Type	Without Carbon Capture and Storage ($gCO_2\ kWh^{-1}$)	With Carbon Capture and Storage ($gCO_2\ kWh^{-1}$)
Natural Gas SMR	285	25
Coal Gasification SMR	675	34

3. Results

Results comparing the total emissions and capacity emissions per individual for both CFBs and CFVs are presented below in 3.1. This analysis was used to determine which method of transport fuel type would be most favourable, dependent upon vehicle capacity, to reduce CO_2 emissions. Analysis of the three different fuelled buses are presented using the four different electricity generation mixes. Further analysis of capacity emissions per individual was undertaken to better understand the lowest emitting bus type for the UK.

3.1. Total emission comparison: CFBs VS CFVs

To better understand the need to switch to public transport, Table 3 compares the total projected CO_2 emissions produced from passenger kms for CFBs and CFVs from 2017, in five-year increments from 2020 onwards.

Emissions for CFBs are expected to peak in 2030 before decreasing, however by 2050, emissions are expected to be 0.02 $MtCO_2$ higher than in 2017. This is due to a 19% increase in the number of buses and 3% decrease in the total distance travelled. Emissions for CFVs are expected to peak in 2020 to 41.5 $MtCO_2$ before decreasing by 7.3 $MtCO_2$ below 2017 levels.

Emission predictions indicate that in 2017, CFVs under both scenarios produced 5 times more emissions than CFBs. By 2050, emissions are 4.5 higher. For CFVs, this decrease in total emissions is due to technological improvements, a decrease of 9% in the distance travelled despite a 25% increase in the number of vehicles between 2017 and 2050.

3.1.1. Capacity emissions per Individual: CFBs vs CFVs

Fig. 1 compares the projected emission levels produced per person from CFBs and CFVs in the UK between 2017 and 2050. Fig. 1 demonstrates the potential emissions in $gCO_2\ km^{-1}$ if both CFBs and CFVs were at 100%, 75%, 50% and 25% capacity. A breakdown of the four different capacity levels for EVs can be seen in **Appendix C**.

Fig. 1 demonstrates that a standard four-person car produced 30 $gCO_2\ km^{-1}$ per person at 100% capacity in 2017. Due to technological advances, emissions per person could decrease to 21.7 $gCO_2\ km^{-1}$ per person by 2050. A bus at full capacity produces 16.3 $gCO_2\ km^{-1}$ per person in 2017 and 14.4 $gCO_2\ km^{-1}$per person by 2050. Therefore in 2050, full capacity CFBs would produce 66% the level of carbon emissions produced by full capacity CFVs.

If a CFV was at 50% capacity with two individuals travelling, per person, emissions would be 60 $gCO_2\ km^{-1}$ per person in 2017 decreasing to 43.5 $gCO_2\ km^{-1}$ per person by 2050. However, at 50% capacity, emissions from a CFB would almost half that of CFVs at 32.5 $gCO_2\ km^{-1}$ per person in 2017. However due to minimal technological advances if a CFB was at 50% capacity in 2050, emissions would be expected to be 28.5 $gCO_2\ km^{-1}$ per person. Therefore in 2050, half capacity CFBs would produce 65% the level of carbon emissions produced by half capacity CFVs.

If a bus only had 25% capacity, then emissions would be almost half that of a CFV at 25% capacity in 2017. A bus at 25% capacity would produce 65.2 $gCO_2\ km^{-1}$ per person in 2017, decreasing to 56.9 $gCO_2\ km^{-1}$ per person. Whereas a car could produce 120 $gCO_2\ km^{-1}$ per person in 2050, decreasing to 87 $gCO_2\ km^{-1}$ per person by 2050. Therefore in 2050, 25% capacity CFBs would produce 65% the level of carbon emissions produced by 25% capacity CFVs.

The analyses indicate that if the usage of public transport remains low while using conventional fuel, full capacity cars produce less emissions per person than low capacity (25%) CFBs. However, as soon as public transport use (i.e. CFBs) increases to 50% then this is approximately equal to 100% capacity CFV usage (32.6 $gCO_2\ km^{-1}$ and 30 $gCO_2\ km^{-1}$ respectively). Given that this method does not include the embedded carbon costs related to personal CFV operation, it is likely that the true emission switch level is below 50% CFB capacity. Additionally, this assumes all cars are at maximum capacity which is unlikely, as the average occupancy rate for personal CFVs is 1.6 individuals per vehicle (DfT, 2019). Carbon emissions for this CFV capacity are significantly more than that of 25% CFBs. For a true reduction in the CO_2 emissions and for the UK to meet their emission targets, more individuals need to travel on buses over personal CFVs as this would enable less vehicles on the roads and an overall decrease in the $gCO_2\ km^{-1}$ per person.

3.2. Electric bus emissions from four national grid scenarios

The EBs scenario as seen in Fig. 2 demonstrates the potential level of emissions produced under the four National Grid electricity generation mixes for a vehicle at full capacity.

For EBs, all scenarios saw a decrease in the level of emissions produced if all urban buses were electric. The largest decrease in the level of emissions was under the two-degree scenario which saw a decrease of 91% of emissions between 2017 and 2050. The steady progression scenario, the most realistic scenario for renewable energy generation also saw a decrease of emissions by 78% by 2050.

Table 3
The projected emissions from CFBs and cCFVs between 2017 and 2050 in the UK in $MtCO_2$.

Transport type	2017 ($MtCO_2$)	2020 ($MtCO_2$)	2025 ($MtCO_2$)	2030 ($MtCO_2$)	2035 ($MtCO_2$)	2040 ($MtCO_2$)	2045 ($MtCO_2$)	2050 ($MtCO_2$)
Conventionally fuelled buses	7.52	7.57	7.63	7.64	7.61	7.59	7.58	7.54
Conventionally fuelled cars	41.8	41.5	40.8	39.8	38.6	37.3	36.0	34.5

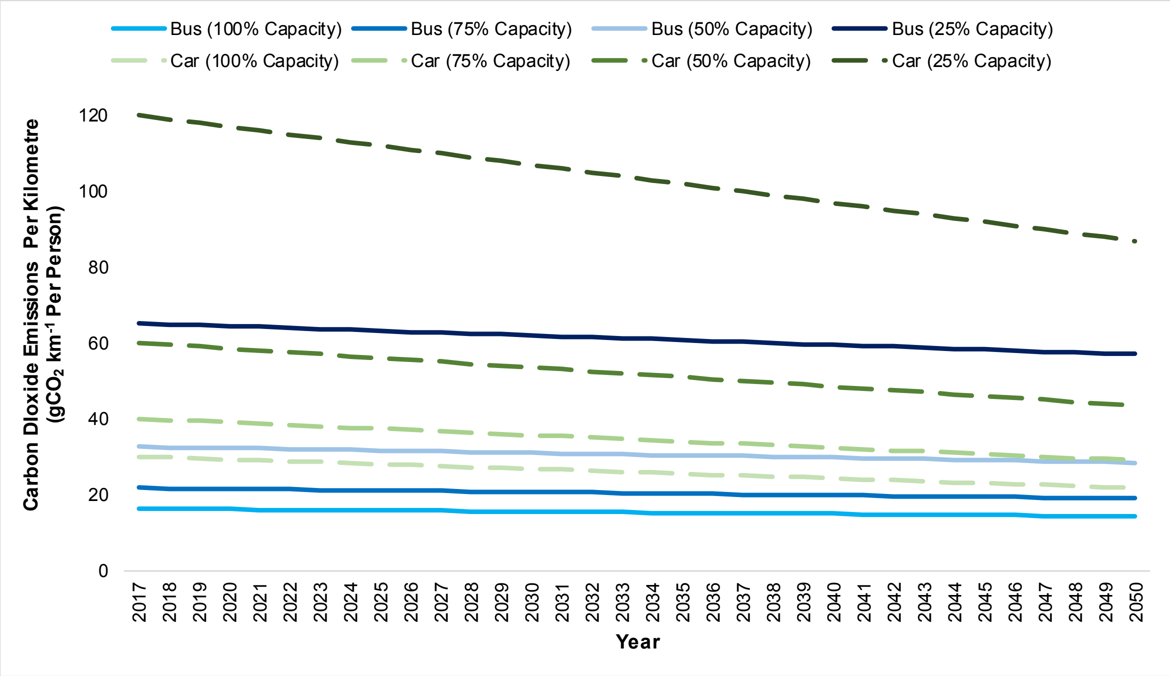


Fig. 1. Projected carbon dioxide operating emissions for 100%, 75%, 50% and 25% capacity for conventionally fuelled buses and conventionally fuelled vehicles in the UK between 2017 and 2050. The blue lines are conventionally fuelled buses and the green dashed lines are conventionally fuelled vehicles.

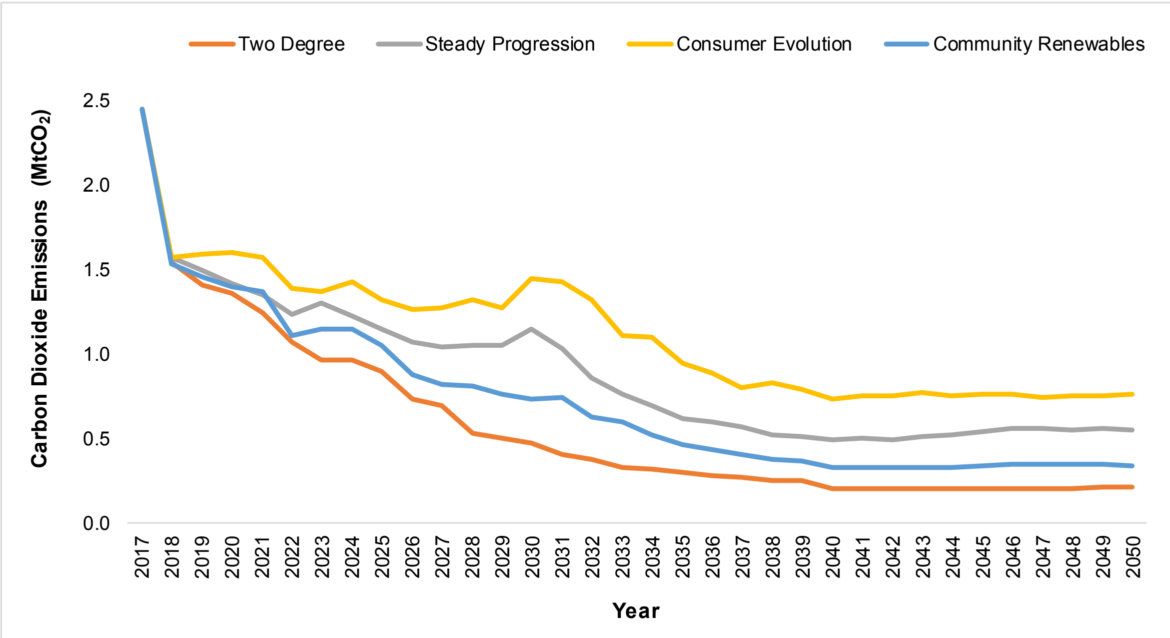


Fig. 2. Carbon dioxide emissions for electric buses using four different electricity generation mixes between 2017 and 2050 in the UK.

Under the consumer evolution scenario, emissions saw the lowest decrease by 69% by 2050. The community renewables scenario saw a decrease in the level of emissions by 86%. Under the best-case scenario (two-degrees) and worst-case scenario (consumer evolution) there is 0.5 $MtCO_2$ difference in emission levels. The worst-case EB scenario remains 6.8 $MtCO_2$ lower than the CFB productions, with CFBs producing around ten times more emissions in total in 2050.

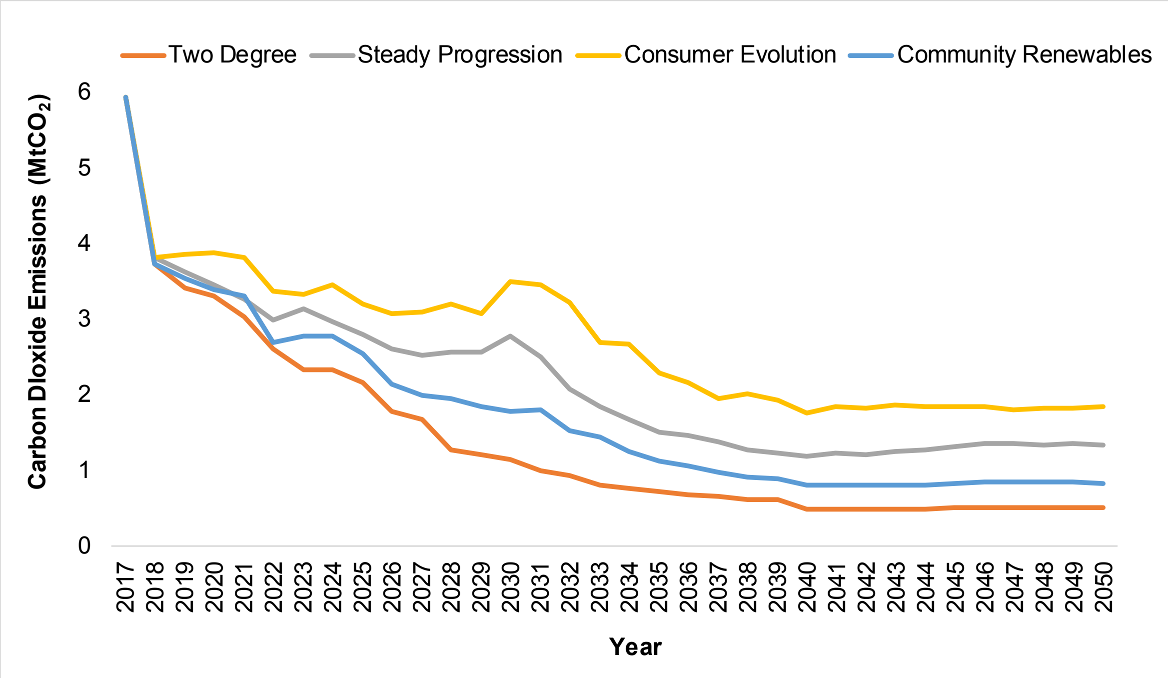


Fig. 3. Carbon dioxide emissions for hydrogen buses using four different electricity generation mixes between 2017 and 2050 in the UK.

3.3. Hydrogen bus emissions from four national grid scenarios

Fig. 3 demonstrates the projected CO_2 emissions from HBs under the four different National Grid scenarios. This analysis assumes that the hydrogen production process is electrolysis, thought to be the most environmentally friendly method. SMR and coal gasification are discussed below, however they could not be analysed the same way due to data constraints. Results indicate that the two-degree scenario will produce the lowest level of emissions for HBs. Between 2017 and 2050, the two-degree saw a decrease in the level of emissions 91%. Under the steady progression scenario, emissions decreased by 78% over the studied period, though the decrease was not linear and contained a secondary peak in 2030. The consumer evolution scenario saw the lowest decrease in emissions of 69%, with emission levels having a secondary peak in 2031 at 3.5 $MtCO_2$ before decreasing to 1.84 $MtCO_{2.}$ The community renewables scenario saw a decrease in the level of emissions 87%.

For HBs, under the best-case scenario (two-degrees) and worst-case scenario (consumer evolution) there is 1.3 $MtCO_2$ difference in emission levels. The worst-case scenario remains 5.7 $MtCO_2$ lower than the CFB productions, with CFBs producing around four times more emissions in total in 2050.

3.3.1. Emissions from different hydrogen generation methods

Using only the values for steam methane reformation and coal gasification with and without CCS in 2018 the projected levels of emissions can be seen in Table 4.

Results indicate the importance of CCS for HBs. Without CCS, emissions using steam methane reforming was 11 times higher and for coal gasification, emissions were 19 times higher. Therefore, if the UK wants to meet their net zero emission targets, the introduction of CCS is essential as the UK switches from non-renewable energy, as it will also hasten the decarbonisation of natural gas generation. Furthermore, comparing Table 4 with the results of hydrogen generation in section 3.3, under all electricity generation scenarios, emissions using electrolysis were lower in 2018 at 5.5 $MtCO_2$ without CCS than SMR or coal gasification. As a more advanced technology, electrolysis using CCS would produce 15 $gCO_2\ kWh^{-1}$ (CCC, 2018). This would result in emissions produced of 0.25 $MtCO_2$ in 2018. Therefore, although significant H_2 production for transport is not entirely feasible on such a large scale yet, electrolysis is the most environmentally friendly form of generation.

Table 4
Emission projections of producing hydrogen through SMR using natural gas and SMR using coal gasification with and without carbon capture and storage ($MtCO_2$) in 2018.

Technology type	Emissions without carbon capture and storage ($MtCO_2$)	Emissions with carbon capture and storage ($MtCO_2$)
Natural gas SMR	6.4	0.56
Coal gasification SMR	15.1	0.78

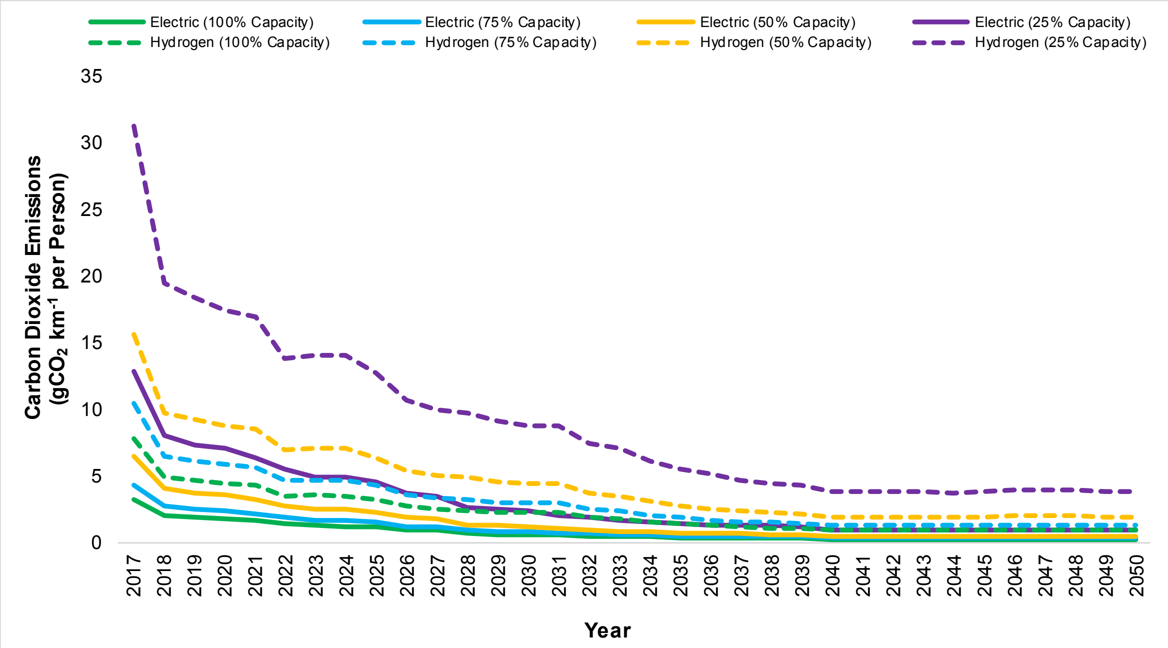


Fig. 4. Projected carbon dioxide emissions for 100%, 75%, 50% and 25% capacity for electric and hydrogen buses in the UK between 2017 and 2050 using the two-degree scenario ($gCO_2\ km^{-1}$ per person). The blue lines are electric buses and the green dashed lines are hydrogen buses.

3.4. Electric vs hydrogen buses

Comparing EBs and HBs will allow a better understanding of what bus types the UK should favour to decrease emissions and meet their net zero emission targets. Emissions from HBs in 2017 started 2.5 times higher at 5.9 $MtCO_2$ than those from EBs at 2.4 $MtCO_2$. Under the two-degree scenario by 2050, emissions from HBs were still 2.5 times higher at 0.5 $MtCO_2$ than those from EBs at 0.2 $MtCO_2$. Under the steady progression scenario by 2050, emissions from HBs were 2.7 times higher at 1.33 $MtCO_2$ than those from EBs at 0.5 $MtCO_2$. Under the consumer evolution scenario by 2050, emissions from HBs were 2.3 times higher at 1.84 $MtCO_2$ than those from EBs at 0.8 $MtCO_2$. Under the community renewables scenario by 2050, emissions from HBs were 2.8 times higher at 0.83 $MtCO_2$ than those from EBs at 0.3 $MtCO_2$. Overall results indicate that the level of emissions for EBs is much lower than those produced from HBs by 2050.

3.4.1. Electric vs hydrogen bus - emissions per person

To highlight and compare the level of emissions from public transport, Fig. 4 demonstrates the level of emissions per person at 100%, 75%, 50% and 25% capacity for EBs and HBs using the two-degree scenario data.

Results indicate that under the 25% capacity emissions from HBs are 31.2 $gCO_2\ km^{-1}$ per person, whereas for EBs emissions are almost three times lower at 12.8 $gCO_2\ km^{-1}$. Under 50% capacity, emissions from HBs were 15.6 $gCO_2\ km^{-1}$ per person with emissions from EBs at almost half this level producing 6.4 $gCO_2\ km^{-1}$ per person. For 75% capacity, HB produced 10.4 $gCO_2\ km^{-1}$ per person, with EBs producing 4.3 $gCO_2\ km^{-1}$ per person. For 100% capacity, HBs produced 7.8 $gCO_2\ km^{-1}$ per person compared to 3.2 $gCO_2\ km^{-1}$ per person for EBs. This highlights that the level of emissions produced per person remains lower for EBs under all capacity scenarios than any other transport type. Switching to EB directly from CFV/CFBs will therefore have the largest impact on emissions, rather than going through secondary options such as hydrogen powered vehicles.

3.5. 50% capacity for CFVs, CFBs, EBs and HBs

Using the two-degree scenario, at 50% passenger capacity, Fig. 5 demonstrates the total level of CO_2 emissions per passenger km for CFVs, CFBs, EBs and HBs. Results indicate that under this scenario, the $gCO_2\ km^{-1}$ per person for CFVs at 50% capacity are almost double that of HBs and six times that of EBs in 2017. CFB emissions remain relatively constant at 50% capacity within the time frame at almost half of CFV emissions in 2017. By 2050, even with technological improvements CFVs remain the highest operating emitting transport mode producing 55 times more emission than EBs and 14 times more emission than HBs. Therefore, results indicate that CFVs need to be phased out in favour of more sustainable transport options.

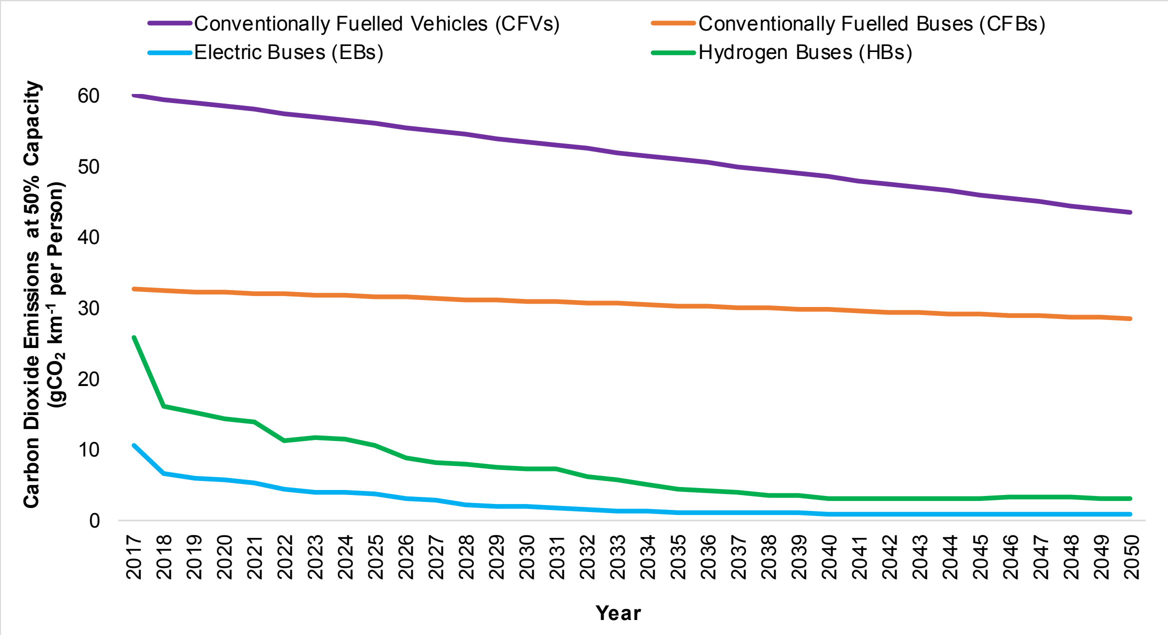


Fig. 5. Projected carbon dioxide emissions at 50% capacity for CFVs, CFBs, EBs and HBs in the UK between 2017 and 2050 using the two-degree scenario (gCO_2 km^{-1} per person).

3.6. Cumulative bus emissions vs cumulative CFV emissions vs cumulative EV emissions

Cumulative emissions from CFBs in the UK between 2017 and 2050 are calculated as 258.3 $MtCO_2$. Cumulative emissions of CFVs between the same time frame was 1315.7 $MtCO_2$. Table 5 demonstrates the cumulative emissions under each of the four National Grid electricity scenarios for EVs, EBs and HBs in the UK between 2017 and 2050. Results indicate that the cumulative emissions of EVs are substantially higher than for both bus types which is due to the higher number of EVs and distance travelled projected between 2017 and 2050. EB emission are almost half that of HBs under all four scenarios. This is to be expected as H_2 generation requires electricity to be converted to H_2 and back again and will therefore be less efficient than direct electric transport.

Overall EBs, followed by HBs, produce the lowest level of cumulative emissions between 2017 and 2050 under all electricity mix scenarios and should be integrated to reduce transport emissions. Cumulative emissions of CFVs and EVs remains high, therefore, demonstrating the need to move away from CFVs, even towards CFBs, whilst the infrastructure is built for more sustainable EBs and HBs.

3.7. gCO2 km^{-1} per person for CFVs, EVs, CFBs, HBs and EBs

By comparing the gCO_2 km^{-1} per person for CFVs, EVs, CFBs, HBs and EBs under the two-degree scenario and assuming 100% capacity, results indicate that emissions are lowest per person when using EBs in both 2017 and 2050. Therefore, switching to EVs as soon as possible has the potential to reduce GHG emissions substantially.

Results do not take into consideration life cycle emissions and assume that all electric modes of transport are electric from 2017, therefore although Table 6 indicates that EVs produce less gCO_2 km^{-1} per person than HBs in 2050, this remains unlikely as 100% EVs by 2050 is not likely achievable. A full breakdown of the different capacity levels for EVs can be seen in **Appendix C**.

Table 5
Cumulative emissions for EVs, EBs and HBs under the four national grid electricity generation mixes between 2017 and 2050 for the UK.

Transport type	**Scenario ($MtCO_2$)**			
	Two-degree	**Steady progression**	**Consumer evolution**	**Community renewables**
Electric vehicles	169.4	260.9	327.2	212.6
Electric buses	19.8	30.5	38.3	24.9
Hydrogen buses	48.1	74.1	92.9	60.3

Table 6
Point emission calculations for a CFV, EV, CFB, EB and HB under the two-degree national grid electricity generation predictions in 2017 and 2050 for the UK (gCO_2 km^{-1} per person, based on 100% capacity).

Transport Type	2017 (gCO_2 km^{-1})	2050 (gCO_2 km^{-1})
Conventionally Fuelled Vehicle	30.0	21.8
Electric Vehicle	15.0	1.1
Conventionally Fuelled Bus	16.3	14.2
Hydrogen Bus	12.9	1.6
Electric Bus	5.3	0.4

4. Discussion

Results from the analysis presented in this paper indicate that widespread utilisation of HBs or EBs will be required if the UK is going to meet national emission targets, as technological advances are not a strong enough mitigating factor for CFBs to meet targets and neither is a simple switch to personal EVs. Both HBs and EBs are expected to produce significantly lower levels of emissions compared to CFBs by 2050, however this is dependent on the energy generation method. If the energy sector is not decarbonised, then any environmental benefits will be diminished . Under all four electricity generation scenarios, emissions produced per person from EBs remained lower than HBs at all capacity levels. Furthermore, these values remained lower than the equivalent capacity values for CFBs, CFVs and EVs demonstrating that promotion of sustainable public transport is essential to reduce the UK's transport emissions.

This study has primarily looked at HBs and EBs in comparison to CFBs. This methodology uses a simple model, which is flexible and easily modified to allow comparisons to other countries. This helps inform policy makers by producing easily comparable results between generation mix options and countries as well as identifying key areas for potential improvements within the transport network. One potential issue that may arise is the cost of competing energy systems, for example SMR generation is still a cheaper method to generate H_2 than electrolysis, as there is currently not the infrastructure to do electrolysis on a large scale. There is therefore a need for technological innovation to help drive emission reduction, though in real terms emissions will peak before decreasing.

However, for widespread integration of either HBs or EBs, several factors will need to be overcome. Firstly, cost. HBs and EBs have reached a high level of technical maturity in recent years, however, they are not currently in large scale production, with current production and operating costs leaving them significantly more expensive than CFBs. Currently HBs cost around one million euros per bus, a standard EB costs 450,000 euros compared to a standard CFBs of 250,000 euros (Hydrogen Europe, 2017). The additional costs are due to the electric mechanisms, for example, the battery package, electric motor and auxiliary system, but above all lack of mass production (Feng and Figliozzi, 2013; Mahmoud et al., 2016). This cost differential will reduce as the technology becomes commonly used. Large scale introduction of HBs and EBs in the UK will require significant investment and policy makers must be confident that they will be fully utilized by the public. This is a 'chicken and egg' scenario as although small commercial scale production of EBs and HBs allows gradual introduction to the UK bus fleet, future development may be dependent upon occupancy and cost. As EBs and HBs are more expensive to purchase than CFBs and further infrastructure will need to be built to power these vehicles. Bus operating costs per person are likely to be higher, unless fares subsidies are implemented, which could result in fewer passengers. To reduce total costs, more individuals will need to use the bus system, however it is unlikely consumers will do this if faced with higher fares and choose cheaper, unsustainable transport options. In addition to this, additional infrastructure, including refuelling stations for HBs, will need to be built around bus networks. This will reduce supply inefficiencies and was the assumed generation approach used in the methodology, assuming localised generation and minimal transmission and distribution losses.

Secondly, to decrease costs of electricity generation for both EBs and HBs and to maximise renewable energy generation, electricity should be stored or converted to H_2 during non-peak times. However, although cost will be low, there currently isn't the technology to store the volumes of energy required for these vehicles on a large scale. It is assumed that most HBs and EBs will be fuelled during the early hours of the morning, therefore there will be an increased peak in network energy demand which may require energy storage to ensure network stability. Building in network capacity can be achieved either at fewer, larger sites situated throughout the country or through many, small capacity locations within communities, depending on technology.

Thirdly, although electricity and H_2 are generally accepted in the UK as a fuel source, encouraging the use of public transport over private cars (both CFVs and EV's), remains a critical issue. Through comparison of kWh km^{-1}, HBs use 1.8 kWh km^{-1}, EBs use 1.2 kWh km^{-1}, whereas EVs use 0.17 kWh km^{-1}. So, if an HB has more than 10 passengers and an EB has more than 7, the bus has less emissions than a full electric car. Use and attraction of public transport could also be enhanced with shared smaller capacity vehicles on low trafficked routes. In addition, lithium costs required by EVs and EB's are inversely proportional in terms of emissions, therefore larger capacity EBs and HBs produce lower emissions than the equivalent total power level EV's (Ellingsen et al., 2014). This work focussed on the evaluation of emissions for various HB or EB capacities. Although not discussed in detail in this paper, operating emissions for personal transport were also considered during this study. Personal CFVs have been shown in previous work by Department for Transport tend to have a comparatively low occupancy rate (1.6 passengers per vehicle) than the occupancy required for personal transport emissions (121.5 gCO_2/passenger/km for new diesel cars and 123.4 gCO_2/passenger/km for new petrol vehicles (EEA, 2019)) to be lower than EB emissions (0.4 – 1.6 gCO_2/passenger/km) in any capacity scenario. EV were also calculated using the two-degree scenario data and the breakdown over the four different capacity levels can be seen in **Appendix C**. Similarly, to CFVs, personal EV transport will always result in a greater level of emissions than if consumers utilise the bus transport network provided. This therefore further highlights the importance of switching away from private vehicle use and switching towards sustainable public transport.

The transition of how we switch to more sustainable transport also needs to be considered. There needs to be a shift towards public transport, including CFBs, whilst the infrastructure is built for more environmentally sustainable transport networks which will likely include personal EV's alongside a more effective public transport network including EBs and HBs. Without a modal shift towards public transport, the UK will be unlikely to meet their net zero emissions target. Central to this is the perceived standard of public transport networks across the UK. Improvements to the bus and rail network can incentivize the public to favour regular usage over short and long distance CFVs and EVs as this is the best way to decarbonize transport. To do this, the introduction of TDM initiatives may be required, including both push and pull measures. For example, encouraging commuters to use park and ride systems by having free parking out with city centres with reduced fare prices and having an integrated rail and bus transport system. This could work alongside the introduction of congestion charges similar to those in London where CFVs that produce high levels of emissions are being penalized by paying a congestion charge to enter certain areas in addition to lower access pricing for EVs with public transport such as HBs and EBs paying no charge. The plethora of push pull measures implemented in London have weaned people out of their cars and onto the buses very successfully and should be applied country wide.

Decarbonisation of the transport sector through increased utilisation of low-carbon public transport will face challenges which change across geographic and temporal scales. More rural areas and smaller towns and villages likely rely more heavily on personal transportation due to restricted public transport availability due to geographical location and cost of provision. Due to varying needs of users, developing a public transport network that caters for the majority of needs from rural areas will be more costly in financial terms than meeting the equivalent demand in more densely populated areas. Cost is mentioned here in terms of financial cost for the development and operation of the network. In rural areas, if transport modality can be changed from individual to public transport with a more integrated system, overall volumes of traffic will decrease so less road investment infrastructure is required, however changes to renewable energy and its distribution structure may be required to power the EBs and HBs. Higher density urban areas will allow the integration of mass transit and buses to be more effective however, land use again becomes an issue, with the infrastructure developments needed to allow for an integrated transport network system linking different travel modes i.e. active travel to buses to trains etc.

In terms of the energy network and energy provision, limitations of the practical application of a low-carbon public transport network will occur and are not solely linked to population size and density. Deep rural areas are often closer to naturally occurring resources utilised by wind, wave and tidal energy developments. This means that while the overall integrated transport network may be more difficult to implement in rural areas, the supply of local clean energy as fuel, either directly as electricity or via hydrogen production, may be more easily implemented. An example of this is the 'Surf and Turf' programme currently in place in the Orkney Islands, where the excess energy produced from a tidal energy testing site is used to produce hydrogen for HB transport links on the islands with future targets set on the introduction of hydrogen powered ferries. This is an example of how geographic location can be used to an advantage when implementing the required transport networks. It's an important factor to be considered by regional and national policy makers and planners since when developing new towns and expanding cities, space should be allocated for clean energy generation capacity, for example mandating rooftop solar generation on buildings, without assumptions being made that the required energy will be met by capacity elsewhere. Taking this approach would involve co-ordination of policy across sectors, however if done properly would enable more effective progress towards meeting the carbon emission targets set out in law.

Finally, for electricity to be produced for EBs and HBs, incorporation of CCS is necessary as although it will not directly influence operating emissions, CCS will help to mitigate some of the emissions produced from fossil electricity generation that provide dispatchable power when renewable generation is low. Careful consideration of how the energy used to power EVs, EBs and HBs is essential to keep emission levels as low as practical. If HBs are to be more widely utilised, then the preferred method of hydrogen generation would be electrolysis using renewable energy technologies as this is a more sustainable method of H_2 generation and can use excess renewable electricity in lieu of shutting down wind generators as is now the case. If H_2 is going to continue to be generated from SMR using natural gas, then emission levels will remain high. SMR is currently the easiest and most cost-effective method, however without CCS implementation the positive effects on dropping emissions would be dampened by the GHG emissions of SMR, furthering the likelihood of the UK missing its emissions targets of net zero.

5. Conclusion

Results from this study, particularly in Fig. 5, indicate that if the UK is to meet its emission targets, the travelling public need to move away from individual transport towards sustainable public transport. Emissions at 50% capacity demonstrate that CFVs produce the highest level of emissions in $gCO_2\ km^{-1}$ per person, followed by EVs, then all bus types, however, emissions can only truly be reduced if the UK public are opting for buses instead of private vehicles. Push and pull TDM measures need to be implemented at a local and national level for policy makers to encourage the uptake of public transport and move away from private vehicles to decrease emissions. The success of the push and pull measures implemented in London to decrease car and increase bus use should be replicated country wide. Other measures for smaller towns including park and ride systems in conjunction with bus only zones within urban centres could be used. However, significant investment by the UK government and local authorities will need to be made for the infrastructure required for widespread integration of EBs and HBs into the mass transit system and to apply the TDM measures.

Our results indicate that the level of emissions produced from CFBs, HBs and EBs are much lower per person than from CFVs and EVs. If proportionally more individuals chose to commute by bus, then total transport emissions would be reduced. From our study, we conclude that EBs produce the lowest level of emission from the three bus types studied and should be more widely integrated into the public transport fleet. Due to current technological advancements, EBs are more suited to shorter routes within cities such as London where as HBs have a larger range and may be suited to longer distances between cities and rural services. Therefore, integrating both bus types in favour of CFVs, EVs and CFBs would be more beneficial if the UK wants to meet their net zero targets. This, however, is dependent upon how the electricity is generated and stored. With a higher renewable and nuclear energy percentage, the total level of operation emissions would be lower. HBs can be fuelled through electrolysis using excess renewable energy and with H_2 generation from SMR using natural gas combined with CCS for low emissions.

As technology currently isn't in place for 100% renewable electricity generation and gas generation will be required as dispatchable power, CCS is required to reduce emissions as far as possible whilst infrastructure is being implemented to achieve complete decarbonisation of electricity generation.

Acknowledgements

This research was carried out under the UK Energy Research Centre (UKERC) as part of the ADdressing Valuation of Energy and Nature Together (ADVENT) funded project. Funding was received from the Natural Environment Research Council (NE/M019691/1), United Kingdom and the School of Biological Sciences, University of Aberdeen, United Kingdom.

The authors would also like to thank Dr Christian Brand, University of Oxford, for giving them access to the Transport Energy and Air Pollution Model UK (TEAM - UK).

Appendix A. The total number of buses (minibus, urban buses and coaches) and distance travelled by urban buses annually per bus between 2017 and 2050 in the UK (Source: Brand et al., 2019)

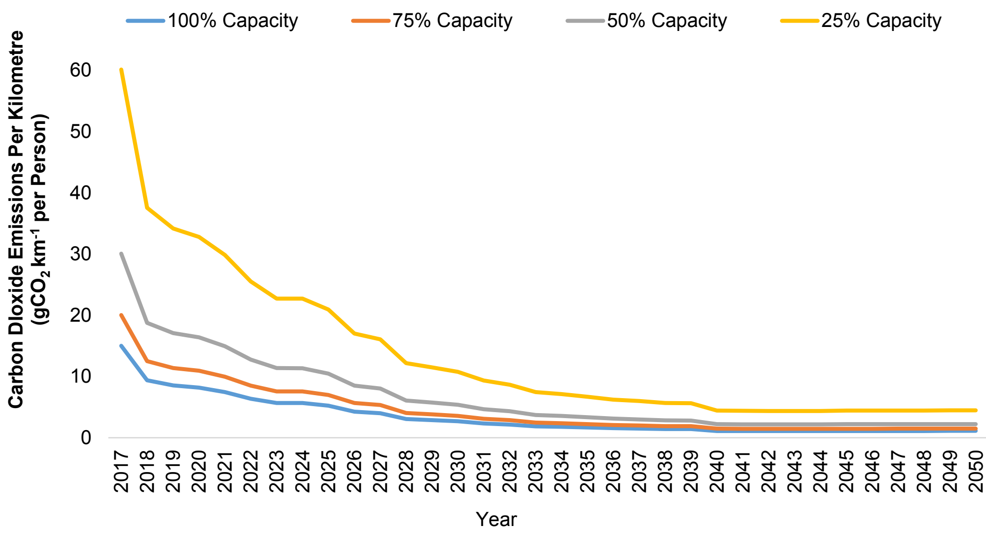
Year	Total Number of Buses	Total Distance Travelled Annually for urban buses (km)
2017	141,365	40,791
2018	142,444	40,740
2019	143,746	40,610
2020	145,271	40,425
2021	146913	40,206
2022	148617	39,969
2023	150348	39,737
2024	151,961	39,531
2025	153,370	39,373
2026	154,506	39,270
2027	155,440	39,215
2028	156,160	39,191
2029	156,822	39,182
2030	157,427	39,177
2031	157,962	39,173
2032	158,516	39,170
2033	159,056	39,168
2034	159,594	39,167
2035	160,126	39,167
2036	160,697	39,169
2037	161,254	39,170
2038	161,810	39,174
2039	162,396	39,178
2040	163,008	39,184
2041	163,644	39,190
2042	164,288	39,197
2043	164,922	39,203
2044	165,544	39,209
2045	166,121	39,213
2046	166,671	392,15
2047	167,222	39,218
2048	167,765	39,220
2049	168,302	39,222
2050	168,836	39,224

Appendix B. The carbon intensity of the electricity generation mix under the four UK National Grid scenarios between 2017 and 2050 (Source: National Grid, 2018)

Year	CO_2 Intensity of Generation ($gCO_2\ kWh^{-1}$)			
	Two Degree	Steady Progression	Consumer Evolution	Community Renewables
2017	266.0	266.0	266.0	266.0

2018	166.1	169.9	169.6	165.7
2019	151.2	160.6	170.4	156.6
2020	145.1	151.5	170.4	148.8
2021	132.1	143.0	166.5	144.7
2022	112.9	129.7	146.7	117.3
2023	100.6	136	143.6	119.8
2024	100.5	127.2	148.3	119.4
2025	92.7	119.2	137.1	108.6
2026	75.3	110.9	130.8	91.0
2027	71.1	106.6	131.0	84.6
2028	53.9	107.8	134.9	82.5
2029	50.8	107.3	129.4	77.2
2030	47.6	116.6	146.5	74.8
2031	41.3	104.1	144.2	74.7
2032	38.3	86.4	133.7	63.4
2033	33.0	76.5	111.5	59.7
2034	31.5	69.5	110.1	51.8
2035	29.6	62.1	93.9	46.5
2036	27.6	59.9	88.3	43.3
2037	26.6	56.0	79.6	40.1
2038	25.2	51.4	82.1	37.3
2039	25.0	49.9	78.1	36.2
2040	19.7	48.2	71.4	32.1
2041	19.5	49.4	73.8	32.3
2042	19.4	48.3	72.7	32.2
2043	19.3	49.5	74.5	32.2
2044	19.3	50.4	73.0	31.6
2045	19.6	52.0	72.9	32.4
2046	19.6	53.7	73.0	33.2
2047	19.7	53.4	70.6	33.2
2048	19.7	52.6	71.4	33.1
2049	19.8	53.3	71.0	32.7
2050	19.8	51.8	71.6	32.2

Appendix C. Projected carbon dioxide emissions for 100%, 75%, 50% and 25% capacity for electric vehicles in the UK between 2017 and 2050



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