Efficient pathways to electrifying UK transport

Impacts on renewable generation of options to decarbonise transport

March 2021

Executive Summary

Decarbonising UK transport by 2050 using renewable electricity is challenging, but achievable given the enormous renewables potential of the UK. However, the scale of transport electricity demand post 2030 means that renewable electricity will remain a 'scarce' commodity and must be used as efficiently as possible. Transport cannot therefore be decarbonised one mode at a time, but instead requires a holistic approach that recognises the greater efficiency of some energy pathways and the limited availability of sustainable biofuels. Priority should be given to directly use electricity where possible, such as through batteries; and minimise the use of energy carriers like hydrogen and synthetic fuels to sectors where these are unavoidable, like shipping and aviation. There is a clear hierarchy for the use of renewable electricity in transport and encouraging the use of e-diesel in road transport or hydrogen in cars comes with a considerable total energy penalty that risks derailing the entire decarbonisation effort.

If the UK selects the most efficient options for using renewable power in transport (including using batteries and electric road systems for all vehicles), by 2050 it will require 369 TWh - slightly more than the total amount of electricity currently being supplied. This would require 92 GW of offshore wind capacity to be deployed over the next 30 years: equivalent to over 13,000 offshore turbines. If a greater reliance is placed on hydrogen, total renewable electricity demand increases by 15% to 426 TWh. If more synthetic fuels are used, 55% more renewable electricity is needed in 2050.

If all passenger cars were battery-electric, charging would require 83 TWh in 2050 (just 24% of current total electricity demand). However, if just 10% were powered using hydrogen fuel cells and 10% by synthetic fuels, renewable electricity demand would rise 9%. Similarly, if all trucks over 16 tonnes were battery electric, demand for renewable electricity would be 40 TWh in 2050. Running half of these trucks on hydrogen fuel cells would increase demand by 46%.

Prioritising direct electrification over other energy carriers in road transport has the added benefit of enabling more smart charging, which would reduce peak energy demand and grid reinforcement costs. This also reduces curtailment of wind and solar, and therefore required renewable electricity capacity. Focusing on efficiency makes the transition to net zero easier and enables a faster shift to sustainable aviation and shipping fuels, without relying on high risk biofuels. Lowering the energy demand in the transport sector by promoting public transport, shared vehicle use, modal shift, logistics efficiency and reducing air travel also helps to reduce the scale of the challenge.

Table of contents

1. Context

It is widely accepted electrification of transport will be a key route to decarbonising the sector, and that largely renewable electricity will be used[1] (complemented by other zero emission generation). Decarbonisation of the power sector is therefore a prerequisite for a zero emission transport system, but it should be noted that the UK's grid is moving rapidly towards that. Indeed, the system operator has stated that it will be able to operate the power system with 100% renewable power by 2025[2]. Supplies of sustainable liquid biofuels will only be able to make a niche contribution. Whilst demand reduction, efficiency and modal shift will all reduce emissions, they cannot get to zero emissions, although they will play a key role in meeting interim milestones in the short term and thus lowering overall energy demand from transport.

How renewable energy should be deployed in transport remains a live debate. For cars and vans there is now consensus that this will be directly through use of battery electric vehicles, but there are still a minority of Japanese carmakers that suggest hydrogen used in fuel cells is a long term solution. In trucks, there is far more debate about how the sector should be decarbonised with the principal options being; battery trucks that are recharged during stops; electric road systems probably using a catenary system (that charges the truck battery whilst it is in motion); hydrogen made from renewable energy (so called blue hydrogen is not a zero emission fuel); or, electrofuels made by combining CO2 with hydrogen using renewable energy. In shipping, there are also a range of options including batteries for short trips; ammonia; or hydrogen. Batteries are unlikely to play a significant role in aviation, but hydrogen (via fuel cells) is a better possibility for short-haul aircraft whilst electrofuels have the greatest potential for long-haul flights.

The efficiency with which electrical energy is converted into useful kinetic energy varies widely between the different energy carriers (as illustrated in Annex II). For cars and trucks direct electrification through storing the electrical energy in batteries is 77% efficient today, and will rise to 81% by 2050. Hydrogen is 33% efficient today and will rise to 42% by 2050. For cars, using power to liquids (electrofuels) is just 20% efficient today and only expected to be 22% by 2050. For trucks, the efficiency is marginally better: 23% today and 29% by 2050. The energy carrier used will therefore have significant implications for the amount of renewable energy required to power transport.

---

[1] T&E, 2018. 'Roadmap to decarbonising European cars'. Available at: https://www.transportenvironment.org/sites/te/files/publications/2050_strategy_cars_FINAL.pdf
[2] Stated by ESO director Fintan Slye. Retrieved from: https://theenergyst.com/national-grid-says-can-go-100-renewables-2025/

Whichever way transport is electrified, it will require very large investments in additional renewable generation capacity and electricity grids (indeed, OFGEM has recently announced future investments of over £10billion in electricity network improvements[3]). In addition to choosing efficient pathways, reducing transport demand by means of behavioural changes or modal shift will play an important role in reducing overall energy demand. Policies like carbon pricing may also influence future transport demand. However, other actors, including city and regional governments, will play a larger role in creating less car-centric cities, promoting public transport, cycling and walking and improving the efficiency of freight deliveries.

This briefing explores in greater detail how renewables can deliver the energy needed for decarbonisation of the transport sector, what is needed by 2030 and in 2050, and whether it is feasible to meet both the transport sector and other sectors demands with additional UK renewables' capacity. We start from the assumption that all electricity demand from transport will be met with additional renewables[4].

This briefing draws on the key findings of a report by Ricardo Energy & Environment, integrating the latest data on renewables, which is published together with this briefing. All figures refer to data for the UK, unless otherwise indicated. This briefing builds on a previous 2018 T&E report: *How to Decarbonise European Transport by 2050*[5].

2. The renewables needed to decarbonise the UK transport sector

2.1. Introducing the three scenarios and their results

To investigate the optimum pathway through which renewable electricity should be used to decarbonise transport (including road transport, shipping and aviation), three scenarios (detailed in Table 1) were developed: each explores the implications of using varying percentages of different

---

[3] OFGEM. (2020) Ofgem Proposes £25 billion to transform Great Britain's energy networks. Retrieved from https://www.ofgem.gov.uk/publications-and-updates/ofgem-proposes-25-billion-transform-great-britain-s-energy-networks

[4] It should be highlighted that the use of biomass is excluded from renewables potential for environmental reasons. Nuclear power stations can, and do, provide zero-carbon electricity, however these are excluded from this study as, at the time of writing, it is unclear exactly how many new nuclear plants will actually be built in the UK.

[5] T&E (2018), 'How to decarbonise European transport by 2050'. Retrieved from: https://www.transportenvironment.org/publications/how-decarbonise-european-transport-2050

energy carriers across different transport modes[6]. The scope covers all domestic transport as well as outbound journeys from the UK by ships and planes.

- Scenario 1 and Base Case – High Electrification: Direct electrification wherever practicable (including for all buses and trucks) and optimal electrofuels selected for other modes.
- Scenario 2 – Higher Hydrogen: Hydrogen displaces electrification and plays a bigger, albeit limited role in both road transport (cars and trucks). In shipping, more hydrogen is used, replacing direct electrification and ammonia.
- Scenario 3 – Higher Synthetic Hydrocarbon Fuels (HSCF): Synthetic hydrocarbon fuels (SHCF) displace electrification in some transport modes. Similar to the 'Higher Hydrogen' scenario, but shipping and aviation would rely on 100% synthetic hydrocarbons.

Table 1: Summary of scenario assumptions.

Scenario	Light Road Transport (Cars, Vans, Motorbikes, Trucks <16t)	Heavy Road Transport (Buses, Trucks >16t)	Shipping	Aviation
Scenario 1 and Base Case - High Electrification.	Road transport 100% electrified	Road transport 100% electrified	Shipping 19% electrified, 27% hydrogen and 54% ammonia	Aviation 84% SHCF, 11% advanced biofuels and 5% direct electrification
Scenario 2 - Higher Hydrogen	90% electrified, 10% hydrogen Motorbikes 100% electrified	50% hydrogen, 50% electrification	Shipping 5% electrification, 75% hydrogen and 20% ammonia	Aviation 90% SHCF, 5% advanced biofuels and 5% hydrogen

[6] All these scenarios share the same assumptions about energy efficiency measures and demand reduction measures. See section 1.5 of the Ricardo report for more details.

Scenario 3 - Higher Synthetic Hydrocarbon Fuels	10% SHCF, 10% hydrogen and 80% direct electrification. Motorbikes 100% electrified	Trucks >16t 50% SHCF and 50% hydrogen; buses 50% SHCF, 25% hydrogen and 25% electrification	100% SHCF	100% SHCF

More detailed descriptions of these scenarios can be found in Annex I.

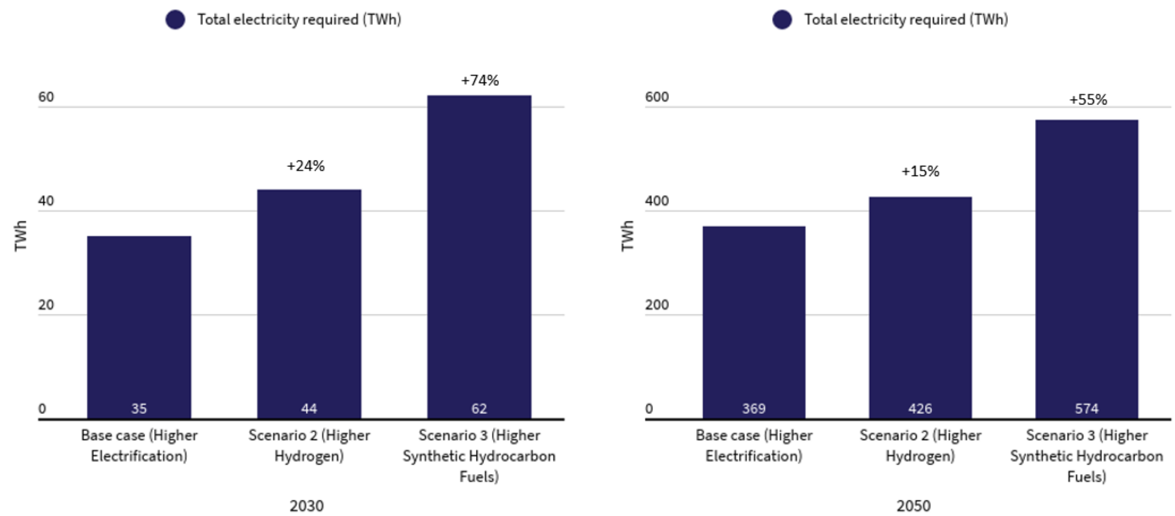
It should be emphasised that the 'higher hydrogen' and 'higher SHCF' scenarios still assume that most of the road fleet is electrified. Almost all cars, vans and lighter trucks (< 16t) not running on fossil fuels are assumed to be battery electric vehicles: 90% in the 'higher hydrogen' scenario and 80% in the 'higher SHCF' scenario[7].

Results

The scenarios emphasise different energy carriers for different transport modes, but the assumptions are not extremely different between the three scenarios. And yet, despite this, the results show that relatively small increases in the use of hydrogen and synthetic fuels in different transport modes can add up to significant differences in extra renewable energy that will need to be produced. **Compared to the base case, by 2030 the 'higher hydrogen' and 'higher SHCF' scenarios require 24% and 74% more renewable energy to be produced respectively. In 2050, the differences remain significant, 15% more for the 'higher hydrogen' and 55% more for the 'higher SHCF' scenario**.

[7] See Annex I for more details and assumptions

Comparison of total electricity requirements in different scenarios for the UK



TRANSPORT & ENVIRONMENT @transportenvironment.org

2.2. Is it possible to combine the decarbonisation of transport and other sectors using additional renewable electricity?

In the modelled base case 2050 scenario, the transport sector will require almost the same amount of electricity as the power sector is expected to generate for all other purposes, even as the power sector integrates new loads from heating, industry and the building sector (369 TWh for transport compared to 388 TWh for the UK power sector, 334 TWh of which is predicted to come from renewable sources[8]). In the case of the 'higher SHCF' scenario, the demand from the transport sector is almost 50% greater than all electricity generated for other purposes by the power sector. Alongside the energy requirements for the decarbonisation of transport, it must be remembered that if the heat sector also to a large extent comes to rely on hydrogen and SHCFs, then this additional energy demand will also

[8] Figures from section 4.1 of the original Ricardo report, which are themselves based on the 'Consumer Evolution' scenario from the National Grid 2019 Future Energy Scenarios.

be considerable and create competition for supply[9]. This begs the question whether the decarbonisation efforts of the transport sector and other sectors are compatible: does the transport demand in 2050 outstrip the UK's 2050 potential for renewable electricity generation?

The Ricardo report offers a reassuring answer. **Yes, the UK has the potential to produce enough electricity to decarbonise the transport, power and industry sectors with renewable energy produced in the UK.** The potential availability of renewable electricity sources from solar, wind and geothermal in the UK amounts to about 7280 TWh (and in the EU over 20,000 TWh)[10]. This potential is more than 7.5 times the highest demand projections from the grid and transport for renewables in 2050 made here and therefore we conclude that **the UK's renewables potential is theoretically not a constraint for decarbonising transport**. However, whilst there are sufficient wind resources, largely in the North Sea, realising even a fraction of the 'potential' represents an enormous challenge and the total renewable electricity generated will therefore remain limited. Accordingly, renewables must be used as efficiently as possible.

Curtailed renewable power to produce hydrogen and electrofuels? A non-starter.

The volume of renewable electricity curtailments is likely to increase with rising levels of renewable electricity, but curtailment alone will not play a meaningful role in delivering sufficient load hours for the electrolyser. In 2015, despite the record-breaking high share of variable renewable electricity sources and grid congestion challenges between wind-rich Scotland and more densely populated southern Britain, curtailed electricity did not exceed a couple of hundreds of hours per year per wind farm and was exceedingly rare for offshore wind. According to estimates made by Joos & Staffell[11] from payments made under the balancing mechanism, in 2015, curtailed energy from wind power did not exceed 1.25 TWh and the estimated curtailment rate was less than 6%. Electrolysers need at least a 30% load factor (about 3000 hours) to sufficiently bring down the production cost of

[9] For more details on competing demands of hydrogen, please see section 5.3 of the study by Ricardo Energy & Environment.

[10] To determine the renewables potential, the study by Ricardo Energy & Environment relied mainly on the 'Energy System Potentials for Renewable Energy' dataset (ENSPRESO).

[11] Michael Joos, Iain Staffell, Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany, Renewable and Sustainable Energy Reviews, Volume 86, 2018, Pages 45-65, https://doi.org/10.1016/j.rser.2018.01.009.(http://www.sciencedirect.com/science/article/pii/S1364032118300091). This is the latest available evidence on this.

electrofuels[12]. This is why relying on curtailed renewable power generation for large-scale electrofuel production is a non-starter.

Another argument against counting on much more curtailed renewable power generation is that curtailed electricity is not 'free electricity'. National Grid must offer compensation to curtailed operators, giving it an economic incentive to avoid curtailment. As a result, a combination of tools (reinforcements of transmission networks, storage solutions and flexibility markets) will have the combined effect of keeping curtailment to a minimum. A hybrid model, whereby electrofuels production uses local renewables, some curtailed power due to local congestion, as well as grid power, is possible in the future. However, the bulk of the energy needed to supply the transport sector with carbon-neutral hydrogen and electrofuels will require a new and additional renewable electricity supply.[13]

Other supply-side constraints such as training a skilled workforce, building up sufficient industrial production capacity and procuring natural resources (e.g. lithium, rare earth materials, etc.) to build the necessary renewable energy capacity were not part of the study, but could equally pose a significant challenge to produce sufficient renewables for decarbonisation. Similarly, the 'embedded emissions' involved in building renewables were outside the scope of this work. Other environmental impacts, such as water demand and air quality, are discussed below though.

2.3. Feasibility of ramping up renewable energy production in line with decarbonisation needs

A distinction between the renewables deployment in the period before and the period after 2030 should be made. The period before 2030 is marked by two developments. Firstly, great efforts are still needed to decarbonise grid electricity with an accelerated deployment of renewables. Secondly, the relatively small additional demand for electricity from the transport sector is mainly driven by road transport, especially passenger cars. The period after 2030 is marked by opposite developments: renewables may still need to grow their share of grid electricity, but will already deliver most

[12] Amela Ajanovic, Reinhard Haas, *Economic prospects and policy framework for hydrogen as fuel in the transport sector*, Energy Policy, Volume 123, 2018, Pages 280-288, ISSN 0301-4215, Retrieved from: https://doi.org/10.1016/j.enpol.2018.08.063

[13] For more details on the potential to curtailed renewable generation for electrofuel production, see section 5.2 of the study by Ricardo Energy & Environment.

electricity. And from the transport sector, the shipping and aviation sectors replace road transport as the main demand driver for additional renewable electricity.

In this briefing, renewable electricity capacity is illustrated in terms of the required offshore wind capacity needed. Offshore wind is well-suited to power electrolysers requiring a high load factor, and therefore is the most relevant renewable technology for the production of electrofuels and hydrogen. The offshore wind potential in the UK is large, and the UK is already a global leader in offshore wind deployment. To produce 1 TWh of electricity annually requires approximately 0.25 GW of offshore wind capacity, or just over 35 turbines[14]. The largest offshore wind farm in the UK is currently Hornsea One, with a capacity of 1.2 GW[15].

2.3.1. Until 2030, road transport drives additional renewables demand, but adds relatively little to overall electricity demand

In the base case scenario, the transport sector will require 35 TWh of electricity by 2030, with road transport (two-wheelers, cars, vans, trucks and buses) accounting for 80% of that (28 TWh). This transport demand should be contextualised by comparing it with the forecasted non-transport electricity demand: 348 TWh in 2030[16]. In other words, making significant progress by 2030 on decarbonising transport only leads to a 10% increase in demand for electricity. Adding 5.2 to 6.9[17] million battery-electric passenger cars on UK roads will lead to 14 TWh of demand in 2030, a 4% increase in electricity demand on that forecasted for the power sector.

---

[14] Capacity factors, turbine size and generation potential have been assumed through to 2050; this assumption is likely to prove highly conservative.

[15] Ørsted (2020). Hornsea One Offshore Wind Farm. Retrieved from: https://orstedcdn.azureedge.net/-/media/www/docs/corp/uk/updated-project-summaries-06-19/sept-2020/200819_ps_hornsea-one_v3_web-aw.ashx?la=en&rev=48e42a118f984711b23e7c11dd9e99ab&hash=D1C8FB48AA297F9095B1C66306B4A6A1

[16] As referenced in the report, assumed energy demand is from the "Distributed Energy" scenario within the Ten-Year Network Development Plan (TYNDP) 2020. ENTSOG and ENTSO-E, "Ten-Year Network Development Plan 2020," . Retrieved from: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2020/Foropinion/TYNDP2020_Main_Report.pdf

[17] Transport & Environment (2020) 'Recharge EU: how many charge points will Europe and its Member States need in the 2020s?', Table A1, Annex 3, p 65. Available at: https://www.transportenvironment.org/sites/te/files/publications/01%202020%20Draft%20TE%20Infrastructure%20Report%20Final.pdf

It should be added that these passenger cars - as 'batteries on wheels' - will be a key asset for grid operators given their significant flexibility potential. Smart charging will help to reduce the curtailment of wind and solar on the grid by 2030, cutting the carbon intensity of grid electricity and reducing the additional renewable electricity capacity needed for road transport.[18] This assumes a significant portion of EV charging is undertaken off peak using slow chargers. Nevertheless, the additional renewable electricity needed remains significant. To offer a sense of scale, the base case scenario requires the equivalent of 8.8 GW of additional offshore wind capacity (about 1260 wind turbines of 7 MW each). Each GW of offshore wind could generate around 4 TWh per year.

This is a significant challenge - equivalent to adding over 7 times Hornsea One[19] - but achievable. The cumulative capacity of offshore wind in 2019 in the UK amounted to 'only' 9.9 GW, but is planned to increase to 40 GW by 2030[20].

The 'higher hydrogen' scenario would require a further 2.1 GW of additional offshore wind capacity to be built by 2030 (or 300 extra wind turbines in addition to the 1260 needed to meet the base case). A greater role for synthetic hydrocarbons before 2030 – as modelled in the 'higher hydrocarbons'

---

[18] The advantages of smart charging were not part of the analysis undertaken by Ricardo Energy & Environment. However, several reports in recent years have already addressed the potential contribution of electric vehicles to reduce curtailment of wind and solar in grids that will have very high shares of renewables by 2030. See T&E (2019) *Batteries on Wheels: the role of battery electric cars in the EU power system and beyond.* Retrieved from https://www.transportenvironment.org/sites/te/files/publications/2019_06_Element_Energy_Batteries_on_wheels_Public_report.pdf and Elia Group (2020) *Accelerating to net-zero: Redefining energy and mobility.* Retrieved from https://www.eliagroup.eu/-/media/project/elia/shared/documents/elia-group/publications/studies-and-reports/20201120_accelerating-to-net-zero-redefining-energy-and-mobility.pdf. Their simulations for 2030 show 1.4 to 1.7 TWh less curtailment of renewables on the German grid, i.e. the equivalent of the annual consumption of 600,000 electric vehicles (out of a total of 11.5 million EVs in Belgium and Germany). Most recently, Nissan, E.ON Energy and Imperial College (2021) *The Drive Towards A Low-Carbon Grid.* Retrieved from https://www.eonenergy.com/content/dam/eon-energy-com/Files/vehicle-to-grid/The%20Drive%20Towards%20A%20Low-Carbon%20Grid%20Whitepaper.pdf. Their modelling shows that potentially whole-system cost savings of up to £883m per year are available.

[19] Capacity 1.2 GW and footprint 407km. Ørsted, 2020. 'Hornsea One Offshore Wind Farm. Retrieved from: https://orstedcdn.azureedge.net/-/media/www/docs/corp/uk/updated-project-summaries-06-19/sept-2020/200819_ps_hornsea-one_v3_web-aw.ashx?la=en&rev=48e42a118f984711b23e7c11dd9e99ab&hash=D1C8FB48AA297F9095B1C66306B4A6A1

[20] HM Government, 2020. The Ten Point Plan for a Green Industrial Revolution Retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

scenario - would require an extra 6.5 GW of offshore wind capacity by 2030 (an extra 935 wind turbines in addition to the base case, or a total of 2190 turbines by 2030).

Crucially, **the generational capacity required would be additional to the generational capacity needed to make significant progress in decarbonising grid electricity**. In 2020, wind, solar and hydro generated 75.3 TWh, or 15% of total generation[21], and the Department for Business, Energy and Industrial Strategy estimates that this will grow to 176 TWh, or 51% of total generation by 2030[22]. It therefore becomes very clear that choices need to be made about the best use of renewable electricity: it is clear that renewable electricity will still be a scarce commodity in 2030. The 'higher hydrogen' and 'higher synthetic hydrocarbons' scenarios show that an inefficient use of renewable electricity in transport will complicate the pre-2030 effort to decarbonise grid electricity by requiring an even steeper ramp-up of renewables.

It should be noted that the additional renewable electricity needed by 2030 would not be sourced exclusively from offshore wind farms in the UK alone. Multiple renewable technologies distributed all over the country will contribute to this effort, and imports will also play a role. Nevertheless, it is clear that the implications of not relying on the most efficient energy carrier – direct use of renewable electricity – in the transport sector where possible has major implications in terms of the amount of renewables needed in the next decade. This then has ramifications as to whether or not the UK achieves its climate change targets.

2.3.2. Between 2030 and 2050, shipping and aviation dominate the additional demand for additional electricity

The growth in demand for additional zero carbon electricity from the shipping and aviation sectors after 2030 is substantial, a near 27-fold increase over 20 years: from a modest 7TWh in 2030 to 187 TWh in 2050 in our 'base case' scenario. Over a period of 20 years, meeting this increase in demand alone will require building the equivalent of almost 45 GW of offshore wind exclusively for the use of these sectors: this equals installing an offshore wind turbine *every day* for nearly 18 years.

---

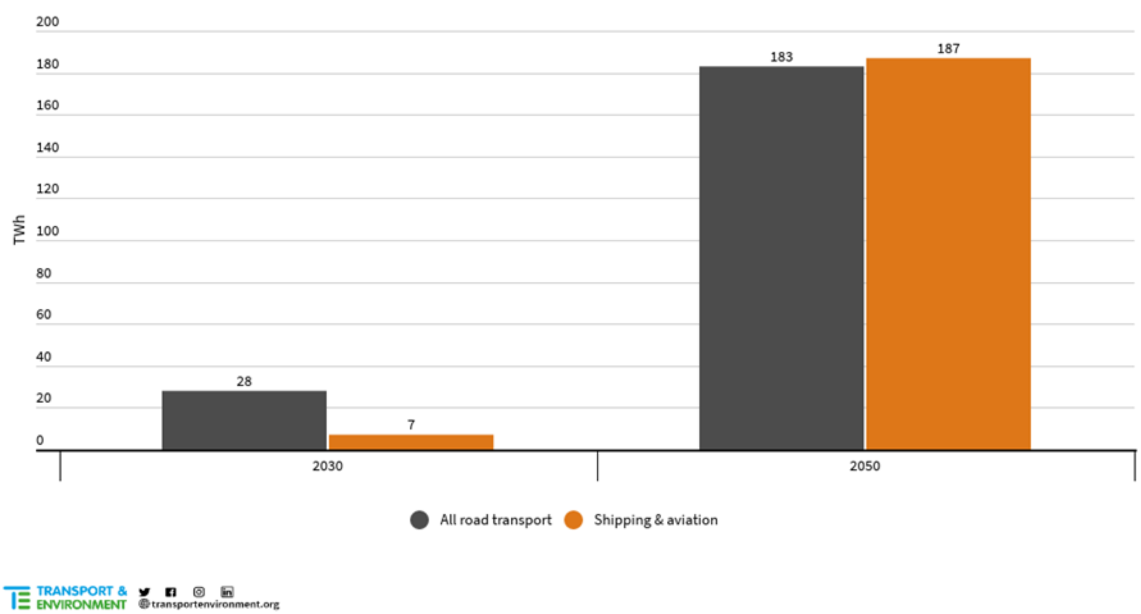
[21] BEIS, Dec 2020, 'Energy Trends Electricity Tables (ODS)' (Table 5.3), Retrieved from: https://www.gov.uk/government/statistics/electricity-section-5-energy-trends

[22] BEIS, 2019, Updated Energy & Emissions Projections v1.0 19-10-2020, Annex J Reference Scenario. Retrieved from: https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2019

Given the enormous energy demand of these long-distance transport modes, it is crucial to prioritize the use of electrofuels in sectors where there is no viable alternative. Using more liquid hydrogen instead of ammonia in shipping accounts for most of the additional 20 TWh in demand in the 'higher hydrogen' scenario (compared to the base scenario), as liquefaction requires more energy than synthesizing hydrogen and nitrogen into ammonia. An exclusive reliance on synthetic hydrocarbons in shipping and aviation ('higher synthetic hydrocarbon' scenario) would add 74 TWh in demand for renewables compared to the base case scenario.

While the renewable electricity demand for electrofuels for shipping and aviation grows very rapidly after 2030, renewable electricity demand for road transport grows less quickly: from 28 to 183 TWh, 'only' a 6-fold increase.

Comparison of electricity requirements for road transport with shipping plus aviation



2.4. There is a window of opportunity for a home-grown electrofuels industry

Despite an excellent start, the scale of the challenge to build sufficient renewables in the UK before 2050 is still huge. Some areas outside Europe have better renewables potential, especially those with better solar irradiation and / or stronger onshore wind resources. This better potential will enable these regions to produce renewable electricity more cheaply and - because the cost of electrofuels is mainly driven by the cost of the renewable electricity - will likely be able to produce lower cost electrofuels as a result.

Hydrogen costs will be cheaper if produced nearer to areas of consumption, due to the reduced transportation costs. **Transporting liquid hydrogen or ammonia via ships from further afield to the UK is currently almost always twice the cost of producing and using hydrogen in the UK.** Significant uncertainties exist about the cost of these bulk hydrogen carriers. Technological developments in this area and market forces will determine exactly how much of the UK's hydrogen demand will be imported, and how much of it can be produced domestically in the UK.

Apart from the costs, **an additional challenge is the lack of a regulatory framework and certification schemes to guarantee high sustainability standards of such renewables-based hydrogen and e-kerosene**.

A last consideration is the energy security angle. The UK has been a net importer of oil products since 2005 and pays £16 billion (2019 prices) annually for oil imports[23]. Pushing long-distance transport modes like shipping and aviation to use cleaner fuels has the added bonus of reducing the UK's reliance on oil imports. However, this is dependent on producing a significant amount of these fuels inside the UK. Swapping the UK's dependence on oil imports for the imports of more expensive hydrogen, ammonia or e-kerosene would fail to deliver the co-benefits of using locally produced fuels. Last, but not least, importing electrofuels from outside the EU must not result in slowing down the necessary decarbonisation path of the exporting countries in question.

In summary, there is a window of opportunity in the early 2020s for a UK electrofuels industry to ramp up production of renewables-based electrofuels and in doing so drive down the cost of electrolysers, synthesis reactors, storage solutions, etc. This will position the UK industry well to export these

[23] BEIS, 2020, DUKES statistics 1.4-1.6 Table 1.4 'Value Balance of Traded Energy'. Retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/923262/DUKES_1.4-1.6.xls

technologies and deploy these on a large scale in areas outside the UK from 2030 onwards. From that point, cheaper imports of electrofuels from countries with better renewables potential will likely play an important role in meeting the surge in demand for these fuels from shipping and aviation (as well as potentially other industrial sectors). For that to happen, the UK must; establish a regulatory framework that ensures high sustainability standards of electrofuels; and adopt demand-side policies that will drive the use of electrofuels, where direct electrification is not feasible.

3. Implications on electricity demand by transport segment

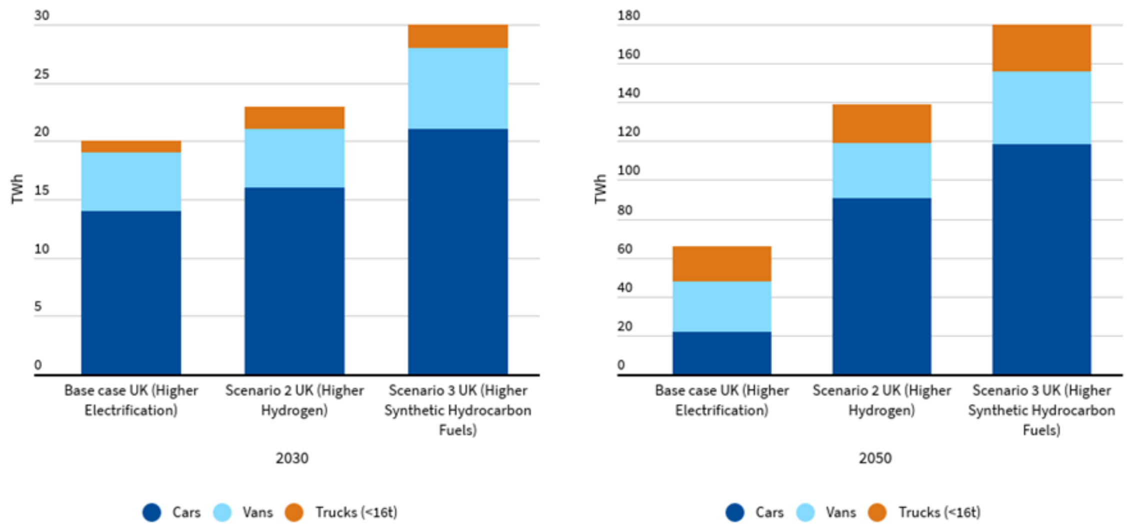
3.1 Cars, vans and lighter trucks (< 16 t): A small share of hydrogen and synthetic hydrocarbon use in light-duty vehicles makes a big difference

The results from the modelling show that **even a relatively small share of light-duty vehicles (10-20%) using hydrogen or synthetic hydrocarbons (e-diesel or e-gasoline) in 2030 will significantly increase the electricity needed for road transport**. If, in 2030, 10% of cars, vans and trucks <16t run using a fuel cell, then renewable electricity demand from this sector will increase by 12%. Relying - in addition - on 10% synthetic hydrocarbons use will increase the renewables demand by 47%. The 'higher hydrogen' scenario will require building an extra 0.6 GW offshore wind capacity by 2030 to meet that extra 2.4 TWh of additional demand. The 'higher synthetic hydrocarbon' scenario will require building an extra 2.4 GW of offshore wind by 2030 to meet the extra 9.6 TWh of additional demand.

While the additional renewable energy demand in the next 10 years is manageable, if unwanted, the long-term implications of promoting electrofuels in light-duty vehicles are significant. The 'higher hydrogen' scenario will require building an additional 2.9 GW of offshore wind by 2050 to meet that extra 12 TWh of additional demand compared to the base case. The 'higher synthetic hydrocarbon' scenario will require building an additional 13 GW of offshore wind farms by 2050 to meet the extra 53 TWh of additional demand. It should be remembered that the additional demand will be needed to enable 'only' 10% of hydrogen and 10% e-diesel in the 2050 fleet. This analysis confirms our initial finding from the 2018 synthesis report[24] that "an approach focused on using the most efficient pathways (direct charging) wherever possible is recommended". In short, UK policy should be focussed on ensuring that all cars, vans and small trucks are powered by a battery. Hydrogen and synthetic fuels should not be used in cars, vans and small trucks.

[24] T&E (2018), 'How to decarbonise European transport by 2050'. Retrieved from: https://www.transportenvironment.org/publications/how-decarbonise-european-transport-2050

Comparison of the electricity requirements for cars, vans and trucks (<16t)



Scenario assumptions for all three modes: **Base case** = 100 % direct electrification; **Scenario 2** = 10% hydrogen + 90% direct electrification; **Scenario 3** = 10% synthetic hydrocarbon + 10% hydrogen + 80% direct electrification

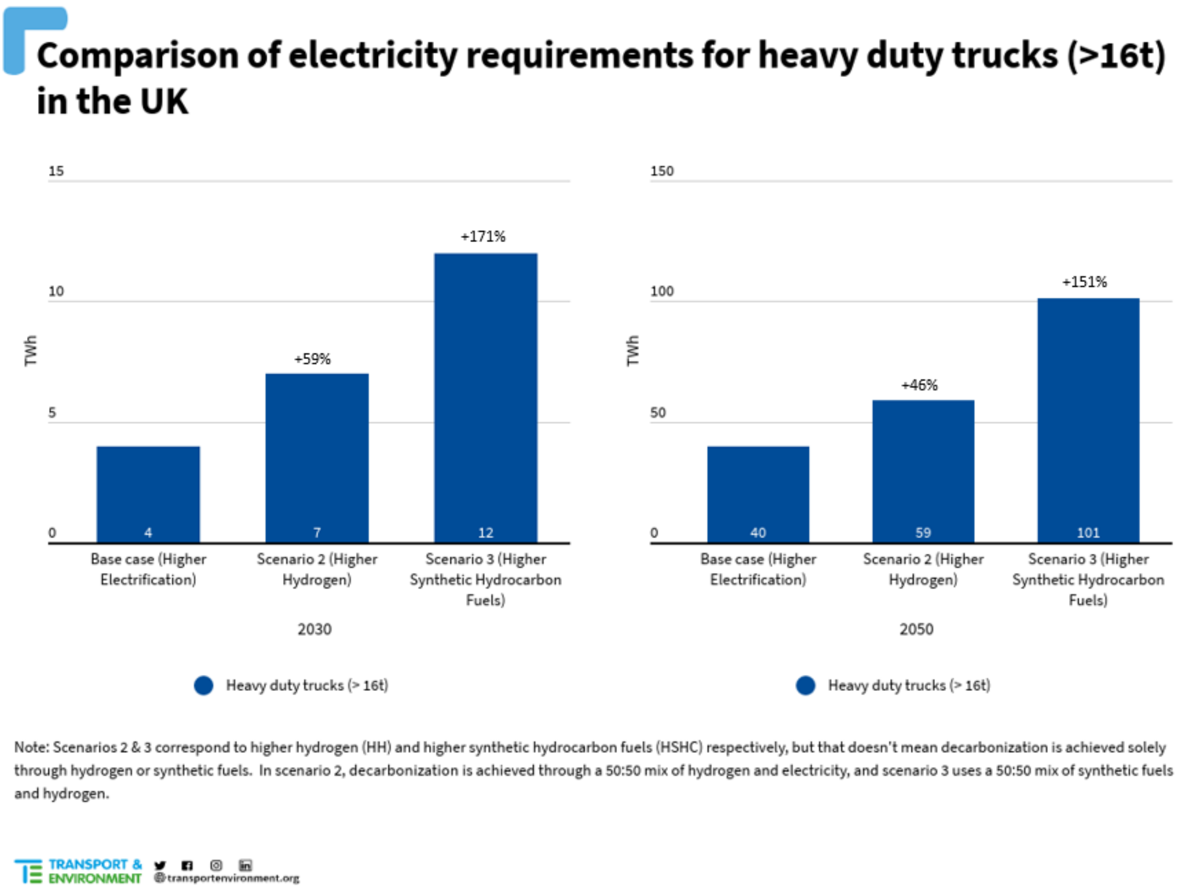
TRANSPORT & ENVIRONMENT @transportenvironment.org

3.2. Heavy-Duty Trucks: avoid e-diesel at all costs

The situation for heavy-duty trucks (>16t) shows a similar picture. **Decisions in the next few years on how to decarbonise the road freight sector will have long-term implications for future renewable electricity demand.** If direct electrification is pushed (as in the base case scenario), heavy-duty trucks will account for 12% of renewable electricity demand in transport (4TWh) in 2030. If half of the heavy-duty trucks belonging to the Zero Emissions Vehicles segment use hydrogen and the other half are battery-electric, heavy-duty trucks would account for 15%, or 7 TWh. That 3 TWh difference between the base case and the 'higher hydrogen' will require an extra 0.6 GW of additional offshore wind capacity to be built. Using e-diesel in half of heavy-duty trucks, and hydrogen fuel cells in the other half will require almost 12 TWh in total: triple the electricity that is needed in the base case. This is equivalent to 1.8 GW of additional offshore wind capacity that must be built by 2030.

Nothing changes when looking at the 2050 scenario figures either. Using e-diesel and hydrogen fuel cell trucks would mean that electricity demand from the truck sector would be 2.5 times what it would be if fully electrified: 101 TWh vs 40 TWh.

Clearly, **running heavy-duty trucks on e-diesel would make transport decarbonisation much more challenging and should be ruled out.** Efforts should be made now to ensure that as many trucks as possible are battery powered in the future.



3.3. Ships: Demand reduction before 2030, surge in electrofuels demand after 2030

The modelling for our study highlights an inconvenient and underappreciated truth : **by 2050, shipping will demand a huge amount of renewable electricity to supply hydrogen and ammonia as shipping fuels** (84 TWh or 23% of all demand for transport electricity in the base case). However, the pre-2030 demand for additional renewable electricity to produce shipping fuels is relatively small: just 3 TWh in the base case. This relatively small demand is because the infrastructure to refuel ships with hydrogen or ammonia simply won't be available at scale in the next decade. To start reducing the climate impacts of the shipping sector, measures to ensure ships operate as efficiently as possible (e.g. slow steaming, wind assistance technologies or improved cargo space utilisation) are needed to reduce energy demand from the sector and can be implemented immediately. The big surge in demand for hydrogen and ammonia from shipping in the period after 2030 (jumping from 3 TWh to 84 TWh or a 26 fold increase over 20 years) needs to be embedded in the UK's future renewable energy plans.

What does it take to refuel one containership with an ammonia fuel cell for a 32-day journey?

An average containership carries 30,200 tonnes of cargo. To refuel just one of these ships, a 2GW offshore wind farm could deliver 85% of the energy needed to power 4 ammonia plants, each consuming 280 MW of renewable energy and producing 700 tonnes of green ammonia per day. This total production - 2800 tonnes - is the amount needed to refuel each one of these larger containerships for 32 days.

3.4. Planes : start small and ramp up after 2030

The aviation sector will need to predominantly rely on synthetic hydrocarbons to decarbonise, supplemented with a very limited amount of advanced biofuels and hydrogen for some short haul flights. By 2050 aviation has the highest energy demand of all transport modes in each of the 3 scenarios. In the base case, aviation will account for 28% of all demand for renewable electricity from transport: 103 of the 369 TWh total. **Aviation demand for electricity in 2050 is higher than the 83 TWh required for all battery electric passenger cars in the UK in 2050.** The high renewables' demand of the aviation sector is the direct result of the conversion losses involved in the production of synthetic hydrocarbons which means that, from an energy generation point of view, as many planes as possible should be directly fuelled by either hydrogen via a fuel cell, or a battery.

Synthetic hydrocarbons can be combusted - just like fossil kerosene today - in a jet turbine, with minimal or no modifications to the aircraft, engines or ground refuelling infrastructure. While their use could in theory be increased rapidly, there are some real world implications to consider. Today, these fuels are still very expensive, at around £2700/ton. [25]

4. Environmental aspects

4.1. Climate impacts

In contrast to the progress made in decarbonising the power sector, emissions from the transport sector have been relatively unchanged since 1990. **Our scenarios will deliver a greenhouse gas reduction of 11% in 2030 compared to 1990 levels[26]**, reducing to 109 Mt CO_2e. This drop in emissions results from relying on additional zero-emission renewable electricity.

[25] Cerulogy (2017, November) *What role is there for electrofuel technologies in European transport's low carbon future?* Retrieved from: https://www.transportenvironment.org/sites/te/files/publications/2017_11_Cerulogy_study_What_role_electrofuels_final_0.pdf

[26] Baseline from the UNFCCC, 2019, 'Summary of GHG Emissions for United Kingdom of Great Britain and Northern Ireland', Retrieved from: https://di.unfccc.int/detailed_data_by_party

Blue hydrogen, low carbon? It depends ...

The study by Ricardo Energy & Environment reviewed the evidence on blue hydrogen, which is produced from steam methane reforming of fossil gas combined with Carbon Capture and Storage. The available evidence shows that the lifecycle emissions are lower than unabated fossil gas, but that the associated emissions are still significant. **The low-carbon status of blue hydrogen depends on optimistic assumptions about emissions throughout the full supply chain**: upstream emissions, the capture rate of CCS, leakage of CO_2 during CO_2 transport and storage.[27] The wide range in the estimates of lifecycle emissions of blue hydrogen – between 30 and 99 g CO_2/kWh[28] – shows the level of uncertainty about the low-carbon status of blue hydrogen. Without resolving these issues blue hydrogen cannot be a realistic long-term solution to achieving full decarbonisation.

4.2. Water demand for electrofuels : significant, but manageable.

Producing electrofuels - using renewable electricity in an electrolyser - will require significant volumes of water. While significant in absolute terms, the water-related impacts of producing electrofuels should be considered in context. The total water volume required to produce the electrofuels in our modelling for the transport sector by 2050 will amount to up to 78 billion litres in the higher SHCFs scenario; this is equivalent to almost 4% of the UK's total annual demand and more than double the current water demand of electricity production[29].

Despite its relatively low water consumption, electrofuels production should not be situated in areas with limited rainfall and where groundwater levels are already stressed. In the UK, this means avoiding the south east of the country. One important caveat should be added: electrolysis requires highly-purified water, whereas nuclear and fossil power plants can use untreated river or sea water.

---

[27] For more details, see the Ricardo Energy & Environment, section 7.3. 'Environmental risks with blue hydrogen'.
[28] Leeds city gate H21, "Uploaded content," April 2017. [Online]. Available: https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf.
AND Committee on Climate Change, "Hydrogen in a low-carbon economy," Committee on Climate Change, UK, 2018.
[29] EEA (2018), 'Water exploitation index plus (WEI+) for river basin districts (1990-2015)'. Retrieved from: https://www.eea.europa.eu/ds_resolveuid/9948286eb23448c780a8ac4a5109e8b5.

This is why coastal areas may be better suited for electrofuels production. Desalination plants can pre-treat the water to the required level of purity. The energy penalty for relying on desalination is small: just 0.1 % of the electricity required for the electrolysis. The waste product of desalination is brine, which needs to be treated and reintroduced to the environment responsibly.

4.3. Air quality: Electrofuels offer limited benefits

Battery electric vehicles, of all shapes and sizes, are the only technologies able to reduce tailpipe emissions of air pollutants to zero. Hydrogen fuel cell vehicles also have negligible impact on air pollution levels (the waste is pure water, which operates as a greenhouse gas when given out by a plane at altitude, but is harmless at ground level). Hydrogen fuel cell vehicles can also actually improve the air quality marginally, when used in a fuel cell with an advanced filtering system attached to the air intake.

However, when hydrogen is combusted in an internal combustion engine, NOx emissions can be elevated: as high as when fossil fuels are combusted. Other pollutants like sulphur dioxide, carbon monoxide, heavy metals and particulates decrease substantially. Selective Catalytic Reduction (SCR) can reduce NOx emissions by 90%. However, such abatement technologies require ongoing operation and maintenance to operate effectively. Without an effective compliance or monitoring programme, truck or ship owners may be tempted to neglect operation and maintenance to save on costs.

The same applies to combusting ammonia in an engine. SCR technologies can reduce NOx emissions. However, if an SCR scrubber is not working optimally nitrous oxide (N_2O) emissions will still be emitted, so the calibration of these systems to minimise N_2O will be important to prevent emissions of this potent greenhouse gas.

When ammonia is used in a Solid Oxide Fuel Cell, this type of fuel cell causes oxygen to react with the ammonia, releasing NOx and water as by-products of electricity generation. As with hydrogen combustion, NOx can be captured at the exhaust by SCR technology. The combustion of ammonia also leads to emissions of particulate matter, albeit in lower concentrations than emissions of conventional fuels, as well as unburnt particles of ammonia. Technologies for better engine calibration and better control of combustion conditions need to be developed in the near future to resolve this problem.

Combusting synthetic hydrocarbons instead of fossil fuels delivers only small benefits in terms of air quality. The exhaust from e-diesel or e-kerosene combustion still contains CO, NOx and particulate matter. Emissions from the first two of these pollutants would be at a similar level to fossil-derived kerosene, but the concentration of particulate matter is likely to be lower due to the absence of impurities. NOx emissions from e-diesel are similar or lower than fossil-derived diesel (but deNOx exhaust aftertreatment technology can help reduce this). Combusting e-kerosene in jet engines will lead to NOx emissions, which increases ground-level ozone formation.

5. Conclusion: Policy recommendations

This study confirms the findings of other studies that it is feasible for renewable electricity to replace fossil fuels to power transport in the UK. However, a range of different energy carriers will be needed, and what proportions of which energy carriers are used dramatically affects the total energy demand required. Before 2030, the additional renewable electricity demand is relatively modest and mainly driven by passenger cars. However, afterwards demand for renewable electricity increases dramatically, whatever the scenario. Decisions taken in the 2020s that unnecessarily increase the amount of renewable generation capacity needed in the 2030s and 2040s should be avoided at all costs. In practice, this means pursuing policies that encourage battery electric transport wherever possible and restricting use of hydrogen to where it is unavoidable.

Our scenarios show that relatively small percentages of hydrogen and e-fuelled vehicles can have a major effect on the amount of renewables generation required. Compared to the base case, by 2030 the 'higher hydrogen' and 'higher SHCF' scenarios require 24% and 74% more renewable energy to be produced respectively. In 2050, the differences remain significant, 15% for the 'higher hydrogen' and 55% for the 'higher SHCF' scenario.

Given the scale of required investment and construction, T&E has concluded the optimal pathway for road transport is to select the most efficient energy carrier that is feasible, and for all cars and trucks this is direct charging. Green hydrogen and electrofuels are energy intensive in their production, and if the challenge posed in producing the amount of clean electricity needed for transport is not to become insurmountable, they should be prioritised for long-distance shipping and aviation - sectors where there is currently no reasonable viable alternative.

Decarbonisation of transport cannot be planned one transport mode at a time. Just as there is not sufficient land for biofuels to meet all transport energy demands, it is also not feasible for renewable electricity to power transport if it is used to manufacture hydrogen and synthetic fuels for all transport modes. The key policy messages from this study are that the Government should:

1. Recognise in the Decarbonisation of Transport Plan that there must be a holistic (ie not mode by mode) approach to decarbonising transport and that demand reduction is important to reduce overall energy demand.
2. Develop a delivery plan to electrify all cars, vans and smaller trucks (<26 tonnes) used for urban and regional deliveries, as it would be a grossly inefficient use of renewable electricity to produce hydrogen for them. Charging should be as smart as possible to minimise impacts on electricity grids and provide demand for offshore wind at night.
3. Rule out the future use of synthetic fuels in long haul trucks and trial battery electric, electric road system and hydrogen options - and recognise that of these, battery electric heavy trucks or using electric road systems are the preferable in terms of total energy demand.
4. Strengthen the incentives to supply e-kerosene to the aviation sector; including by developing a mandate requiring an increasing share in UK aviation fuel (potentially complemented by a contract for difference approach to support the manufacture of new UK production).
5. Include UK shipping in the ETS under the geographical scope of the UK shipping MRV regulation, and mandate the uptake of green hydrogen and ammonia by UK shipping via operational energy carbon intensity standards.

It is clear the additional demand for renewable electricity will be significant, whatever choices are made. Lowering the energy demand in the transport sector by promoting public transport, shared vehicle use, modal shift, logistics efficiency and reducing air travel when there are land-based alternatives are therefore important complementary policies to help to reduce the scale of the challenge. Nevertheless, it is clear that if the UK uses renewable electricity in smart and efficient ways it is possible to fully decarbonise the transport sector through UK generated electricity only: it will not be necessary to rely upon biofuels or offsetting (except possibly for indirect greenhouse gas emissions from aviation) to meet the UK's net zero goal.

Further information

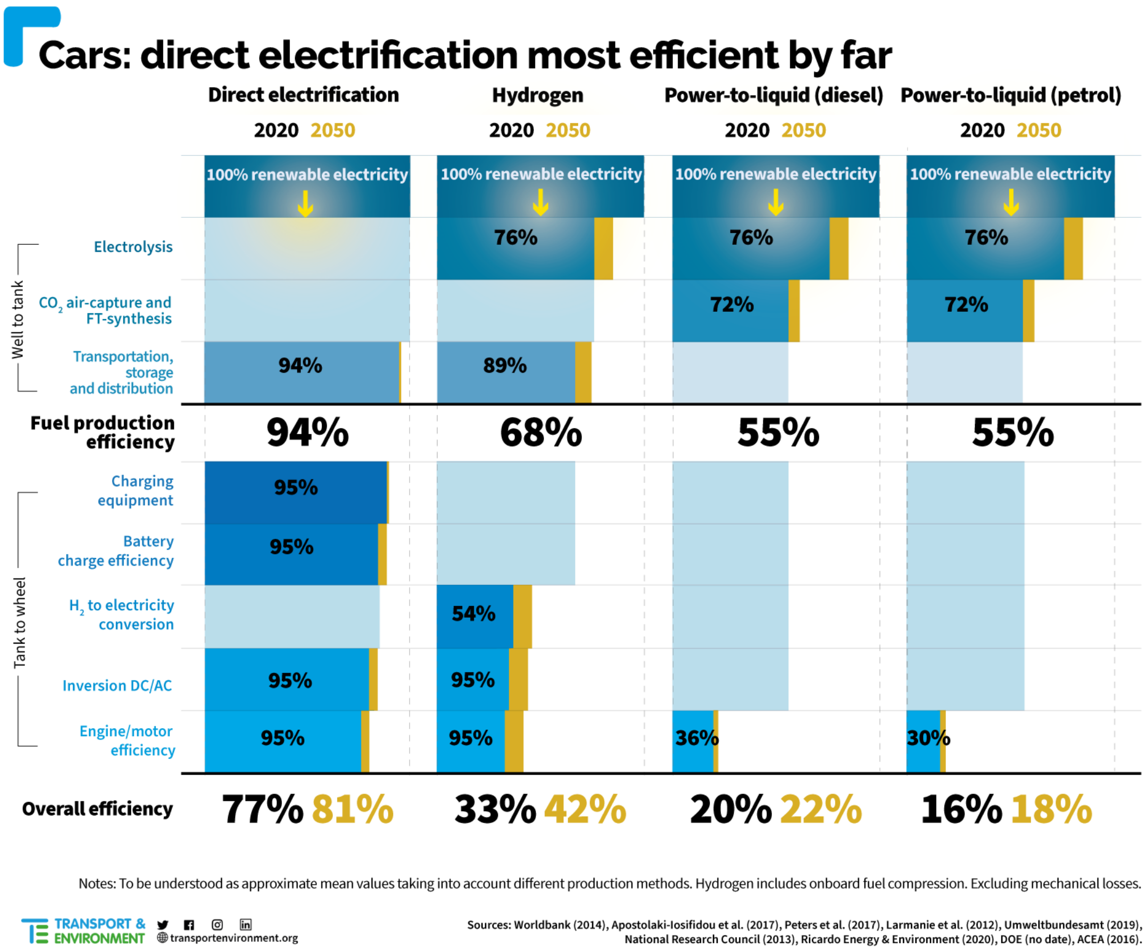
Matt Finch
UK Policy Manager
Transport & Environment
matt.finch@transportenvironment.org
Mobile: 0044 (0) 7881 812 398

ANNEX I: Scenario assumptions for all transport modes

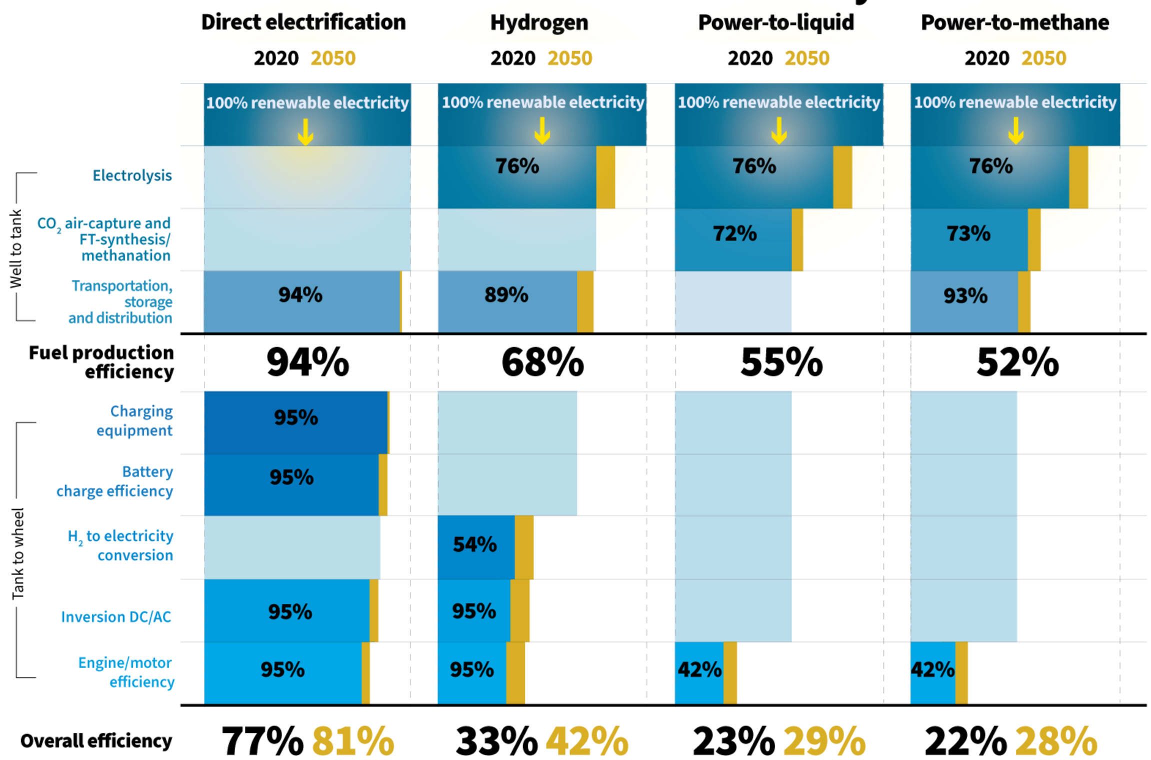
Summary of assumptions for the three scenarios.

Modes	Base Case – High electrification	Scenario 2 – Higher hydrogen	Scenario 3 – Higher SHCF
Motorbikes	100% direct electrification	100% direct electrification	100% direct electrification
Cars	100% direct electrification	10% hydrogen + 90% direct electrification	10% SHCF + 10% hydrogen + 80% direct electrification
Vans	100% direct electrification	10% hydrogen + 90% direct electrification	10% SHCF + 10% hydrogen + 80% direct electrification
Buses	100% direct electrification	50% hydrogen + 50% direct electrification	50% SHCF + 25% hydrogen +25% direct electrification
Trucks (<16t)	100% direct electrification	10% hydrogen + 90% direct electrification	10% SHCF + 10% hydrogen + 80% direct electrification
Trucks (>16t)	100% direct electrification	50% hydrogen + 50% direct electrification	50% SHCF + 50% hydrogen
Shipping	19% direct electrification + 27% hydrogen + 54% ammonia	5% direct electrification + 75% hydrogen + 20% ammonia	100% SHCF
Aviation	84% SHCF + 11% advanced biofuels + 5% direct electrification	90% SHCF + 5% advanced biofuels + 5% hydrogen	100% SHCF

ANNEX II: Conversion efficiencies



Trucks: direct electrification most efficient by far



Notes: Efficiency rates of long-haul HGVs. To be understood as approximate mean values taking into account different production methods. Direct electrification represents both BEVs running on batteries and/or overhead catenaries. Hydrogen includes onboard fuel compression, while power-to-methane includes fuel liquefaction. Assuming same engine efficiency for diesel and dual-fuel HPDI gas vehicles. Excluding mechanical losses.

TRANSPORT & ENVIRONMENT transportenvironment.org

Sources: Worldbank (2014), Apostolaki-Iosifidou et al. (2017), Peters et al. (2017), Larmanie et al. (2012), Umweltbundesamt (2019), National Research Council (2013), Ricardo Energy & Environment (2020), Delgado et al. (2017).

Energy type	Conversion step	Efficiency[30]		Source
		2030	2050	
Fossil petrol	Engine efficiency for cars	30%	30%	U.S. Department of Energy (no date). Where the Energy Goes: Gasoline Vehicles. Retrieved from https://www.fueleconomy.gov/feg/atv.shtml
Fossil diesel	Engine efficiency for cars	36%	36%	ACEA (2016). Differences Between Diesel and Petrol. Retrieved from https://www.acea.be/news/article/differences-between-diesel-and-petrol
	Engine efficiency for trucks[31]	42%	42%	Delgado et al. (2017). Fuel efficiency technology in European heavy-duty vehicles: Baseline and potential for the 2020-2030 timeframe. Retrieved from https://theicct.org/sites/default/files/publications/EU-HDV-Tech-Potential_ICCT-white-paper_14072017_vF.pdf
Fossil HVO	Engine efficiency for ships	51%	51%	Anantharaman et al. (2015). Marine Engines and their Impact on the Economy, Technical Efficiency and Environment. Marine Engineering. 50. Retrieved from https://www.jstage.jst.go.jp/article/jime/50/3/50_360/_article and Wärtsilä (2020). Wärtsilä engine fuel efficiency development. Retrieved from https://www.wartsila.com/sustainability/innovating-for-sustainable-societies/improving-efficiency
Fossil	Engine efficiency for	39%	43%	National Academies of Sciences,

[30] It should be noted that the illustrative figures above represent the efficiency rates for 2020 and 2050, whereas the table lists the respective values for 2030 and 2050.
[31] In the case of the average brake thermal efficiency of long-haul trucks, it was assumed that the current engine efficiency of 42% remains constant over time. The conversion efficiency rates in the figures above also show the maximum technical engine efficiency potential of 48% that could theoretically be achieved.

kerosine	planes			Engineering, and Medicine (2016). Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. Washington, DC/US. Retrieved from https://www.nap.edu/catalog/23490/commercial-aircraft-propulsion-and-energy-systems-research-reducing-global-carbon
Direct electrification	Electricity transmission and distribution	95%	95%	Worldbank (2014). Electric power transmission and distribution losses for the European Union. Retrieved from https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?l&locations=EU
	Conversion AC/DC	95%	95%	Apostolaki-Iosifidou et al. (2017), Measurement of power loss during electric vehicle charging and discharging, Energy, 127. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360544217303730
	Battery charge efficiency	96%	99%	Peters et al. (2017). The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews. 67. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S1364032116304713
	Inversion DC/AC	95%	95%	Larmanie et al. (2012). Electric vehicle technology explained. 2nd edition. Wiley. West Sussex/UK.
	Motor efficiency	95%	95%	Larmanie et al. (2012).
Renewable hydrogen	Electrolysis	79%	85%	Wachsmuth et al. (2019). Roadmap Gas für die Energiewende – Nachhaltiger Klimabeitrag des Gassektors. Retrieved from https://www.umweltbundesamt.de/sites/de

				fault/files/medien/1410/publikationen/2019-04-15_cc_12-2019_roadmap-gas_2.pdf
	Transport, storage and distribution incl. compression	89%	89%	Wachsmuth et al. (2019).
	Transport, storage and distribution incl. liquefaction	75%	75%	U.S. Department of Energy (2019). DOE Hydrogen and Fuel Cells Program Record. Current Status of Hydrogen Liquefaction Costs. Retrieved from https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf
	Hydrogen to electricity conversion (PEM)	56%	61%	National Research Council (2013). Transitions to Alternative Vehicles and Fuels, The National Academies Press, Washington, DC/US. Retrieved from https://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels
	Inversion DC/AC	95%	95%	Larmanie et al. (2012).
	Motor efficiency	95%	95%	Larmanie et al. (2012).
Power-to-liquid	Electrolysis	79%	85%	Wachsmuth et al. (2019).
	CO_2 direct air-capture and FT-synthesis	72%	72%	Ricardo Energy & Environment (2020). Renewable electricity requirements to decarbonise transport in Europe with electric vehicles, hydrogen and electrofuels.
	Engine efficiency for cars (synthetic petrol)	30%	30%	U.S. Department of Energy (no date).
	Engine efficiency for cars (synthetic diesel)	36%	36%	ACEA (2016).
	Engine efficiency for trucks (synthetic diesel)	42%	42%	Delgado et al. (2017).

	Engine efficiency for ships (synthetic diesel)	51%	51%	Anantharaman et al. (2015) and Wärtsilä (2020).
	Engine efficiency for planes (synthetic kerosene)	39%	43%	National Academies of Sciences, Engineering, and Medicine (2016).
Power-to-methane	Electrolysis	79%	85%	Wachsmuth et al. (2019).
	CO_2 direct air-capture and methanation	73%	73%	Ricardo Energy & Environment (2020).
	Transport, storage and distribution incl. liquefaction	93%	93%	Wachsmuth et al. (2019).
	Engine efficiency for ships (synthetic methane)	51%	51%	Anantharaman et al. (2015) and Wärtsilä (2020).
Power-to-ammonia	Electrolysis	79%	85%	Wachsmuth et al. (2019).
	Ammonia-synthesis	78%	78%	Pfromm (2017). Towards sustainable agriculture: Fossil-free ammonia. Retrieved from https://aip.scitation.org/doi/10.1063/1.4985090
	Ammonia to electricity conversion (SOFC)	56%	61%	National Research Council (2013).
	Inversion DC/AC	95%	95%	Larmanie et al. (2012).
	Motor efficiency	95%	95%	Larmanie et al. (2012).
	Engine efficiency for ships (synthetic ammonia)	51%	51%	Anantharaman et al. (2015) and Wärtsilä (2020).
Power-to-methanol	Electrolysis	79%	85%	Wachsmuth et al. (2019).
	CO_2 direct air-capture	72%	72%	Ricardo Energy & Environment (2020).

	and FT-synthesis			
	Engine efficiency for ships (synthetic methanol)	51%	51%	Anantharaman et al. (2015) and Wärtsilä (2020).