# Comparative evaluation of battery electric and hydrogen fuel cell electric vehicles for zero carbon emissions road vehicle fuel in Scotland.

J. M. Low*~, R S Haszeldine **~, J Mouli-Castillo***~

July 2020

Date last saved: 16/07/2020 15:13

## Abstract

Decarbonisation of road transport is essential in a Net-Zero transition. Currently neither hydrogen nor electricity are inevitable. Is electrification the single obvious solution, or is a combination with hydrogen more functional and cost-effective? Scotland makes a good exemplar of transport Transition, with a defined geography, a world leading Net-Zero ambition, and proven pathways for generating large amounts of renewable energy.

We identified essential elements of the new transport systems, including CapEx and OpEx and emissions through transition. We developed five scenarios modelled for transition around varying the pace of change for some or all vehicle classes. Monte Carlo simulations investigated the emissions, vehicle mixes, construction speed, and costs.

CapEx to install generation and refuelling infrastructure for electricity or for hydrogen favours hydrogen by a substantial margin, with multi £Bn cost-reductions. Untaxed OpEx costs favour electricity, such that whole system costs are broadly similar for any mix, although untaxed per-km fuel costs for either should be lower than hydrocarbons. User experience, energy storage, vehicle characteristics, social factors, use of natural resources – almost all favour increased hydrogen use. Hydrogen interseasonal storage at national scale is feasible in salt caverns, with re-purposing of the transmission pipeline grid, and huge scale-up of generation; interseasonal electricity storage does not exist at national scale, and significant electrification penetration requires immense infrastructure upgrades.

A no regrets action is the rapid deployment of hydrogen infrastructure for buses, trucks and large fleets, with enough to facilitate hydrogen car ownership. Jobs could be created and maintained locally in hydrogen manufacturing, installation and servicing.

* Corresponding: john.low@ed.ac.uk
Orcid. https://orcid.org/0000-0001-6220-4736

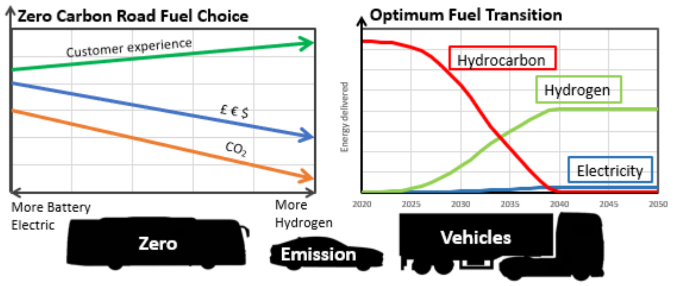
** Orcid. https://orcid.org/0000-0002-7015-8394

*** Orcid. https://orcid.org/0000-0003-0811-6780

~School of GeoSciences, University of Edinburgh, EH9 3FE, Scotland, UK

## Broader Context

For the world to reach Net-Zero greenhouse emissions, it will be necessary to essentially eliminate road transport emissions. In our example study of Scotland, road transport currently accounts for ~25% of greenhouse emissions. The primary technology for this to date has been electricity, stored in batteries; this has captured around 2% of the new vehicle market. However, this technology has many disadvantages limiting its widespread growth including immense expense on infrastructure. Large and commercial vehicles generally require rapid refuelling, all-day range, small on-board fuel storage mass and low fuel cost - all also desirable in cars. Batteries to supply all existing vehicles in the world using current technology require more Cobalt and Lithium than is available in known reserves. These factors favour "hydrogen as the new diesel" over electrification. We built a comprehensive model, focussed on Scotland, comparing electricity and hydrogen in five scenarios of cost and timing. We show that capital cost and emissions through transition greatly favour hydrogen, while untaxed fuel cost favours electricity. Combined costs come out even at any mix proportion of the two. We recommend a pathway for a substantial deployment of hydrogen fuel for commercial vehicles and a seed network for cars and similar.




Modelled analysis of optimum share of Zero Emissions fuel, considering hydrogen and battery electricity. Assessing costs, emissions and non-quantifiable factors.

# Introduction

Decarbonisation of road transport will be essential for the world to meet its needed reductions in emissions. The main technological solution used and planned to date is electricity, stored in batteries on board vehicles. There are several limitations to this, which we discuss in this paper.

The most promising zero carbon alternative to battery electric vehicles (BEV) is hydrogen fuel cell electric vehicles (FCEV), which appear to address almost all of the practical shortcomings of BEVs.

The aim of this research is to identify the optimum combination of hydrogen and electricity in use as road vehicle fuels, based on a combination of cost, transition emissions, and non-quantifiable 'soft' factors.

We have chosen Scotland as an example for analysis for two primary reasons –

- The Scottish Government's commitment to unusually demanding targets for early decarbonisation, with an all-sector reduction of 75% from 1990 levels to be achieved by 2030, followed by net zero by 2045[1].
- Scotland's current, planned and potential high level of renewable electricity means that we can be confidently & realistically expect that both electricity and hydrogen could be produced through carbon free means. This is backed up by local natural gas sources, which may also be used to produce hydrogen.

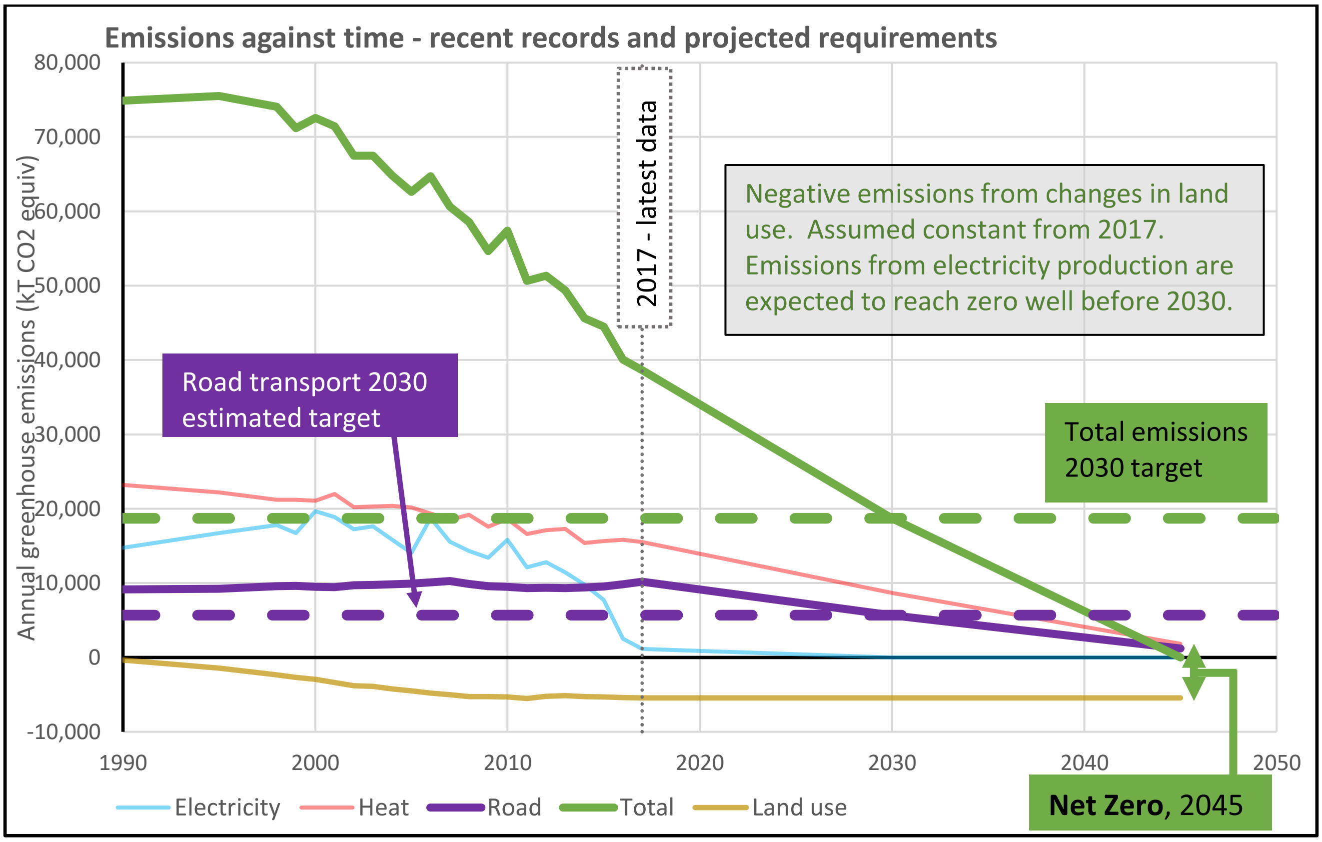



*Figure 1 Scottish emissions targets, showing overall government targets, road transport estimated target for 2030, and energy related emissions history and required trajectories to achieve ultimate net zero target. Non-energy emissions not shown but accounted for in the net-zero calculated end points.*

Figure 1 shows these targets in the context of the recent emissions records and the primary energy related emissions sources.

This shows a required reduction of approximately 44% in road transport emissions by 2030 and 88% by 2045, compared to current levels. (See supplementary publication for further details).

Until recently, most Scottish governmental plans and public perception has been that, in order to deliver these targets, the widespread use of Battery Electric Vehicles (BEVs) will be required. For example:

- Scottish Government – free to use public electric charging points, interest free loans for purchase of zero emissions or plug in hybrid vehicles [2, 3]
- European Union – vehicle emissions targets are set such that cars and vans (which could be decarbonised using BEV technology) are required to reach levels that will require zero emissions vehicles fairly quickly, while targets for larger vehicles, e.g. buses and heavy goods vehicles (which for practical intents and purposes could not be widely decarbonised as BEVs) are set to allow increased efficiency diesel engines[4].
- "Electrify Everything"[5]
- Scottish Power 'Zero Carbon Communities' setting out all-electrified future[6].

Also, anecdotally, electrification is all that people in general seem to be aware of.

However, take up to date is slow, with only 11,000 (<0.4%) out of Scotland's approximately 3 million road vehicles being BEVs[7]; current market share is approximately 1.6% of new vehicle sales[8]. With a service life of around 14 years for cars and 10 years for HGVs, that is not even close to the required pathway.

Several factors have been proposed for this, including:

- Limited availability of batteries to manufacturers
- Range anxiety
- Slow refuelling time
- Unfamiliar use pattern
- High purchase price of vehicles

An alternative zero emissions technology is to use hydrogen, usually in a Fuel Cell Electric Vehicle (FCEV) but also, rarely, in internal combustion engines. A few manufacturers have released FCEVs on the market in the UK and/or other markets – cars and buses are both available, and heavy goods vehicles are in development[9-11].

The use of hydrogen FCEV, illustrated in Supplementary Figure 2, can overcome all of these issues with BEVs –

- Far less battery capacity is needed – a small one of around 1kWh is used to recapture energy from regenerative braking.

- Hydrogen systems weigh considerably less than battery ones, so more fuel can be taken on board providing for longer range between refuelling / recharging. The weight of the fuel itself is negligible. The volume required for storage is a significant issue.
- Refuelling with hydrogen, in the form of pressurised gas recharging the on-board tank, is similar to the way in which hydrocarbon fuels are used, and it also takes just a few minutes. This also reduces range anxiety, in that the time needed to refuel will not make a significant difference to journey time.
- At large production volumes, FCEVs should end up cheaper than even internal combustion engines, because of the inherent simplicity of a fuel cell (which has no moving parts). Batteries are likely to remain expensive because of the quantity of rare raw materials needed to produce them[12], unlike fuel cells which are primarily common materials with only a very small amount of platinum catalyst – comparable to a hydrocarbon vehicle's catalytic convertor.

The two primary disadvantages of hydrogen are (1) hydrogen requires a considerably larger fuel tank than petrol or diesel for the same range, and (2) there is currently a lack of refuelling infrastructure. Unlike a BEV, an FCEV cannot be recharged at home and requires a refuelling station in the same way as petrol or diesel.

In this paper we present the results of modelling and related investigations into:

- The place that hydrogen vehicles should hold in the decarbonisation of road transport
- The effects of different strategies and prioritisations for roll out.
- Whole system costs to implement the transition.

The key metrics we use are related to emissions, cost, and practicality of implementation.

We conclude with recommendations of the optimum pathway to deliver zero carbon road transport in Scotland, and the appropriate steps to deliver it.

This research should also be generally transferable to other areas of the world, although local factors including typical vehicle life, annual distance travelled per vehicle, and local emissions from the production of hydrogen and generation of electricity will all be significant.

## Hydrogen as a fuel

The element Hydrogen is the most common in the universe and, more relevantly, the 10th most common on earth by mass[13]. Hydrogen does not occur in significant quantities in nature in its pure form; it is invariably bound in a more complex molecule – the most common being water and methane – from which it must be separated to use. A number of different processes can be used for this, described in section 0 below.

When used a fuel, hydrogen produces no carbon dioxide or other greenhouse gas emissions. It is most commonly used in fuel cells, which make electricity which is then used to power electric motors driving the vehicle at around 50% overall efficiency. The only by-product of its use water[14].

It is also possible to burn hydrogen in an internal combustion engine, at around 25% efficiency, either co-combusted with diesel (conversions are commercially available now from Ulemco) or as 100% hydrogen (understood to be in development). Hydrogen combustion can create NOx depending on fuel-air mix and combustion temperature[15]. This may have useful applications in the transition phase away from petrol & diesel, especially if existing vehicles can be practically converted. However, we expect this to be a fairly niche application in the longer run, and we have not developed it further in this paper.

Hydrogen is likely to compete as a transport fuel with battery stored electricity in BEVs, although – as currently with petrol and diesel – there are pros and cons to each, and we can expect that there will be a need and a place in the market for both.

Some important characteristics of hydrogen are set out in table 1:

| | Specific Energy (kWh/kg) | Density ($kg/m^3$) |
|---|---|---|
| Hydrogen at 700 bar | 33.0[16] | 39[16] |
| Petrol | 12.8[16] | 715-780[17] |
| Diesel | 12.6[16] | 820-845[17] |
| Li-ion batteries | 0.125[18] | 2250-2500[19] |

*Table 1 Specific energy and density values for various potential vehicle fuels. Lower Heating Value is used – this assumes that heat generated in the process cannot be recovered.*

These characteristics have real world practical consequences:

- High specific energy, i.e. energy per unit mass. This means that a hydrogen system will be considerably lighter than one using batteries. For a typical family car, the hydrogen vehicle would weigh approximately 500kg less than an equivalent battery fuelled vehicle, or about the same as a petrol/diesel powered vehicle[9, 20]. This weight saving would translate in actual use to permit lower powered engines and lower fuel consumption. It would also reduce wear on brakes and tyres, responsible for a significant amount of urban particulate emissions, and on road surfaces[21].
- Low density i.e. mass per unit volume. Even at the high pressures (700 bar) used in road vehicles, the density of compressed hydrogen is only around 39 $kg/m^3$, about

one-twentieth that of petrol, increasing the size of the fuel tank required (see calculations within the model, accessed through the supplementary publication).

Taken together, these two factors mean that a hydrogen powered vehicle will weigh about the same as a petrol / diesel vehicle, but will require a fuel tank approximately 4x or 6x as big as for petrol or diesel respectively, to get a comparable range.

For a battery vehicle, the battery would be larger than a petrol or diesel tank, but slightly smaller than a comparable hydrogen fuel tank, and would be considerably heavier than either.  The trade-off between these usually means a reduced luggage space for an FCEV compare to a similar sized hydrocarbon vehicle, and extra weight but a smaller reduction in space for a BEV.  Comparison of similar vehicles from the same manufacturer (Mercedes Benz) illustrates this:

| Model | Fuel type | Boot capacity | Weight | Range |
|---|---|---|---|---|
| GLC 220d | Diesel | 550 litres | 1950 kg | 440 miles / 700km |
| GLC F-Cell | Hydrogen | 400 litres | 2055 kg | 300 miles / 480km |
| EQ-C | Battery | 500 litres | 2425 kg | 190-250 mi/3-400km (weather dependent) |

*Table 2 Characteristics of similar vehicles with different fuel systems. Note that the GLC F-cell also contains a 13.5 kWh battery, uniquely in a hydrogen car, which negatively affects the boot & weight. EQ-C battery is 80 kWh).* [9, 22-24].

The upshot of this is that hydrogen lends itself more to larger and longer range vehicles, especially those harder to decarbonise such as HGVs[25].  BEVs are more likely to suit smaller, short range vehicles.  The overlap between the two is likely to be around family cars and small vans – in many ways similar to that between diesel and petrol (Illustrated in Supplementary Figure 3).

# Methods

We planned to analyse the situation in order to:

- Understand the rate of Zero Emissions Vehicle (ZEV) sales needed, and how that should develop.
- Understand the infrastructure and associated costs to support those sales.
- Identify the optimum roles that BEV and FCEV should play from the point of view of cost and emissions reduction.
- Understand the effects of different strategies for rolling out ZEVs and associated infrastructure.
- Understand the factors affecting the rate of implementation and other non-quantifiable factors of FCEVs compared to BEVs.

## Modelling

We carried out a predictive modelling assessment examining the likely impact, cost and implementability of various ways of reaching the targets in respect of road transport, over the period 2020 to 2050.

We created (1) a base case where zero emission vehicles (ZEV) are deployed at the same rate, the rate being chosen to meet the 2030 and 2045 targets.

We also considered four comparison assessments –

(2) More Trucks, Same Cars - Accelerated deployment of larger vehicles (buses and heavy goods vehicles). As zero emissions heavy goods vehicles are not expected to be commercially available until 2022/23, the deployment of those is delayed in the model until 2023.
(3) More Trucks, Fewer Cars – Accelerated deployment of larger vehicles as in (2), but deployment of ZEV cars and vans slowed down so that the 2030 emissions target is only just met.
(4) Laid back – an easier to achieve rate that would meet the 2045 target but not necessarily the 2030 target.
(5) Foot to the Floor - a very fast acceleration of all zero emission vehicle sales.

These additional comparisons were all simulated by varying the inputs of the gradient constant (k) and the sales transition mid-point (xo) in the logistic function used in step 2 of the model (vehicle sales generation), described below and in the supplementary publication.

We built a model using Microsoft Excel, with a basic structure as illustrated in Figure 2:

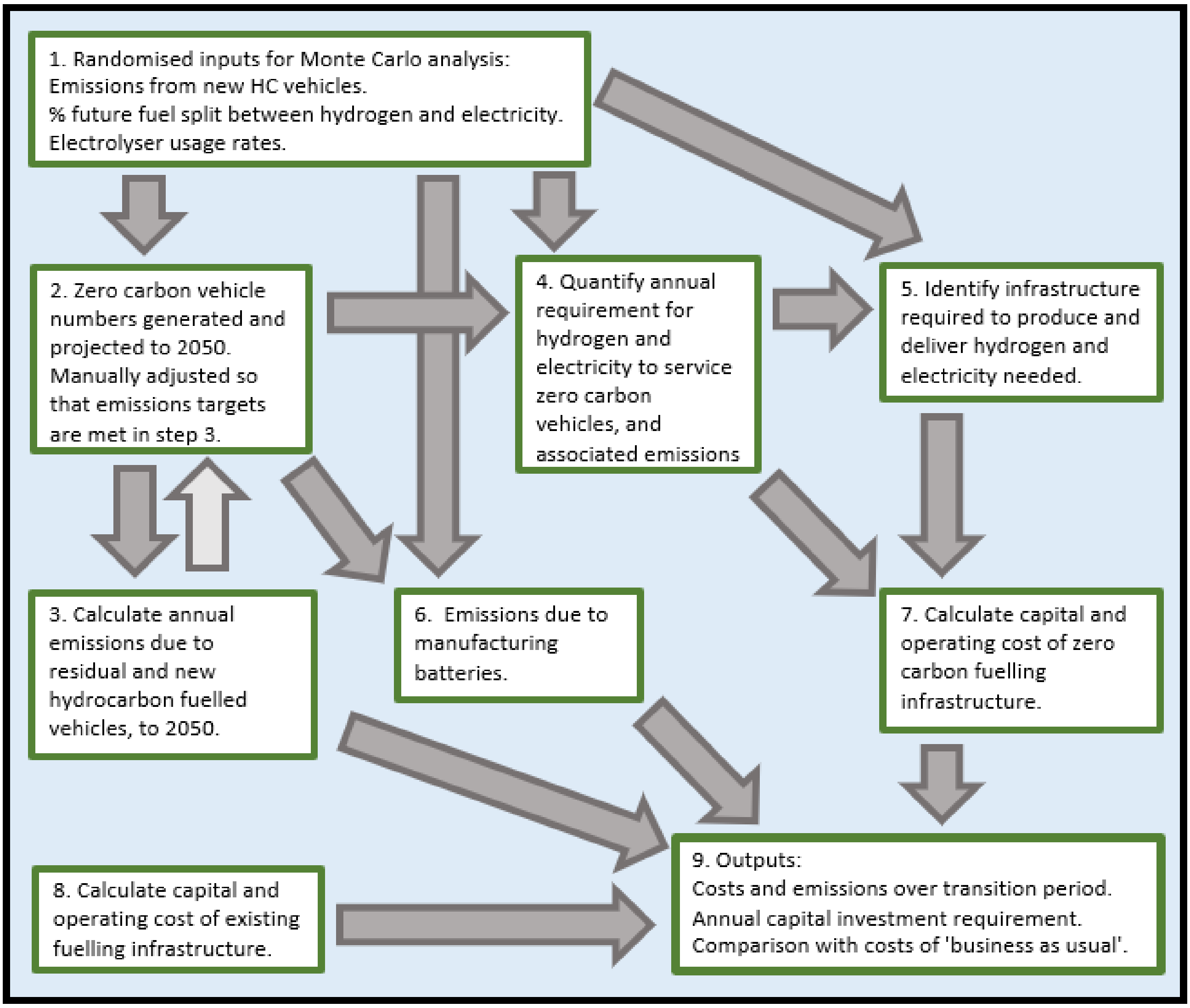



*Figure 2 Schematic of model created to analyse required fuels to meet emissions targets.*

A more detailed description of each step, together with a link to a reviewable online version of the model, is presented in the supplementary publication. Key underlying assumptions are set out below:

- The total number of vehicles in each class will be constant. In fact in recent years there has been a gradual upwards trend in vehicle numbers following a dip from 2008[7], which we attribute to the effects of the global recession at that time. For this assumption to hold, there will therefore require to be some management of demand for new vehicles.
- Annual new vehicle sales will be constant at current levels, and gradually all will become zero emissions vehicles.
- No new hydrocarbon cars or light goods vehicles will be sold after 2032, in accordance with Scottish Government policy to remove the need for these by that date. Note that this is not expressed as ban[1].
- Vehicles of each class continue to be scrapped at the same average age as at present.

Costs and other quantifiable assumptions are presented in the supplementary publication.

## Desk based research

We also examined the factors that could not be readily quantified adequately within our model, but are likely to have a bearing on the ease of implementation.  We introduce the implications of these in the Discussion.

We carried out desk-based research supplemented with discussions with a number of experienced people in relevant industries – fuelling operation, vehicle manufacturing, hydrogen fuelling systems manufacture.  We examined academic publications, published information from manufacturers, and grey literature sources such as Scottish, EU and UK government departments and agencies.

We examined the key issues limiting the development of BEV growth, and other issues than need to be addressed with the use of BEVs.  We investigated the characteristics of hydrogen FCEVs in relation to these issues, and considered where BEVs might retain some benefits.

# Modelling Results

## New vehicles and associated emissions (Base Case)

We started out examining the Base Case for the numbers of new Zero Emissions Vehicles (ZEV), either BEV or FCEV, that would be required to deliver the necessary emissions displacement.

Assuming roll out of ZEVs in all vehicle classes at an equal rate (see Figure 6), the required development of zero emission vehicle numbers to achieve the 2030 target is illustrated below in Figure 3:

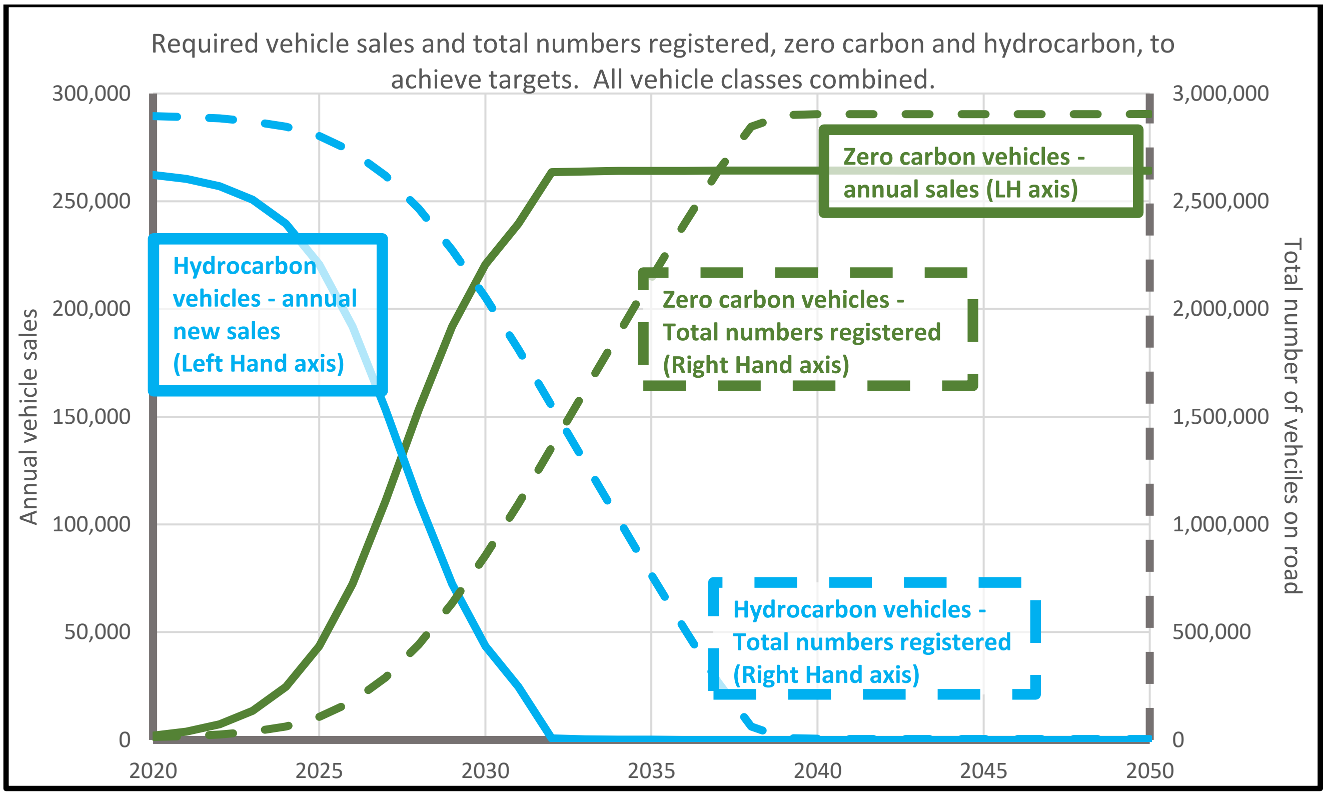



*Figure 3 Total new zero carbon and hydrocarbon vehicle sales required to meet emissions targets, shown with the changing total numbers of zero carbon and hydrocarbon vehicles registered. The apparent misalignment at 2032 reflects the desire to end hydrocarbon car sales by that date.*

As can be seen in Figure 3, by 2025, approximately 17% of new vehicles in this scenario will have to be zero emissions vehicles. By 2028, this will be 50%.

However, the overall numbers are dominated by passenger cars, while larger vehicles such as buses and HGVs are present in much smaller numbers – around 2% of the total - but represent around 21% of all road vehicle emissions[7]. The above total new zero emission vehicle numbers can be broken down by class (shown in Supplementary Figure 4), where it can be seen that the rate of new zero carbon vehicle sales is the same for all vehicle classes in this Base Case, using a log based series generation.

These vehicle numbers were chosen, by adjusting the constants in the logistic function used to generate the numbers of new vehicle sales, so that for the majority of cases the 2030 emissions meet the target as shown in Supplementary Figure 5.

This projection meets the 2030 emissions target for the majority of potential emissions cases.  It also comfortably overshoots the requirement for 2045.  This means that if the trend identified to enable the 2030 target to be met can be delivered and sustained, the requirements for 2045 would be comfortably exceeded.

## New vehicles and associated emissions (additional cases)

Similarly, we looked at the numbers of new ZEVs that would be required for the additional cases.

For the additional vehicle rates comparisons, the resulting vehicle sales for the different scenarios are shown in Figure 4. This is comparable to Figure 3, although for clarity only new ZEV sales have been shown.

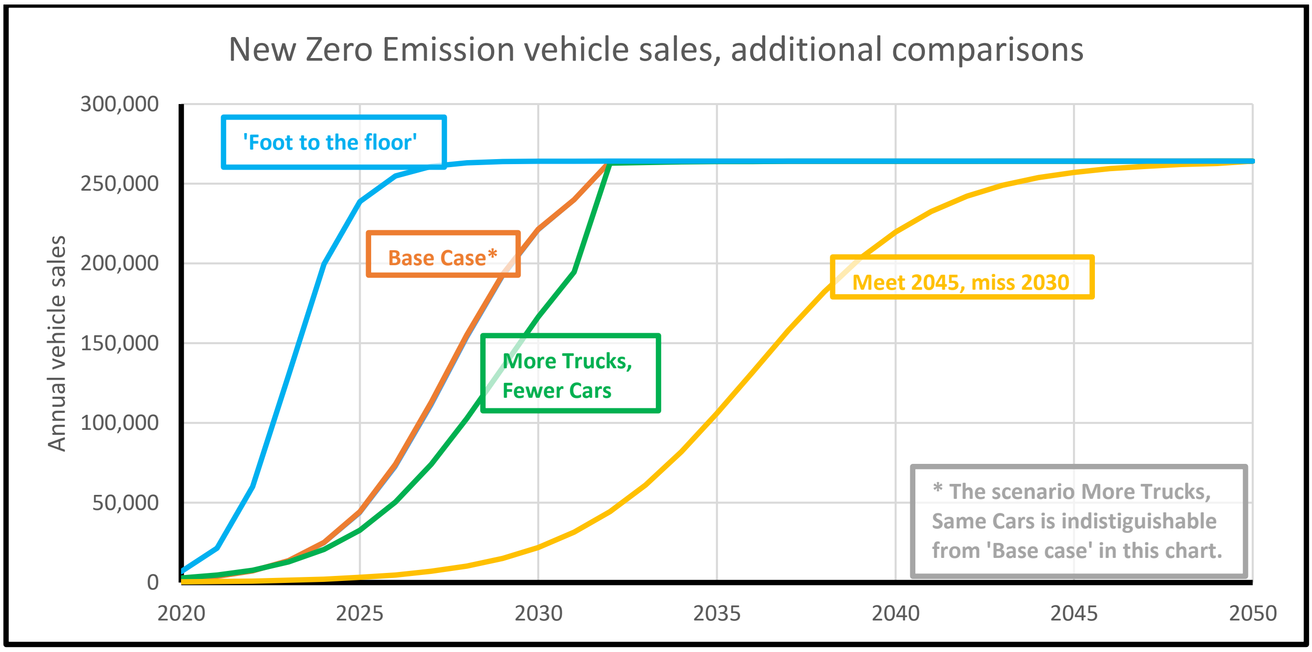



*Figure 4 New sales of zero emission vehicles, projected for various additional scenarios.*

These give rise to future reducing emissions as shown in Figure 5 below.

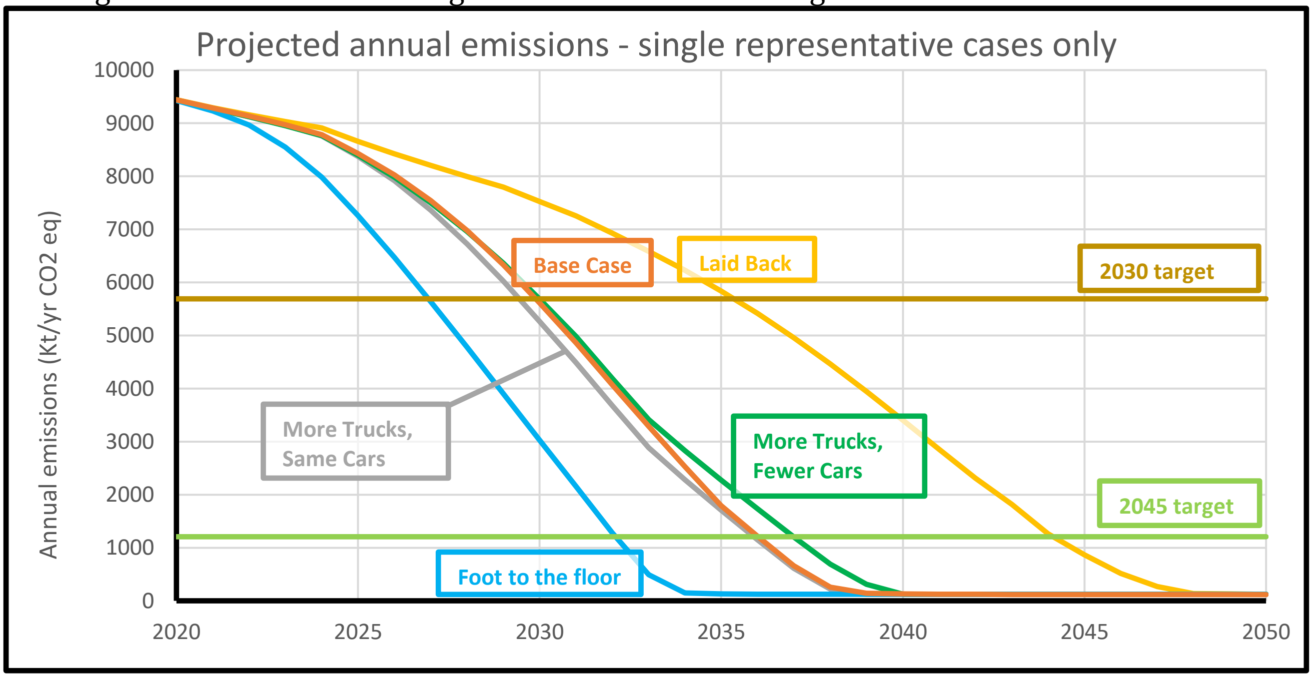



*Figure 5 Reduction in emissions through transition period, projected for various additional scenarios. This analysis was carried out based on the full range of future vehicle emissions cases developed in step1, but only single representative traces are shown, for clarity.*

[Type here]

The difference between the Base Case and the More Trucks, Fewer Cars case appears to be small in terms of emissions, and as shown below the cost difference is also small. However, an examination of the required vehicle numbers shows that by 2025 the required number of annual new vehicle sales to meet targets is significantly lower than for the base case – 33,000 per year instead of 44,000 per year. By 2030 the gap has widened to 167,000 and 222,000 respectively; only after that does the gap start to narrow again.

**This lower requirement for vehicles – predominantly cars – will mean that a considerably smaller number of ZEV cars will be needed to deliver the legislative objective of the 2030 emissions target than would otherwise have been the case, making achieving it a more realistic possibility.**

There appears to be little overall benefit in accelerating large vehicle sales without reducing others – the More Trucks, Same Cars case - there is a small, but not insignificant, reduction in emissions by 2030 although the base case closes the gap by 2035.

The Laid Back case shows that it should be possible to meet the long-term climate goals even if the 2030 target proved unattainable, while the Foot to the Floor case shows for comparison what might be possible as an extreme, but is unlikely to be practical due to limits in availability of suitable materials, vehicles and infrastructure.

## Cost & Emissions based balance points (base and additional cases)

Next, we considered the impacts on cost and emissions through the transition period of differing proportions of hydrogen and battery electricity, on the assumption that all ZEVs would be either BEV or FCEV. These are illustrated below in Figures 6 and 7.

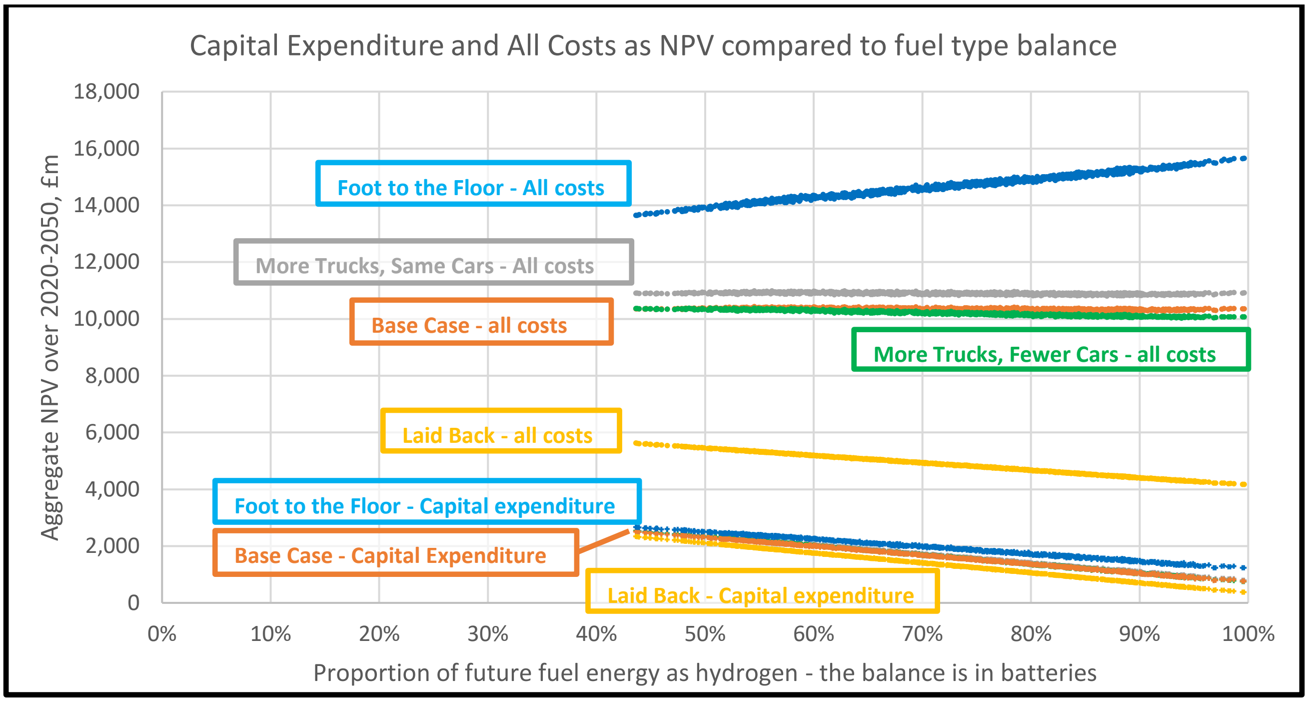



*Figure 6 Capital Expenditure and Total costs as NPV relative to fuel type proportion, for the five cases through transition period. Based on Monte Carlo simulation output, each data point (dot) represents one modelled scenario. In Capital Expenditure, the two "More Trucks" scenarios are indistinguishable from the Base Case.*

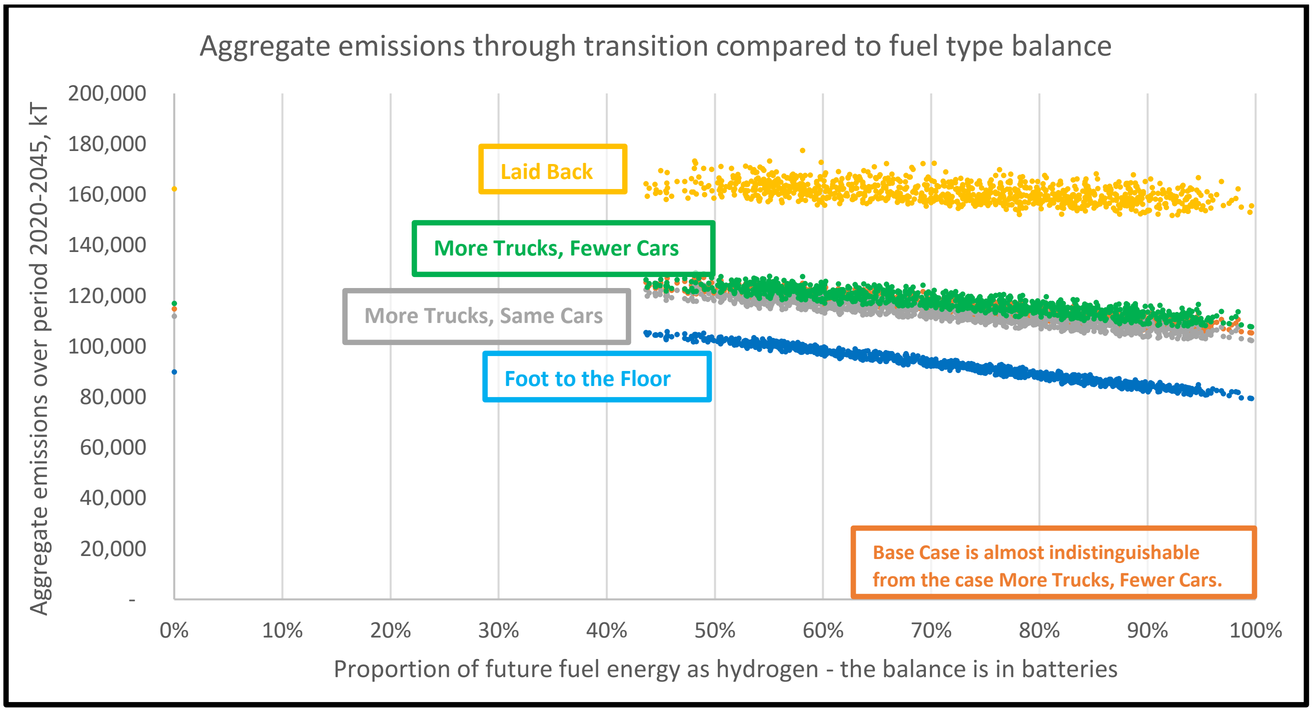



*Figure 7 Total emissions through transition against proportion of hydrogen fuel used, for the five cases.*

Here we consider the costs and emissions resulting from the five transition cases. Comparisons in this section relate to the balance between hydrogen and batteries as zero carbon fuel, assuming that ultimately all vehicles are one or the other. The Monte Carlo simulation method used profiles for randomly generated proportions of each vehicle class using either hydrogen or electricity.

The effect of the balance between hydrogen and battery vehicle use is illustrated in Figure 6 and Figure 7 above. Each vehicle class had upper and lower bounds set for the proportion of hydrogen and electricity used as fuel within that class. The bounds were set such that buses and HGVs are only permitted a small proportion of battery power due to the practical limitations of batteries in large vehicles. This has the effect of requiring a minimum hydrogen demand of around 45% of all zero carbon fuel. Then randomly generated values between those bounds were created for 1000 permutations, with a square distribution. For each permutation, the capital and operational cost of infrastructure and supplying fuel was the calculated for each year and then normalised into a Net Present Value using a discount rate of 6%.

Figure 6 shows the result of each of those permutations as a separate data point, plotting the NPV against the proportion of hydrogen fuel used, for both the capital expenditure and the total costs. For the five cases considered, it can be seen that for the Base Case and the two More Trucks cases, there is little variation in overall cost whatever the future hydrogen – electricity fuel balance point ends up as. The case More Trucks, Fewer Cars shows a slight fall in overall costs with more hydrogen used, but this is unlikely to be significant. The other two suggest that broadly slower progression to the net-zero target would favour more hydrogen on a cost basis, and vice versa.

However, figure 6 also shows that for any scenario, the capital cost of infrastructure is lower as more hydrogen is used – at maximum hydrogen, the total cost is less than half that at 45% hydrogen and indeed this can be extrapolated back to an all-battery figure of around £4bn, approximately 5-6 times as much as for all hydrogen for the Base and More Trucks cases.

This is a very significant factor. Even though the overall costs, once the cost of fuel is taken into account, are very similar, when considering the capital investment required alone, there are enormous savings to be had in moving towards hydrogen as a fuel source. Given also that the wholesale cost of hydrogen as a fuel is likely to become lower than the current cost of petrol on a per-km basis (both excluding fuel duty and VAT), we suggest that the fuel cost is not in fact very significant in this context, and the capital cost represents the cost of transition. This cost represents the cost to install the fuel production, distribution and dispensing facilities. It does not include the cost of providing additional services (non-fuel sales) at retail sites, the cost of extra land required for electric charging due to the extra time each vehicle would have to spend there, the cost of providing strategic operational storage, or any tax.

Similarly, the emissions in use and manufacture were assessed at each of the fuel balance permutations, and are plotted above in Figure 7 for all five cases. As can be seen, there is a clear trend in favour of hydrogen in all cases – this is primarily due to the significant amount of greenhouse gases released in the manufacture of the battery itself (this is modelled to decrease over time); other emissions factors are essentially equal between FCEV and BEV in use, since we assume that both hydrogen and electricity would be produced from renewable carbon free sources.

As might be intuitively expected, the Foot to the Floor and the Laid Back cases result in higher cost but lower emissions, and lower cost but higher emissions, respectively.

From the above, it is also clear that the capital cost per kT of greenhouse emissions mitigated through the transition will be lower in all cases where more hydrogen is used.

## Fuel and Infrastructure requirements

Base on the optimum "More Trucks, Fewer Cars" case we identify above, we looked into the quantities of each fuel type that would be required, and the infrastructure needed to deliver it.

Figure 8 shows how the demand for hydrocarbon, electricity and hydrogen will change through the transition. For this, we assumed an end point of 90% hydrogen fuel used, and 10% electricity. In terms of capital costs, as above, the lowest costs would be at 100% hydrogen; however, it seems likely that there will still be some demand for BEVs, so we created a scenario where 90% of the fuel was hydrogen. This results in an ultimate 400,000 BEVs, predominantly cars and vans, and 2,600,000 FCEVs, including almost all buses and lorries.

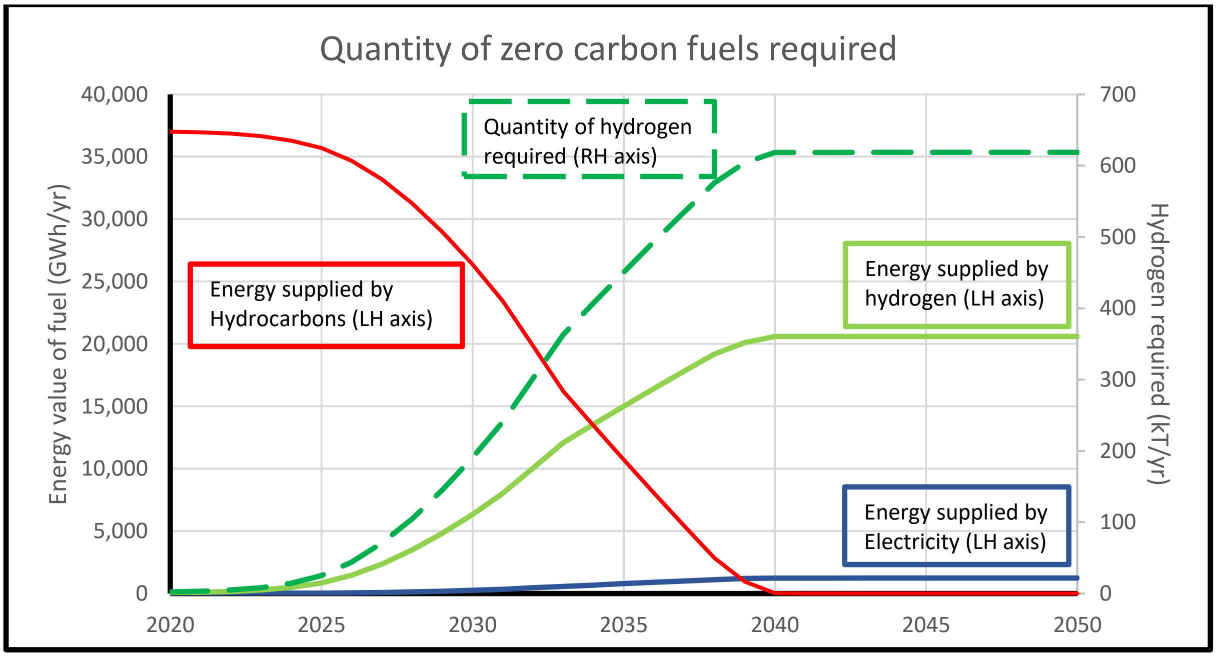



*Figure 8 Energy demand from all fuels at the example point of 90% Hydrogen, based on the More Trucks, Fewer Cars case. Shown with the quantity of hydrogen fuel required. Note that the energy supplied values do not exactly match the intended fuel use proportion, due to the different thermodynamic efficiencies of FCEVs and BEVs.*

The driving force for the infrastructure development is the quantity of fuels needed of all types. Figure 8 shows how the demand for fuels will vary through the More Trucks, Fewer Cars case (the difference from the More Trucks, Same Cars and the Base Case is not significant).

Looking at the key early years, we see that by 2025 there will be a need for 25 kT/year of hydrogen and 41GWh/year of electricity – equivalent to (for example) around 5 large commercial vehicle scale refuelling stations of 7,500 kg/day, 100 introductory scale hydrogen car refuelling stations of 400 kg/day, and 4,200 public chargers of various capacities.  The undiscounted capital investment cost to reach this point is estimated to be around £250M.

By 2030 this rises to 191 kT/year of hydrogen (40 large and 125 mid-sized refuelling stations of 2,300 kg/day) and 263 GWh/year of electricity (11,500 public chargers). Undiscounted capital investment to reach this point from the start is estimated at £950M.

The ultimate requirement will be for 619 kT/year of hydrogen (e.g. 80 large plus 540 mid-sized refuelling stations) and 1,256 GWh/year of electricity (20,500 public chargers), reaching this level by 2040.  The capital investment for this from the start of the programme is forecast at £2.0bn gross, or £1.1bn Net Present Value at a discount rate of 6%.

For context, typical hydrocarbon fuelling stations deliver around 4.5 million litres per year (ranging from small stations of about 2 million litres/yr. up to 15 million, which is a large HGV refuelling facility).  This is equivalent in useful energy to about 2,300 kg/day, or 0.85 kT/year, of hydrogen.

## Capital Expenditure Profile

We then examined specifically the capital expenditure profile based on three fuelling scenarios:

(1) All electric
(2) All hydrogen
(3) The balance point, above, between the two, of 90% hydrogen.

These infrastructure requirements break down as shown in Figure 9.  As above, this is based on the case More Trucks, Fewer Cars and a fuel split of 90% hydrogen and 10% electricity.

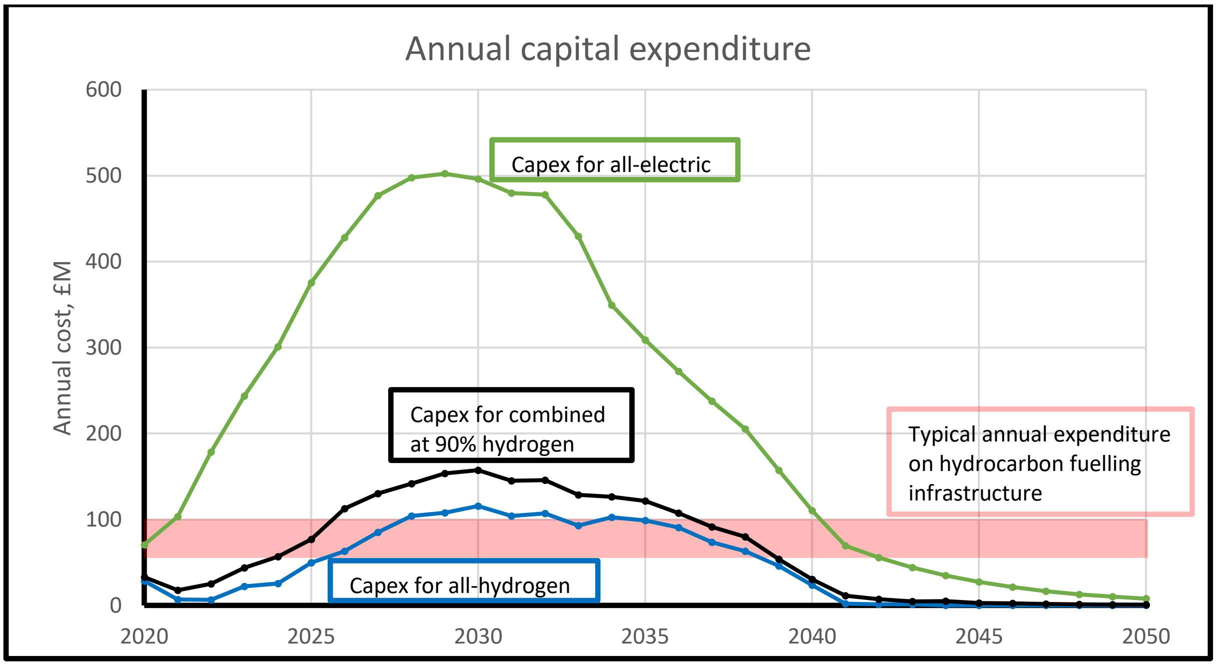



*Figure 9 Annual capital expenditure through transition at three points: 100% battery electric, 100% hydrogen, and optimised balance of 90% hydrogen, 10% battery electricity (optimised including fuel costs). Annual expenditure on hydrocarbon fuelling is shown as an indicative comparison. This chart is based on the case "more trucks, fewer cars".*

It clear from Figure 9 that even a modest increase in the amount of electricity used as vehicle fuel will result in a substantial increase in capital investment costs.

It is also clear that the capital cost for constructing only hydrogen facilities will be close to the typical annual expenditure on refurbishing fuel filling facilities, suggesting that the capital outlay could be managed substantially within the existing commercial refurbishment programmes.

Note that Figure 9 does not include the longer term replacement of aging zero carbon refuelling infrastructure.

## Sources of Hydrogen and Electricity

We made various assumptions about where hydrogen and electricity would come from.

Electricity – over and above that currently produced – will be made by offshore wind. Hydrogen will in the short term be made from local electrolysis using grid supplied electricity, and in the long term will be made offshore using electrolysis with wind generated electricity, piped to shore and distributed through the existing gas network ('Green hydrogen'). When produced at large scale, this is estimated to cost approximately £1.64 per kg delivered to shore, equivalent to around 5 pence per kWh. This calculation is based on the method presented by Babarit et al[26], with modifications to the input data to reflect the more up to date cost information available.

We also assumed that fuelling stations in areas with no local gas grid connection will continue to use grid electricity, with agreements about taking otherwise curtailed production.

These methods produce no greenhouse gases at the point of generation, so we consider these the best environmental solutions.

An alternative is to consider centrally produced hydrogen using Steam Methane Reformation (SMR) with Carbon Capture and Storage (CCS) of the associated carbon dioxide produced ('Blue hydrogen'). This could also be done without CCS as a short-term interim measure – it would still release considerably less carbon dioxide than combustion of petrol or diesel in road vehicles. This might provide a quicker way of producing enough hydrogen, at a cost potentially lower than green hydrogen production although at a cost of some potential leakage of carbon dioxide[27].

Other ways of producing hydrogen are in development at the research stage. It is also produced in potentially significant quantities as an industrial by-product for certain processes. These are not considered further in this paper.

The total electricity requirement, for both electricity and hydrogen generation, could ultimately be provided by an offshore windfarm/s supplying around 25.9 TWh per year. This would be approximately equivalent to duplicating Scotland's existing annual renewable electricity generation of 26.5 TWh[8], or slightly more than the current and consented offshore wind generation of around 22 TWh per year; offshore generation is anticipated to rise to around 53 TWh per year by 2030, given an availability factor of 2[26]. A contribution to this might be drawn from curtailed wind generation; in 2019, 1.9 TWh of wind powered electricity generation was curtailed in Scotland[28].

## Discussion

The Scottish Government's targets of 75% reduction in emissions by 2030 and Net-Zero by 2045 will be challenging to meet, but the technology exists to do this at a sensible cost and within the required timescale.

It is clear from our modelling and investigations that there will be a considerable benefit and cost saving in including a substantial proportion of hydrogen in future vehicle fuelling – indeed, decarbonisation of large vehicles (buses and heavy goods) will be almost impossible without it.

The capital investment required will be considerably lower with more hydrogen used – moving from 100% electricity to 100% hydrogen should entail a capital cost reduction in the region of a factor of six – approximately £4bn reducing to approximately £700M. Even considering the slightly higher cost of hydrogen as a fuel – a cost that would be passed through to consumers – the whole system costs will be largely similar, at any proportion share between hydrogen and battery electricity. However, as the cost of fuel should in any case end up lower than the cost of petrol per km travelled (calculation shown in supplementary publication), we consider that the cost of fuel is less important in this respect than the capital investment requirement.

Furthermore, other cost factors, not incorporated into the model, will all move the overall cost further in favour of hydrogen. These include storage for operational flexibility, interseasonal storage, battery manufacturing, additional land requirement for battery chargers due to the time needed to recharge, value of peoples' time spent refuelling / recharging, road damage due to heavier vehicles. In terms of storage costs, it is telling that in the medium to long term, Jülch [29] assesses that based on current research, the cheapest storage for electricity will be to convert it to hydrogen, store it underground, then convert it back to electricity when required.

We do not, however, expect that a solution of 100% hydrogen would be a likely end position; there are some benefits to electric vehicles, and thousands are already registered. We continued our analysis on the basis of 90% hydrogen, 10% battery.

Since total emissions through transition will be reduced with more hydrogen being used, it is also clear that capital cost in relation to the amount of carbon dioxide emissions mitigated through the transition period, that is £/kT CO2 eq. mitigated, will be substantially lower with increased use of hydrogen. This is also the case when considering the overall cost including fuel, as shown below in Figure 10 Total NPV and NPV related to mitigated emissions against fuel mix, for various discount rates. Constraints on large vehicles have been removed, allowing the hydrogen proportion to fall to near zero i.e. full electrification.Figure 10.

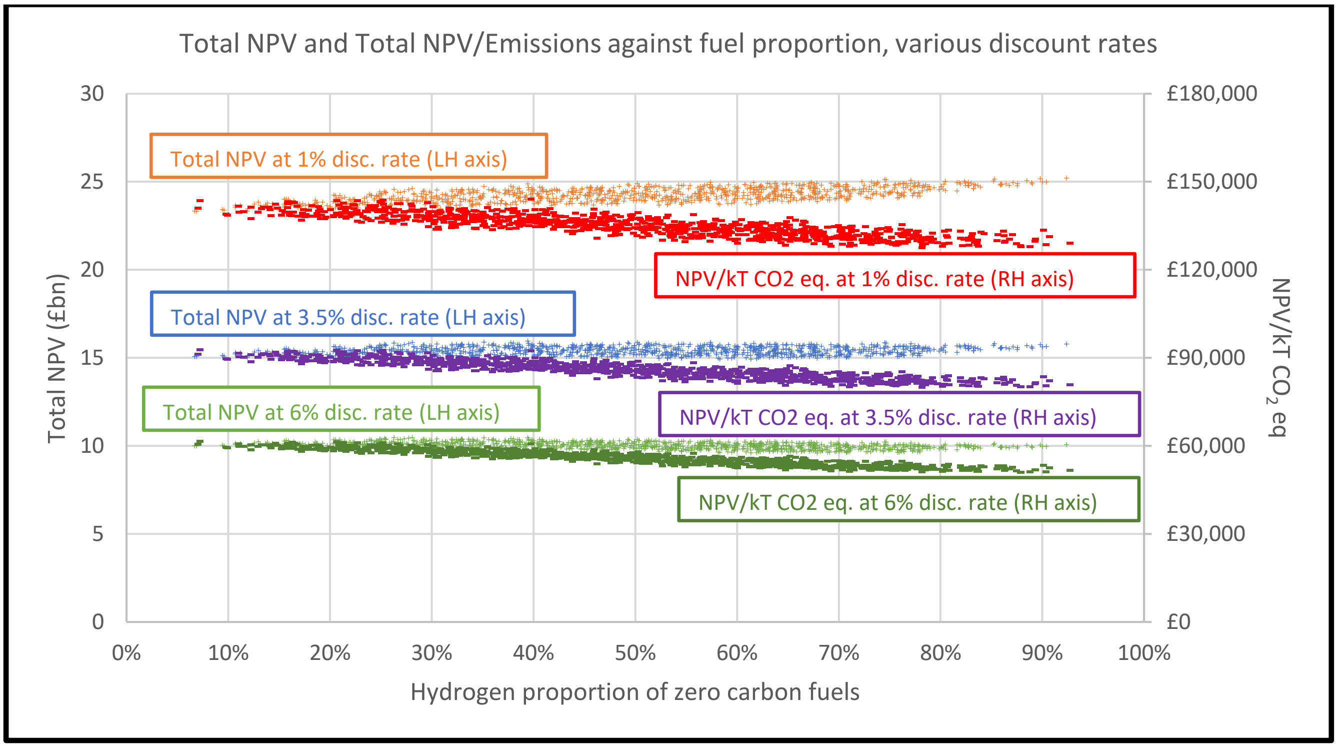



*Figure 10 Total NPV and NPV related to mitigated emissions against fuel mix, for various discount rates. Constraints on large vehicles have been removed, allowing the hydrogen proportion to fall to near zero i.e. full electrification.*

We can see from Figure 10 that while the overall cost does not vary significantly with fuel proportion, the cost per kT of carbon dioxide mitigated through the transition becomes lower as more hydrogen is used.

Figure 10 also draws out two further sets of information. First, the general trends in costs and emissions relating to fuel mix (curtailed at around 45% throughout the results section above) do continue to the point where almost everything is battery electric. Second, we can see the effect of changing the discount rate assumed in the NPV calculations – moving from the 6% figure actually used in most of the model to a conservative 1%, we see that the NPV estimate increases by a factor of around 2.5. We can also see that the trend of the total NPV moves to slightly increasing with more hydrogen at very low NPV values. However, the variability is low and we consider that at all discount rates, the NPV can be considered constant within the limits of accuracy of this model. Relative to emissions mitigated, however, the trend is always to a lower cost per kT emitted with more hydrogen.

Beyond the simple system cost and transition emissions, it is important to consider the ease with which the transition can be implemented. We considered a number of ‘soft factors’ which would affect the practicality of the transition. These are illustrated in Figure 11 below.

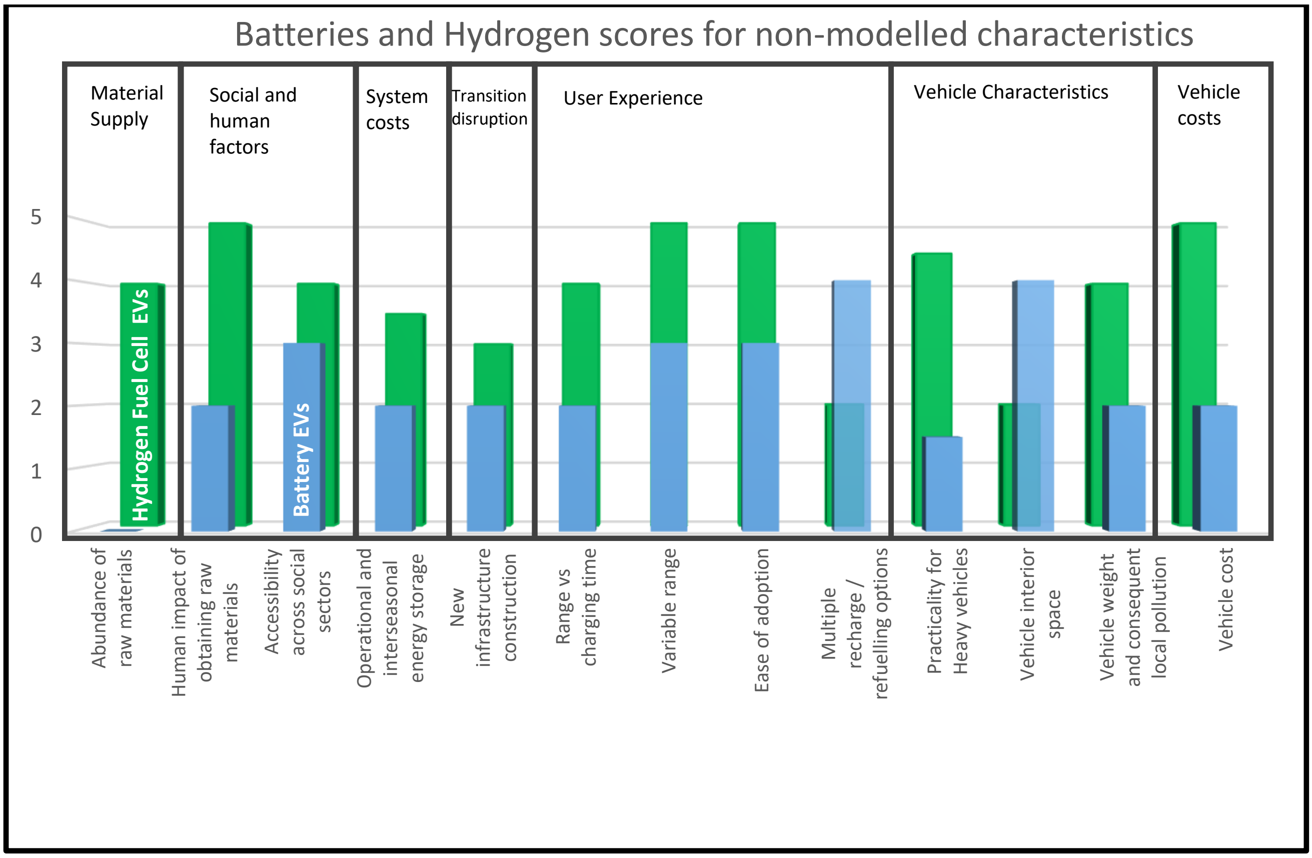



*Figure 11 Non-modelled characteristics – Soft Factors showing the differences in the harder to quantify factors that will make a big difference to the acceptability of the new fuelling systems.*

These factors are expanded further, with references, in the supplementary publication.

Clearly, the soft factor benefits of hydrogen FCEVs exceed those of BEVs in almost every respect, especially in convenience in use.

A few key points arise:

The abundance of raw materials. Based on current battery technology and current known deposits, even with 100% recycling there is not enough raw material to supply the current number of vehicles in the world with batteries for BEVs[12]. On a global basis, this will be a red light issue for BEVs in the long term if not resolved with, e.g., new battery technology or finding new mineral deposits. It seems likely that the consequences of this will fall most heavily on developing nations, as wealthier nations will be able to pay more for the materials required for battery supply and are likely to make the transition earlier. Hydrogen FCEVs do use a battery to recapture braking energy, but they typically require a battery only around 1-2% of that of a BEV. Also with respect to raw materials, much of the worlds supply of Cobalt – essential for batteries using current technology – is mined in exploitative working conditions. While we would hope that this could be addressed independently of technology, limiting the demand for batteries should also help to reduce this situation.

Local road damage, and other environmental collateral damage, are likely to increase by a factor of around 3 times due to extra vehicle weight with BEVs compared to FCEVs and Hydrocarbon vehicles[30] with the same number of vehicles. However, the gross weight of the largest articulated vehicles is limited by legislation to 44T; numbers of such vehicles would be up to about 45% higher with batteries, simply due to the required 5-8 tonne battery weight reducing the approx. 25 tonne payload leading to a proportionate increase in vehicle numbers. In fact, the increase would be even higher, although hard to quantify at present, in uses where the corresponding extended battery charging time reduces the vehicle service availability below that currently required.

Range against charging / fuelling time is around 100km range added per minute for hydrogen (similar to a petrol car), compared to around 10km/minute (highly variable) for batteries. This means a filling time of around 5 minutes for a hydrogen car, similar to petrol, but anything from 30 minutes to multiple hours for a battery one.

The maximum benefit of BEVs is obtained with domestic charging facilities, which can partially offset the extended charging time above as well as accessing more favourable tariffs[31]. However, approximately 37% of Scottish households are in flats[32], which we consider are unlikely to be able to access a domestic charging point. An unknown number of houses are also likely to have such difficulties. Since it is likely that households in flats are on average in a lower income bracket than those in houses, this will restrict ready access to BEVs from less well-off households. This issue is resolved with fuel station based refuelling with FCEVs.

This convenience in use is borne out by an assessment carried out of the use of Metropolitan Police (Met) and Transport for London (TfL) vehicles. These organisations both operate a number of hydrocarbon (HC), hydrogen FCEV, and BEV vehicles. The analysis found that the hydrogen vehicles are used between 21% less (Met) and 48% more (TfL) than their HC fuelled equivalents, while the BEVs are used 42% and 46% less than their HC equivalents respectively – this despite the expectation that a BEV could have advantages in an urban environment[33].

It's also important to realise that there will still be a need for a large number of battery vehicles – at the suggested 90% hydrogen, 10% electricity examined, there will ultimately be a need for over 400,000 BEVs and around 2,500,000 FCEVs on Scotland's roads. This compares to 11,000 BEVs at the moment – so enormous growth in BEVs will be required alongside FCEVs. These BEVs are likely to be primarily smaller vehicles such as motorbikes, or urban cars or vans.

We analysed five scenarios: Base Case (an approach to meeting the 2030 target by changing each class overt to ZEV at the same pace; faster deployment of large vehicles ("More Trucks, Same Cars"); faster deployment of large vehicles with reduction in deployment of smaller ones ("More Trucks, Fewer Cars"); faster; slower. These were analysed for potential hydrogen and electricity fuel mix proportions from all hydrogen to, in some cases, all electricity.

The optimum scenario was More Trucks, Fewer Cars. This means accelerating the deployment of large zero emissions hydrogen FCEVs, (buses and HGVs), as soon as possible. This makes a small reduction to overall system costs or emissions, but will enormously reduce the number of ZEVs required overall in the early years of transition. This will make the target much more achievable in practical terms.

On this basis, 28,000 new hydrogen and 5,000 new battery vehicles per year will be required by 2025; 144,000 and 23,000 respectively by 2030 and 227,000 and 37,000 by 2040. This appears likely to be a stretch for manufacturers, especially in the initial stages, but not impossible.

To deliver the required hydrogen and electricity would require, for example, 5-10 large (7500 kg/day) and 100 small (400kg/day) hydrogen fuelling points by 2025, and 80 large and 540 medium (2300 kg/day) ones by 2045. In practice, there will be a range of sizes depending on expected use. For comparison, an average current fuelling station dispenses petrol and diesel equivalent to 2300 kg/day of hydrogen (equivalent on a per-km basis). There would also be a requirement for 4,200 public electric charging points of various sizes by 2025 and 20,000 by 2045, as well as around 190,000 domestic (or equivalent) charging facilities. While challenging, we think that with planning and co-operation between the various parties this is achievable.

These figures are illustrative examples of the scale; in practice a range of sizes will be required. This might require more detailed analysis, but in due course it might also be acceptable for fuelling companies to simply plan for and respond to demand in the same way as at present.

The capital costs of delivery will peak at around £150M per year for actual refuelling infrastructure up to 2029, decreasing after that. Current renewal and maintenance expenditure by fuelling station operators is typically around £50-100M per year, so it seems likely that the fuelling industry could finance a substantial part of the transition, but may require some support or guarantees to address the unknown risks.

Overall, the key constraints are likely to be the availability of vehicles, fuelling equipment and hydrogen generation. We see the practical delivery of these in the in the required timescale as a bigger hurdle than the cost or the development of new technology.

At the time of writing, progress in moving to hydrogen as a fuel has been slow, although not zero. In March 2020, Logan Energy opened the first hydrogen refuelling station in the central belt of Scotland, while Europe's largest a fleet of hydrogen buses has been operating in Aberdeen for some years and the use of surplus wind energy in Orkney is being used to generate hydrogen for local heat and transport. Commercial organisations are understandably proceeding with caution until a market is developed. However, to deliver the required emissions reductions, a faster pace of change is required.

There will be a number of costs and other factors which, in the early stages, are likely to discourage people from adopting FCEVs. These are –

- Cost of vehicle, whether purchase or leased;
- Cost of fuel
- Risk and costs of new technology investment by fuelling companies
- Availability of fuelling infrastructure

We propose that a programme of government driven market stimulation should be developed to support these prices and risks, similar to that which started the BEV market, and a strategic seed network of around 100 car focussed hydrogen fuelling stations and 5-10 or more larger fuelling stations for commercial vehicles be developed around Scotland, while the battery vehicle charging network development should continue.

It will also be of especial importance to work with operators of large vehicles and large fleets to start them moving to hydrogen vehicles as quickly as possible; ideally they would allow their fuelling facilities to be used by private cars where safe to do so. Public sector vehicle fleets should be a good place to start, given the influence of the Scottish Government over them.

We recognise that the demands made of the supply chain in all aspects of this will be high, if the Scottish Government's targets are to be met. However, the rest of the world is not generally pursuing such stringent targets, with 'net zero by 2050' a common theme derived from the IPCC report of 2018[34]; there is therefore scope for Scotland to work with manufacturers to develop the necessary supply chain, with ideally a significant amount of the economic benefit remaining in Scotland.

There are some Scottish and UK manufacturers in the supply chain; In Scotland these include: ADL buses in Falkirk; Logan Energy, fuelling systems, in East Lothian; HV Systems, hydrogen truck and van manufacturer, in Glasgow.

So, we propose that the Scottish Government also develops a partnering strategy with vehicle manufacturers, fuelling companies, energy companies, academia, and others in order to accelerate the delivery timescale and overcome the chicken-and-egg hurdles. This partnering strategy could be further enlarged to a create a centre of excellence in Scotland. The size and location of Scotland means that it could viably become a pathfinder market for the development of hydrogen fuelled road transport, with effort focussed here to develop the necessary integrated systems. Such an approach could and should be carried out in such a way as to support the development of the local supply chain in Scotland, given that the global supply chain is massively underdeveloped to meet the forthcoming demands on it and will afford enormous growth potential in the coming decades. In our view, a partnering approach of this type is likely to be essential if the challenging targets are to be met.

# Conclusion

Our aim was to identify the optimum combination of hydrogen and electricity as future carbon-free road fuels in Scotland.

We built a model to include realistic local costs and timelines for electrification and/or hydrogen deployment, looking primarily at Capital expenditure, Operational expenditure (predominantly fuel production) and carbon emissions.

This enabled Monte Carlo investigation of 5 scenarios to examine (1) different rates of deployment of vehicle classes and (2) mix proportions of hydrogen and electricity.

Our key findings were:

- Increased hydrogen has lower capital cost and emissions to battery electricity.
- 100% hydrogen has around one-sixth of the capital cost of 100% electric, in NPV terms at a 6% discount rate – approximately £700m compared to £4bn.
- In non-modelled factors, hydrogen is preferable in almost all areas.
- Hydrogen fuel costs will be higher than electricity; however when produced at scale, hydrogen is still expected to cost less than petrol or diesel (untaxed values).
- Combined costs are very similar between hydrogen and electricity.
- Other costs including energy storage, vehicle costs, and land use are all lower when more hydrogen is used.

The optimum approach would be to accelerate the deployment of hydrogen large vehicles to the maximum practical extent, while allowing cars and vans to progress slightly more slowly – this benefits deliverability, rather than any significant impact on emissions or cost.

To initiate this, an infrastructure network of 5 – 10 large vehicle / fleet hydrogen refuelling centres plus around 100 car-focussed introductory sized hydrogen fuelling points of 400 kg/day would be required by 2025, alongside the existing programme for the development of electric vehicle charging infrastructure, which by 2025 should have around 4,200 public charging points.

We propose that this programme of hydrogen refuelling points and large vehicle / fleet fuelling points should be pushed forward as an initial seed and development network with some urgency.

Short to medium term market stimulation for fuelling systems, vehicle sales and fuel costs will almost certainly be required until commercial risks and costs reduce, as we anticipate they will, to a level comparable with current hydrocarbon systems.

We also recommend developing a partnering strategy, involving government, academia, vehicle manufacturers, energy and fuelling companies and others as soon as possible to push this forward, if the challenging targets are to be met. This would ideally develop into a permanent centre of excellence. The world supply chain is currently massively under-developed for the forthcoming demands, so there is scope to boost Scotland's related industry not only for local supply, but also globally.

## Acknowledgements

JML is partly funded by the University of Edinburgh

RSH is funded by EPSRC UKCCSRC 2017 EP/P026214/1 and HyStorPor P/S027815/1, and Scottish Gas Networks Academic Alliance H100 project from Ofgem

JM-C is funded by Scottish Gas Networks Academic Alliance H100 project from Ofgem, and UKRI.

## Conflicts of Interest

There are no conflicts to declare.

## References

1. Scottish Government, *Journal*, 2019.
2. ChargePlace Scotland, ChargePlace Scotland, https://chargeplacescotland.org/, (accessed 16 April, 2020).
3. Energy Saving Trust, Electric Vehicle Loan, https://energysavingtrust.org.uk/scotland/grants-loans/electric-vehicle-loan, (accessed 16 April, 220).
4. European Union, *Journal*, 2020.
5. B. Dolter, *Alternatives Journal*, 2017, **43**, 32-35.
6. Scottish Power, *Zero Carbon Communities*, Scottish Power, 2020.
7. UK Department of Transport, *Journal*, 2019.
8. Scottish Government, *Journal*, 2018, **2019**.
9. G. Kable, *Journal*, 2018.
10. H2Bus, H2Bus, https://h2bus.eu/index.html, (accessed 16 April, 2020).
11. Nikola Inc, Nikola, https://nikolamotor.com/, (accessed 19 December, 2019).
12. M. Weil, S. Ziemann and J. Peters, in *Behaviour of Lithium-Ion Batteries in Electric Vehicles*, ed. G. L. Pistoia, B, Springer International Publishing AG, 2018, DOI: https://doi.org/10.1007/978-3-319-69950-9_3.
13. P. Stewart, *EDUCATION IN CHEMISTRY-LONDON-*, 2003, **40**, 23-24.
14. C. C. Chan, *Proceedings of the IEEE*, 2007, **95**, 704-718.
15. H. Eichlseder, T. Wallner, R. Freymann and J. Ringler, *The potential of hydrogen internal combustion engines in a future mobility scenario*, Report 0148-7191, SAE Technical Paper, 2003.
16. K. Mazloomi and C. Gomes, *Renewable and Sustainable Energy Reviews*, 2012, **16**, 3024-3033.
17. The Engineering Toolbox, The Engineering Toolbox. Fuels - Densities and Specific Volume https://www.engineeringtoolbox.com/fuels-densities-specific-volumes-d_166.html, (accessed 18 June, 2020).
18. H. Jung, R. Silva and M. Han, *World Electric Vehicle Journal*, 2018, **9**, 46.
19. Z. P. Cano, D. Banham, S. Ye, A. Hintennach, J. Lu, M. Fowler and Z. Chen, *Nature Energy*, 2018, **3**, 279-289.
20. M. Saunders, *Journal*, 2019.
21. V. R. Timmers and P. A. Achten, *Atmospheric Environment*, 2016, **134**, 10-17.

22. Electric Vehicle Database, Electric Vehicle Database, https://ev-database.uk/car/1135/Mercedes-EQC-400-4MATIC, (accessed 17 April, 2020).
23. Carbuyer, Mercedes GLC SUV, https://www.carbuyer.co.uk/reviews/mercedes/glc/suv/review, (accessed 17 April, 2020).
24. Mercedes Benz UK, *Journal*, 2019.
25. Committee on Climate Change, *Hydrogen in a Low Carbon Economy*, Committee on Climate Change, London, 2018.
26. A. Babarit, J.-C. Gilloteaux, G. Clodic, M. Duchet, A. Simoneau and M. F. Platzer, *International Journal of Hydrogen Energy*, 2018, **43**, 7266-7289.
27. M. Voldsund, K. Jordal and R. Anantharaman, *International Journal of Hydrogen Energy*, 2016, **41**, 4969-4992.
28. Renewable Energy Foundation, *Electric Vehicles in Scotland's Energy Future Consultation*, 2020.
29. V. Jülch, *Applied Energy*, 2016, **183**, 1594-1606.
30. R. Addis and R. Whitmarsh, *Relative damaging power of wheel loads in mixed traffic*, Report 0266-7045, 1981.
31. Ecotricity, Our Electric Highway, https://www.ecotricity.co.uk/for-the-road/our-electric-highway, (accessed 26th June, 2020).
32. National Records of Scotland, *Journal*, 2020.
33. Auto Express, *Journal*, 2019.
34. IPCC, *Global Warming of 1.5°C.*, Intergovernmental Panel on Climate Change, 2018.