Electrofuels? Yes, we can ... if we're efficient

Decarbonising the EU's transport sector with renewable electricity and electrofuels

December 2020

Executive Summary

The scale of decarbonising transport using renewable electricity is challenging, but the EU is well positioned to meet that challenge : the renewables potential in the EU far outstrips future demand. The EU could meet the transport sector's demand for the direct use of renewable electricity, the electrofuels produced from renewable sources in sectors like shipping and aviation where direct use of electricity is not feasible as well as meet the electricity and hydrogen demand in other sectors like power and industry.

In the next decade, there is a window of opportunity for European industry to become leaders in developing and driving down the costs of the technologies involved in producing renewables-based hydrogen and other electrofuels. Currently, the major costs involved in transporting hydrogen over longer distances via ships (by liquefaction or conversion into ammonia) creates an opportunity for production in the EU or importing it via pipeline from its immediate neighbourhood.

But for the EU to live up to this challenge, there is no scope to use renewable electricity inefficiently. Enabling the use of e.g. synthetic hydrocarbons in road transport, where technical alternatives such as the direct use of electricity exist, comes with a huge energy penalty and risks derailing the entire decarbonisation effort.

The study underpinning this briefing outlined three scenarios, which emphasize different energy carriers for different transport modes. A base case scenario relying on direct electrification of all transport whenever feasible, a scenario with a greater reliance on hydrogen and a scenario with more synthetic hydrocarbons. While the scenario's assumptions are quite similar (e.g. all assume that at least 80% of all cars, vans and trucks under 16 tonnes will be battery electric), the results show that relatively small variations in the use of hydrogen and efuels can add up to large differences in terms of the renewable energy that will need to be produced.

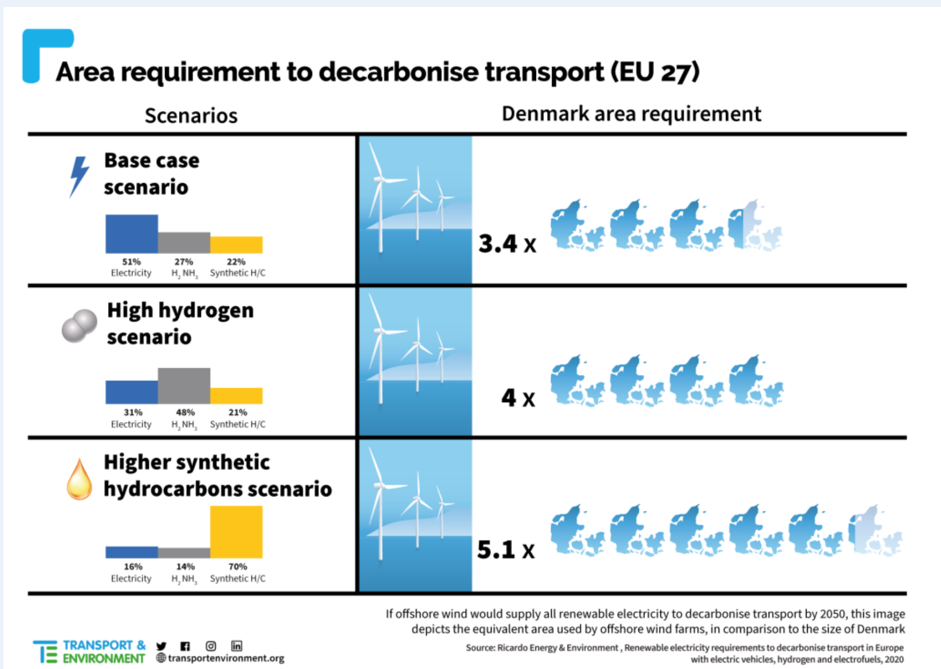
- For the EU27, the base case scenario shows that the decarbonisation of transport will require 2414 TWh of renewable electricity in 2050. To give a sense of scale, this would be the equivalent of 305 offshore wind farms with 2 GW capacity (or the equivalent of about 87,000 wind turbines of 7MW) to be deployed over the next 30 years.
- The 'higher hydrogen' scenario would require about 15% more renewable electricity or a total of 2797 TWh. Given the limited number of fuel cell vehicles currently on the market, this scenario assumes a relatively small share of hydrogen - 10% for cars, vans and trucks, but a bigger 50% share for buses and heavy-duty trucks. A greater role for fuel cell vehicles than assumed in this scenario would of course increase the renewable electricity well beyond the 15%.
- The 'higher synthetic hydrocarbon' scenario - using only synthetic hydrocarbons in shipping and a small share in road transport - would require 40% more renewable electricity or a total of 3598 TWh.

For example, if 100% of passenger cars were battery-electric, charging them would require 417 TWh in 2050 (just 15% compared to current total electricity demand). Enabling only 10% hydrogen plus 10% of synthetic hydrocarbons in cars would push up demand to 598 TWh or a 36% difference. Similarly, if all trucks over 16 tonnes were battery electric, demand for renewable electricity would be 347 TWh in 2050. Running half of these trucks on fuel cells would increase renewable electricity demand to 506 TWh or a 37% difference.

Prioritising direct electrification over electrofuels in road transport has the added benefit that smart charging of passenger cars as 'batteries on wheels' will help reduce the curtailment of high shares of wind and solar on European grids by 2030, potentially reducing the additional renewable electricity needed to charge them by almost 10%. By 2050, this potential could be even greater with a near 100% electrified road fleet and very high shares of renewables across the EU.

These major differences between the three scenarios in terms of the renewables deployment illustrates the importance of efficiency from an energy systems perspective; promoting even a limited use of synthetic hydrocarbons in road transport now will lock the EU's transport decarbonisation in a pathway that will require a much greater deployment of renewables than necessary. This makes the transition harder to accomplish and could complicate the decarbonisation of the long-distance transport modes like aviation and shipping.

The land use involved in decarbonising transport with renewable electricity helps to bring the size of the challenge to life : delivering the energy needed for the base case scenario will require an area equivalent to 3.4 times the size of Denmark, if offshore wind would supply all of the additional electricity needed to decarbonise the transport sector. The 'higher hydrogen' scenario will require 4 times and 'higher synthetic hydrocarbon' scenario even 5.1 times the area of Denmark.



Lowering the energy demand in the transport sector by promoting public transport, shared vehicle use, modal shift, logistics efficiency and reducing air travel can help to reduce the scale of the challenge.

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1. Context

The debates on decarbonizing the EU economy and transport in particular have been marked by many silver bullets, offering simple solutions to complex problems : the proposals are as diverse as the groups that propose them. Silver bullets include drastic demand reductions in transport, with dramatically less air travel, fewer cars and less freight transport. Other silver bullets include a switch from oil to biofuels or synthetic hydrocarbons like ediesel, switching the fuels but not the powertrain. The gas industry has promoted renewable gaseous fuels like biomethane or e-LNG as shipping fuels. The current hype about hydrogen as an energy carrier to decarbonise the entire EU transport sector – importing a lot of it from sunnier and windier places – will also not fail to disappoint.

Steering away from the easy answers, Transport & Environment published between 2017 and 2019 a series of roadmaps with detailed decarbonisation scenarios. These scenarios have tried to avoid the pitfalls of silver bullets by outlining decarbonisation pathways for all transport modes.[1] These pathways have charted an ambitious trajectory for the EU's transport sector. Demand reduction by means of behavioural changes or a modal shift plays an important role, but can only reduce emissions by a certain amount; it cannot achieve full decarbonisation. EU policies like carbon pricing will influence future transport demand. However, other actors like cities and regions will play a bigger role in creating less car-centric cities, promoting public transport, cycling and walking. This is why the T&E scenarios mostly focused on technological solutions from a powertrain or fuels perspective.

We concluded that the only form of zero emission energy that has the potential to power transport at scale is renewable electricity. It can be deployed either directly (e.g. battery cars, catenary trucks) or in the form of other energy carriers (hydrogen, electrofuels made from electricity from additional

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[1] T&E (2018) *How to decarbonise European Transport by 2050 - Synthesis report*. Retrieved from https://www.transportenvironment.org/sites/te/files/publications/2018_11_2050_synthesis_report_transport_decarbonisation.pdf With all modes rapidly decarbonising to zero by 2050, the transport sector as a whole manages to remain within the 2°C carbon budget. The cumulative emissions of European transport are well above the 1.5°C carbon budget. See section 5 'Carbon budget' for more details.

renewables). This also means that the decarbonisation of the power sector is a prerequisite for a zero emission transport system.

In our 2018 synthesis report, we already recognized the need for very large investments in the renewables and electricity transmission grids. We alerted policy-makers that shipping and aviation are sectors where vast amounts of hydrogen and synthetic fuels will be required. And that if all transport modes would be decarbonised by using synthetic fuels, the decarbonisation challenge would be unattainable due to the amount of clean electricity required. We concluded that the most optimal pathway for road transport would be based on mostly direct charging, whenever technically feasible. Electrofuels (hydrogen and synthetic hydrocarbons), which involve major energy conversion in their production, should be prioritized for those transport modes like long-distance shipping and aviation.

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 transport's and economy-wide demands with additional renewables' capacity in Europe. We start from the assumption that all electricity demand from transport will be met with additional renewables.

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 EU27, unless otherwise indicated.

2. The renewables needed to decarbonise the EU transport sector

2.1. Introducing three scenarios and their results

Three scenarios were investigated to explore the implications of prioritising different energy carriers for transport, including road transport, shipping as well as aviation.[2] The scope covers all domestic transport as well as outbound journeys from the EU by ships and planes.

- **Scenario 1 and Base Case – High Electrification**: Direct electrification wherever practicable (including for buses and all trucks) and optimal electrofuels selected for other modes.

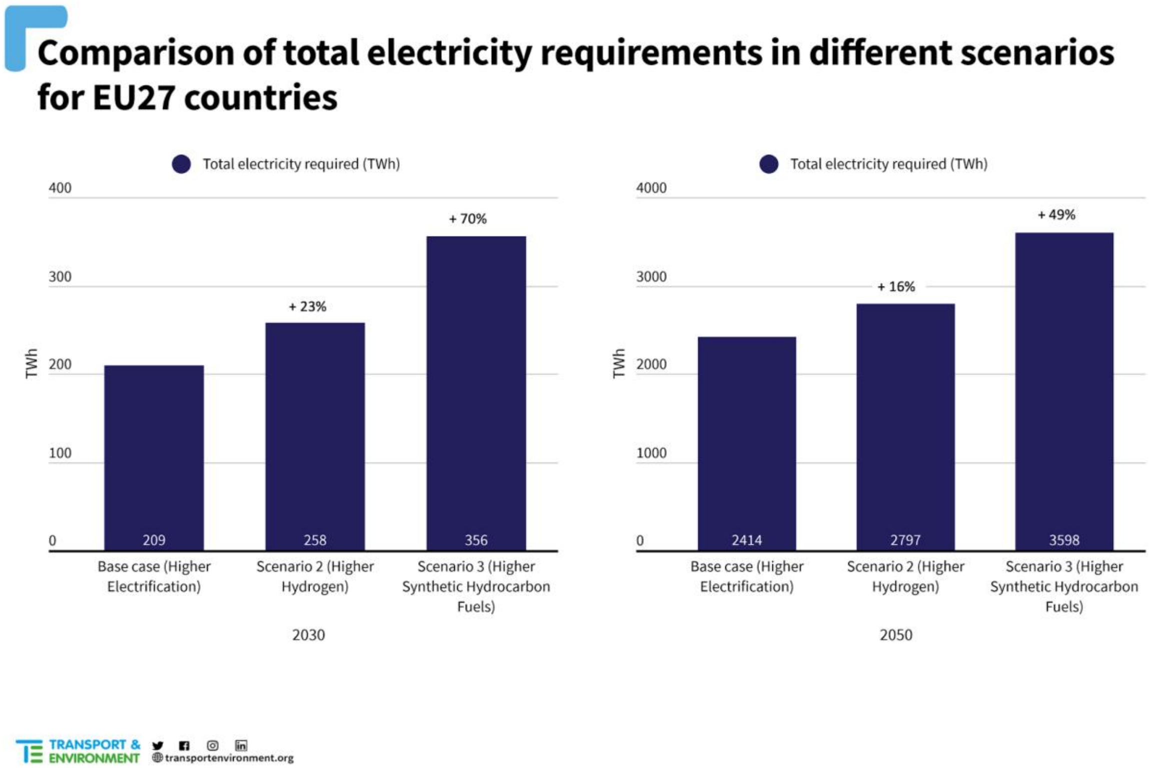
[2] All these scenarios share the same assumptions about energy efficiency measures and demand reduction measures. See section 1.5 of the Ricardo report for more details.

- **Scenario 2 – Higher Hydrogen**: Hydrogen displaces electrification and plays a bigger, albeit limited role in road transport. In shipping, more hydrogen is used, replacing direct electrification and ammonia.
- **Scenario 3 – Higher Synthetic Hydrocarbon Fuels (HSCF)**: Synthetic hydrocarbons displace electrification in some transport modes. Similar as the 'Higher Hydrogen' scenario, but shipping and aviation would rely on 100% synthetic hydrocarbons.

It should be emphasized that the 'higher hydrogen' and 'higher SHCF' scenarios do not rule out electrification for road transport altogether. 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.[3] See the assumptions in Annex I.

The scenarios emphasize 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 differences can add up to significant differences in terms of the renewable energy that will need to be produced. Compared to the base case, the 'higher hydrogen' and 'higher SHCF' scenarios require in 2030 about 20% and about 50% more renewable energy to be produced. In 2050, the differences remain significant, 15% for the 'higher hydrogen' and 26% for the 'higher SHCF' scenario.

[3] See Annex I for more details



2.2. Is it possible to combine the decarbonisation of transport and other sectors with EU renewables?

By 2050, the transport sector will require more than two thirds of the electricity as the power sector is expected to generate, even as the power sector integrates news loads from the industry and the building sectors (2414 TWh compared to 3497 TWh for the EU27). In the case of the 'higher SHCF' scenario, the demand from the transport sector is almost level with all electricity generated by the power sector. Even the most efficient 'base case' scenario requires almost as much - about 80% - *renewable* electricity generation for transport in 2050 as the power sector will generate (2414 TWh for transport compared to 3007 TWh in the power sector). This begs the question whether the decarbonisation efforts of the power and transport sector are compatible and maybe even mutually exclusive: does the demand in 2050 outstrip the renewable electricity potential in the EU?

The report offers a reassuring answer. **Yes, the EU has the potential to produce enough electricity to decarbonise both the transport, power sector and industry sector with renewable energy produced in the EU.** The potential availability of renewable electricity sources from solar, wind and geothermal in the EU27 amounts to about 20,000 TWh.[4] This potential exceeds about four and half times the highest demand projections from the grid and transport for renewables in 2050. Clearly, the EU's renewables potential is theoretically not a constraint for decarbonising the EU economy. It should be highlighted that the use of biomass is excluded from the renewables potential for environmental reasons. The analysis shows that the EU's renewables potential could deliver sufficient renewable hydrogen in 'worst-case demand' scenario, where hydrogen would be widely used in industry and even in heating (even though more efficient alternatives like heat pumps are available) .

Curtailed renewable power to produce 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 2020, curtailed electricity did not exceed a couple of hundreds of hours per year, even in countries like Germany and Ireland with high shares of variable renewable electricity sources and grid congestion challenges. Electrolysers need at least a 30% load factor (about 3000 hours) to bring down the production cost of electrofuels. 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 grid operators have an economic incentive to avoid paying large renewable electricity plants a compensation for curtailing their production. In other words, curtailed electricity is not 'free electricity'. 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 electrofuels will require a new and additional renewable electricity supply.[5]

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

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

Other supply-side constraints such as the 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 impacts such as land use, water demand and air quality are discussed below.

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

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

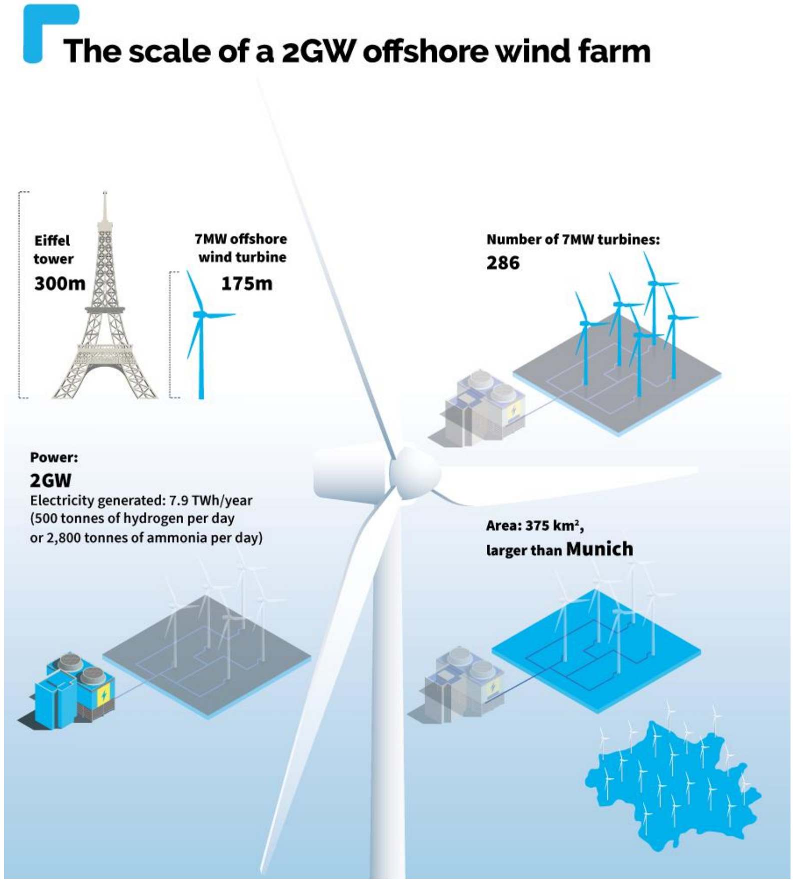
In this briefing, the renewable electricity capacity is illustrated in terms of the required offshore wind farms needed and this for several reasons. Offshore wind is relevant for the production of electrofuels, as it has higher capacity than other renewable sources. This makes offshore wind well-suited to power electrolysers requiring a high load factor. The offshore wind potential is quite evenly distributed across the EU - compared to PV - and sits in between PV and onshore wind in terms of the surface area needed.

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 an additional 209 TWh of renewables by 2030, with road transport accounting for 80% (167 TWh). This additional demand from transport should be contextualised by comparing it with the forecasted non-transport electricity demand, namely 3129 TWh in 2030. In other words, making significant progress by 2030 on decarbonising transport leads only to a small demand increase for electricity, below 7%. Adding just over 30 million battery-electric passenger cars on European roads will lead to 85 TWh of additional demand, a below 3% increase in overall electricity demand. 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 European grids by 2030, cutting the carbon intensity of grid electricity as well as reducing the additional renewable electricity needed for road transport - and passenger cars in particular - by almost 10%.[6]

Nevertheless, the additional renewable electricity needed remains significant. To offer a sense of scale, the equivalent of about 26 offshore wind farms with each a capacity of 2 GW (total capacity of 53 GW - about 7400 wind turbines of 7 MW each) would need to be constructed by 2030 to meet the additional renewables demand from transport. One such 2GW wind farm could generate 7.9 TWh per year. This is a tall - albeit achievable - order, knowing that the cumulative capacity of offshore wind in 2019 in the EU amounted to 'only' 22 GW. **To keep transport decarbonisation on track, (the equivalent of) the EU's offshore wind capacity would need to be more than doubled (x 2.4) by 2030.** This requires on average 2.6 of such 2GW farms to be constructed every year between now and 2030 or about 740 wind turbines of 7MW capacity each annually.

[6] 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).



This example offers a sense of scale of the renewables deployment needed. The 'higher hydrogen' scenario would require an additional 6.2 of these 2GW wind farms to be built by 2030. This would add about 180 wind turbines to be constructed in addition to the 740 needed annually to meet the base case. A greater role for synthetic hydrocarbons before 2030 – as modelled in the 'higher hydrocarbons' scenario - would require an additional 18.6 of these 2GW wind farms to be built by 2030. This would add 532 wind turbines to be constructed in addition to the 740 needed annually to meet the base case.

It should be kept in mind that these 209 TWhs or 740 wind turbines annually would come on top of the offshore wind farms and other renewables needed to make significant progress in decarbonising grid electricity. The decarbonisation of grid electricity should already be well underway by 2030 with renewables already supplying 64% (wind and solar alone 44%) of grid electricity.[7] Or a total of 2003 TWh from renewable electricity sources in 2030. Wind, solar and hydro already generated about 1000 TWh in 2019, about a 35% share of electricity generation.[8] However, this will need to be almost doubled again between now and 2030 to achieve the 55% greenhouse gas savings target set in the EU's Climate Target Plan.[9] 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 than necessary.

It is clear that renewable electricity needed by 2030 would not be sourced exclusively from offshore wind farms in the EU alone. Multiple renewable technologies distributed all over Europe will contribute to this effort and imports may 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 – has major implications in terms of the ramp up of renewables needed in the next decade.

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

The growth in demand from the shipping and aviation sectors after 2030 is staggering, a 24-fold increase over 20 years, from a modest 43TWh in 2030 to 1274 TWh in 2050 in our 'base case' scenario for the EU27. Over a period of 20 years, the building of the equivalent of 280 wind farms with a 2 GW capacity will require a more concerted effort to decarbonise both road transport as well as shipping and aviation. Every year, about 14 of these offshore wind farms would need to be built, about 4000 wind turbines (7MW each) in total.

Given the enormous demand of these long-distance transport modes, it is crucial to prioritize the most efficient use of electrofuels. Using more liquid hydrogen instead of ammonia in shipping accounts for most of the additional 113 TWh in demand for renewables, as liquefaction ('higher hydrogen' scenario)

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[7] The 2030 estimates are based on the forecast in the TYNDP Distributed Energy scenario. Source: ENTSOG and ENTSO-E (2020) Ten-Year Network Development Plan 2020. Retrieved from https://www.entsog.eu/tyndp#entsog-ten-year-network-development-plan-2020

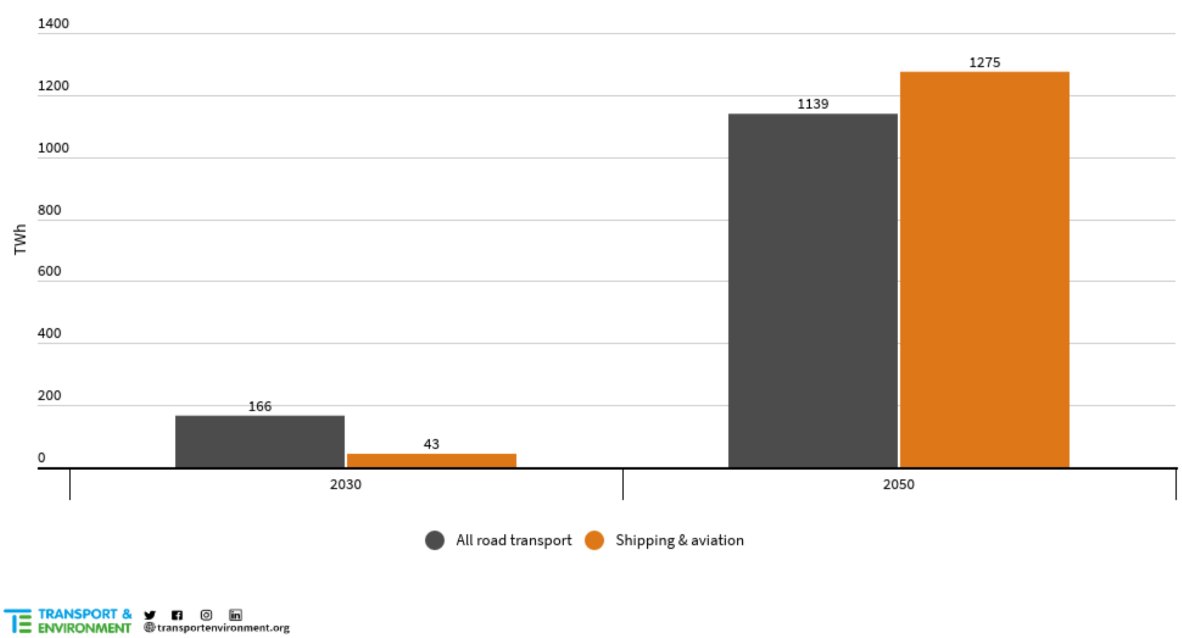
[8] Ember & Agora EnergieWende (2020, February) *The European Power Sector in 2019*. Retrieved from https://ember-climate.org/project/power-2019/

[9] European Commission (2020, September) *Commission Staff Working Document Impact Assessment Accompanying Communication 'Stepping up Europe's 2030 climate ambition' - Renewable energy supply and demand*, p. 57. Retrieved from https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en

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 252 TWh in demand for renewables.

While the demand for electrofuels for shipping and aviation grows very rapidly after 2030, road transport demand for renewable electricity also keeps growing, albeit at a lesser pace: from 166 to 1140, 'only' a 7-fold increase compared to the 30-fold increase experienced by aviation and shipping. Leading up to 2050, very high shares of wind and solar power could lead to high levels of curtailment, unless flexibility options are used. The combination of a near 100% electrified road fleet and close to 100% renewable grid in many EU member states offers great potential for smartly charged electric vehicles to reduce curtailment of renewables and reduce the need for additional renewables for road transport.[10]

Comparison of electricity requirements for road transport with shipping plus aviation in EU27

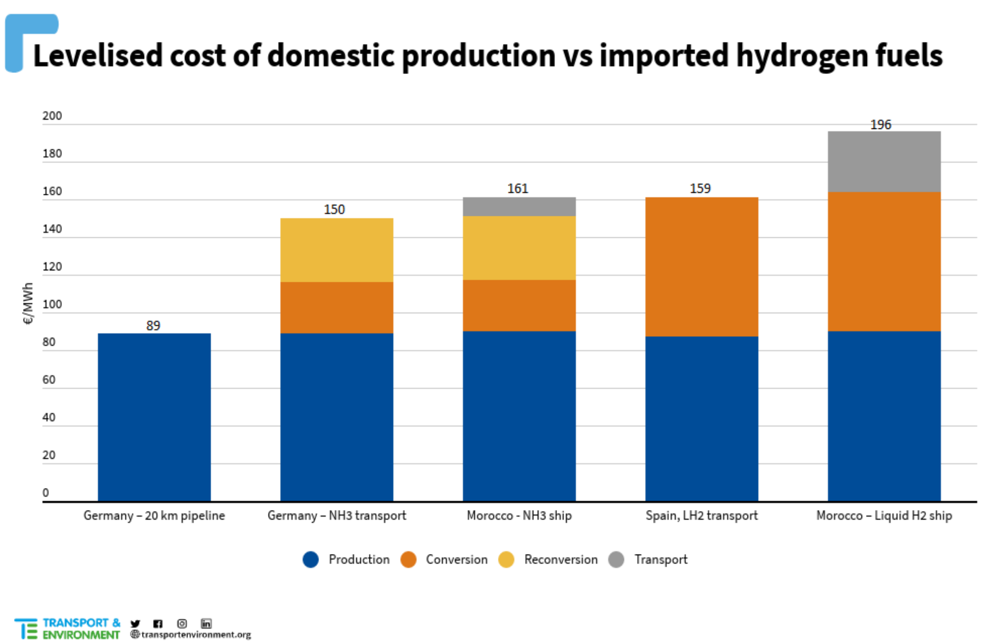


[10] Zerrahn, Schill & Kemfert (2018) On the economics of electrical storage for variable renewable energy sources in *European Economic Review* 108 (2018) 259–279 retrieved from https://www.sciencedirect.com/science/article/pii/S0014292118301107?via%3Dihub

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

The scale of the challenge to build sufficient renewables in the EU may tempt policy-makers to rely more heavily on imports of electrofuels. Areas outside the EU have a better renewables potential, with better solar irradiation and stronger 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 electrofuels at a lower cost as a result. However, the current cost of importing electrofuels from outside the EU is significant, in some cases costing more than the production of green hydrogen itself (especially when liquefied).

Hydrogen production will be cheaper closer to the areas of consumption inside the EU or importing it via pipeline from countries with a better renewables potential in its immediate neighbourhood. **Transporting liquid hydrogen or ammonia via ships from further afield to Europe is currently almost always twice the cost of producing and using hydrogen in the EU.** Significant uncertainties exist about the cost of these bulk hydrogen carriers. Technological developments in this area and market forces will determine how much of the EU's electrofuels demand will be imported and how much of it can be produced domestically in the EU.



Apart from the costs, **an additional challenge is the lack of a regulatory framework and certification schemes to guarantee the sustainability of such renewables-based electrofuels**. Discussions have started at EU level about how to ensure that such so-called 'Renewable Fuels of Non-Biological Origin' are produced with additional renewable energy and deliver at least 70% greenhouse gas savings compared to fossil fuels. The verification of whether these fuels from outside the EU meet the requirement of the Renewable Energy Directive will be challenging. Given the major gap between the production costs of grey and green hydrogen, there is a considerable fraud risk. Robust criteria coupled with effective certification schemes and testing procedures are needed to ensure that imported electrofuels deliver the claimed emission reductions.

A last consideration is the energy security angle and the EUR 211 billion price tag (2018 prices) that Europeans pay annually for oil imports[11]. Pushing long-distance transport modes like shipping and aviation to use cleaner fuels has the added bonus of reducing the EU's reliance on oil imports from conflict-prone regions or regimes that do not respect human rights. However, this is dependent on producing a significant amount of these fuels inside the EU. Swapping the EU'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 not only sufficient renewables potential, but also a window of opportunity in the 2020s for a European 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 EU industry well to export these technologies and deploy these on a large scale in areas outside the EU 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 in shipping and aviation (as well as other industrial sectors). But for that to happen, the EU must do its homework first by establishing a regulatory framework on the sustainability of electrofuels and by adopting demand-side policies that will drive the use of electrofuels, where direct electrification is not feasible.

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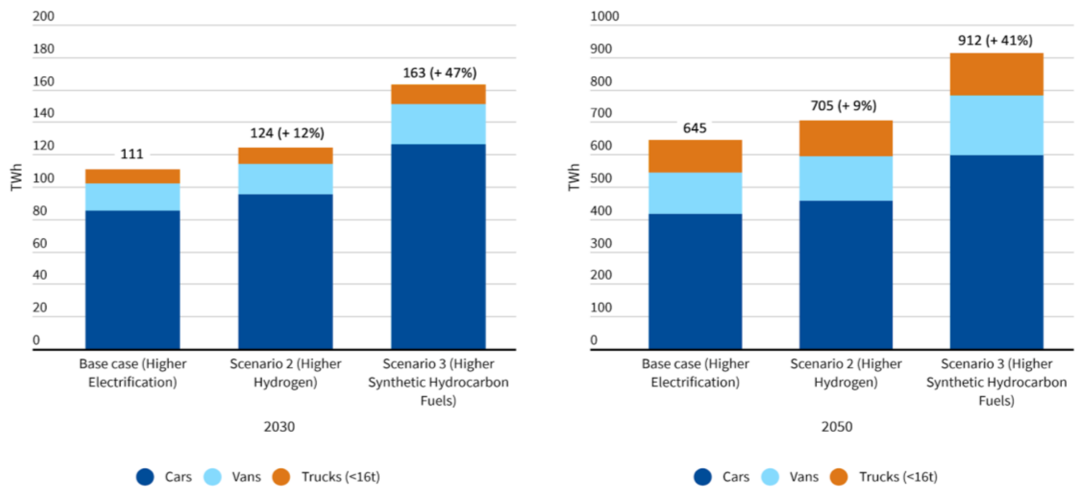
[11] T&E (2020, July) *Europe's deepening dependency on foreign oil*. Retrieve from https://www.transportenvironment.org/publications/europe%E2%80%99s-deepening-dependency-foreign-oil

3. Scenario's implications for renewable electricity to be supplied to different transport modes

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

As emphasized in section 2.1, direct use of electricity by battery electric vehicles is the optimally efficient pathway to decarbonise road transport. 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 needs for road transport**. By 2030, relying on just 10% fuel cell vehicles will increase the renewable electricity demand by 12%. Relying - in addition - on 10% synthetic hydrocarbons use will increase the renewables demand by 31%. The 'higher hydrogen' scenario will require building about 1.7 extra 2 GW offshore wind farms by 2030 to meet that extra 13 TWh of additional demand. The 'higher synthetic hydrocarbon' scenario will require building more than 6 extra 2 GW offshore wind farms by 2030 to meet that extra 52 TWh of additional demand.

Comparison of electricity requirements for cars, vans and trucks (<16t) in EU27 countries



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

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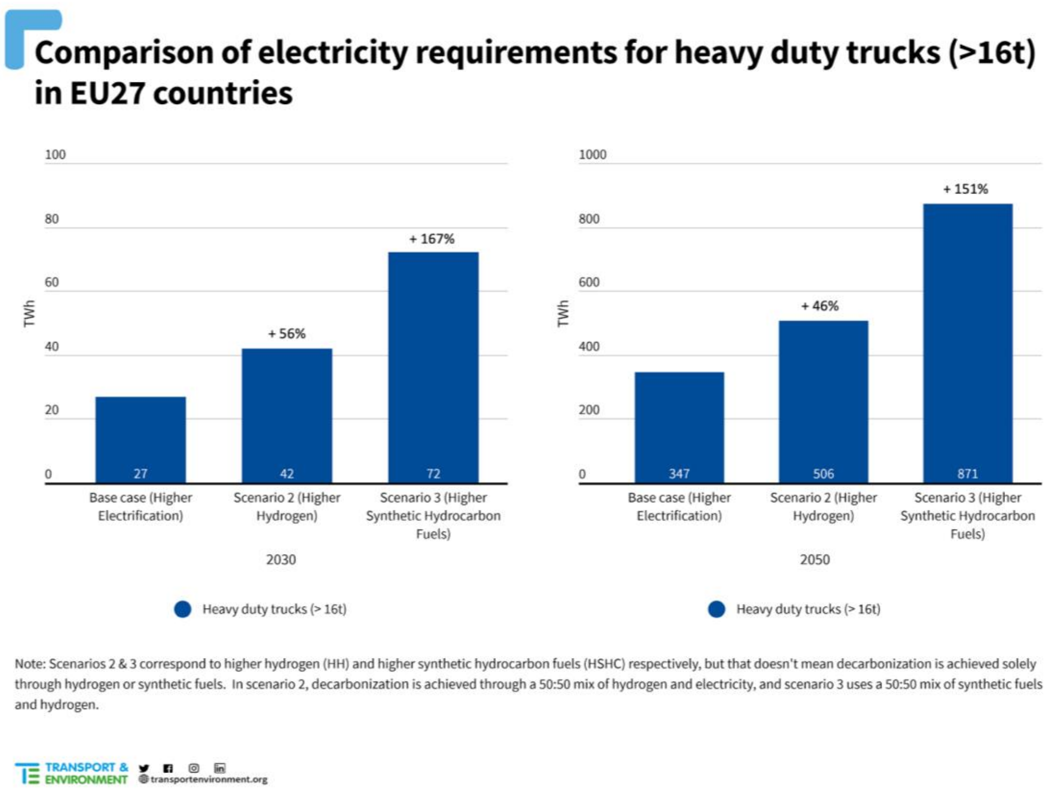
While this may not seem overly dramatic in the next 10 years, the long-term implications of promoting electrofuels in light-duty vehicles are significant. The 'higher hydrogen' scenario will require building almost 8 extra 2 GW offshore wind farms by 2050 to meet that extra 60 TWh of additional demand. The 'higher synthetic hydrocarbon' scenario will require building almost 34 extra 2 GW offshore wind farms by 2050 to meet that extra 267 TWh of additional demand. Again, this significant additional demand will be needed to use 'only' 10% of hydrogen and 10% ediesel in the 2050 fleet. This analysis confirms our initial finding from the 2018 synthesis report that "an approach focused on using the most efficient pathways (direct charging) wherever possible is recommended".

3.2. Trucks: don't put all the eggs in the hydrogen basket

The situation for heavy-duty trucks shows a similar picture. **Decisions now on how to decarbonise the road freight sector will have long-term implications for the future renewable electricity demand.** If direct electrification is pushed (as in the base case scenario), heavy-duty trucks will account for 14% of renewable electricity demand in transport or 27 TWh 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 18% of renewable electricity demand in transport or 42 TWh. That 15 TWh difference between the base case and the 'higher hydrogen' will require almost 2 additional 2GW offshore wind farms to be built by 2030. Not switching the drivetrain in half of heavy-duty trucks and using ediesel and fuel cell trucks for the other half will require 72 TWh or an additional 45 TWh, more than double the electricity that is needed in the base case. This is equivalent to almost 6 extra offshore wind farms of 2 GW capacity to be built by 2030.

Clearly, **running heavy-duty trucks on e-diesel would make transport decarbonisation much more challenging and must be ruled out.** The demand for renewable energy in 2050 would be 2.5 times as high: 871 TWh vs 347 TWh. Even promoting a significant role for hydrogen in heavy-duty trucks (50%) locks the EU into building more renewables to deliver the extra 159 TWh needed compared to 100% direct electrification (or importing it from outside the EU). That is equivalent to 20 extra offshore wind farms of 2 GW capacity to be built by 2050. The 'higher hydrogen' scenario requires 56% more electricity in 2030 and 46% more in 2050.



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 likely be the transport sector with the biggest demand for renewable electricity to supply hydrogen and ammonia as shipping fuels** (739 TWh or 31% of all demand for electricity in transport). Compared to road transport, the pre-2030 demand for additional renewable electricity to produce shipping fuels is limited, just 29 TWh in the base case.[12] This relatively small demand is because the infrastructure to refuel ships with hydrogen or ammonia won't yet be available at scale in the next decade. To already 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 29 TWh to 739 TWh or a 26 fold increase over 20 years) should add a sense of urgency for EU-level discussion on the Alternative Fuels Infrastructure Directive, reform of the Emissions Trading System and the EU MRV regulation, as well as the forthcoming FuelEU Maritime initiative to get the infrastructure ready to deliver hydrogen and ammonia to ports and ships. This will be crucial to be ready starting from the mid-2020s and accelerated from 2030 to meet the demand of ships using fuel cells for propulsion or co-combusting hydrogen or ammonia.

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

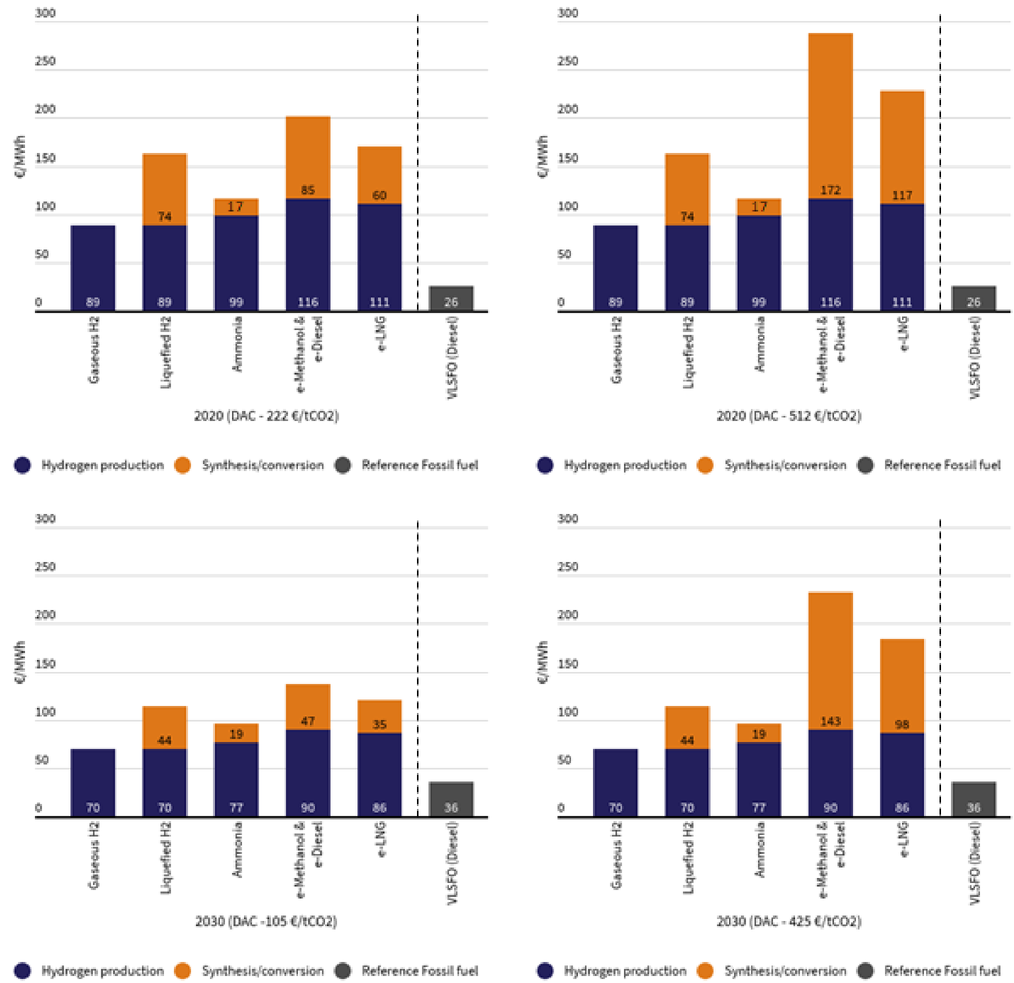
Every day, 13 containerships dock on average in the Antwerp port, each carrying 30,200 tonnes of cargo. To refuel just one of these ships, a 2GW offshore wind farm (see image in section 2.3.1) could deliver 85% of the energy needed to power 4 ammonia plants, each consuming 280 MW of renewable energy and producing 700 tonnes of green ammonia per day. This ammonia production of 2800 tonnes per day is the amount needed to refuel each one of these larger containerships.

Depending on the advances in CO_2 direct air capture (DAC), other synthetic hydrocarbons could achieve cost cuts, yet still more expensive and energy intensive than green ammonia. This is one of the "black swans" technologies that one could keep under consideration. But for a sector like shipping, where

[12] 1 kilotonne of heavy fuel oil (typically used in shipping) equals 0,01125 TWh. The 29 TWh needed in 2030 by shipping equals 0.33 kilotonne. 739 TWh needed in 2050 equals 8.3 kilotonnes.

energy costs make up around 60% of operating costs, expensive synthetic hydrocarbons are unlikely to become cost-competitive against cheaper green alternatives such as hydrogen or ammonia.

Comparison of levelised costs of shipping fuels in 2020 & 2030



Reference fossil fuel LSHFO cost is adapted from (Lloyd's register & UMAS, 2020).

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3.4. Planes : start small and ramp up after 2030

The aviation sector will need to rely for its decarbonisation on synthetic hydrocarbons like e-kerosene - supplemented with a very limited amount of advanced biofuels. As a consequence, the difference in results between the three scenarios remains relatively limited to just under 10%, much lower than for the other transport modes. In 2050, aviation will account for 22% of all demand for renewable electricity in transport, 535 TWh in total in the base case. **Aviation demand in 2050 is higher than the 500 TWh required for all battery electric passenger cars in the EU 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 and the synthesis process in particular.

The required demand for energy from this sector is the product of decades of underregulation, which has grown this energy demand in excess of efficiency savings. A failure to introduce meaningful CO_2 standards[13], lack of carbon pricing and support for airport expansion have all contributed to the sector requiring an enormous quantity of fuel to operate. This underscores the need for governments to adopt a "Fuels+" strategy, with support for efuels accompanied by drives for greater efficiency, more effective pricing and reconsideration of expansion plan.

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, around EUR 3000/ton. This is six times higher than fossil kerosene.[14] As this industry is just starting its development, T&E has recommended to promote synthetic hydrocarbons in aviation with a low target : an efuels mandate of 1-2% of fuels supplied to intra & extra EU aviation by 2030.[15] This should enable a European electrofuels industry to scale up, drive down the production

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[13] ICCT (2018, October) *U.S. Passenger Jets under ICAO's CO_2 Standard, 2018-2038*. Retrieved from https://theicct.org/publications/us-passenger-jets-icao-co2-standard

[14] 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

[15] T&E (2020, July) *How EU legislation can drive an uptake of sustainable advanced fuels in aviation*. Retrieved from https://www.transportenvironment.org/publications/how-eu-legislation-can-drive-uptake-sustainable-advanced-fuels-aviation

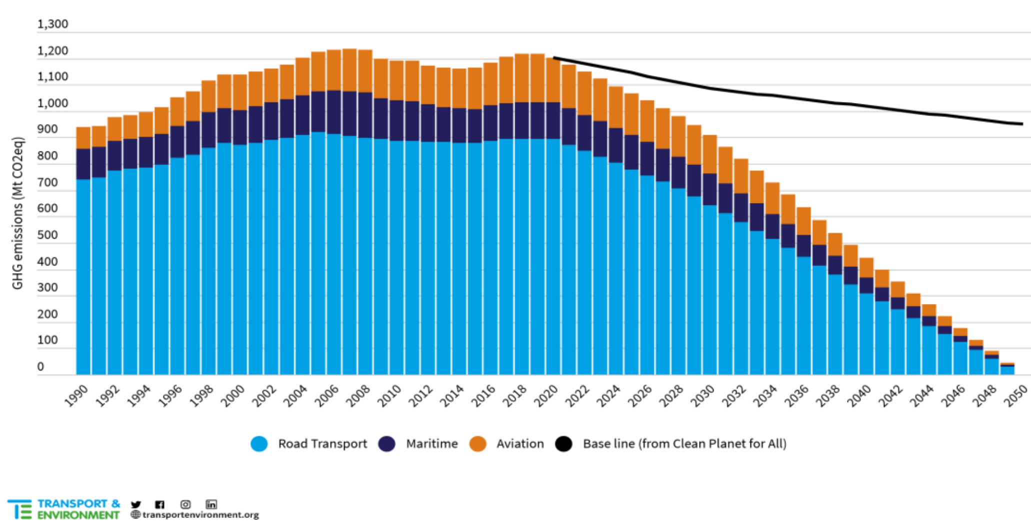
costs and then rapidly ramp up after 2030, from 1-2% to - theoretically and depending on demand evolution - 100% in 2050.

4. Environmental aspects

4.1. Climate impacts

After years of growing emissions from the transport sector (almost 30% since 1990), **our scenarios will deliver a greenhouse gas reduction of 16% in 2030 compared to the baseline**[16], reducing to 912 Mt CO_2e (for EU27+UK). **This result will be a significant shift from the business as usual trend.** This drop in emissions results from relying on additional zero-emission renewable electricity or using zero-emission electricity to produce electrofuels.

Comparison of GHG emissions by transport sector against a baseline projection, for EU27 and UK



16 Baseline from European Commission (2019) *A Clean Planet For All*, with the addition of international shipping emissions projections without GHG mitigation. Clean Planet For All Retrieved from: https://ec.europa.eu/clima/policies/strategies/2050_en

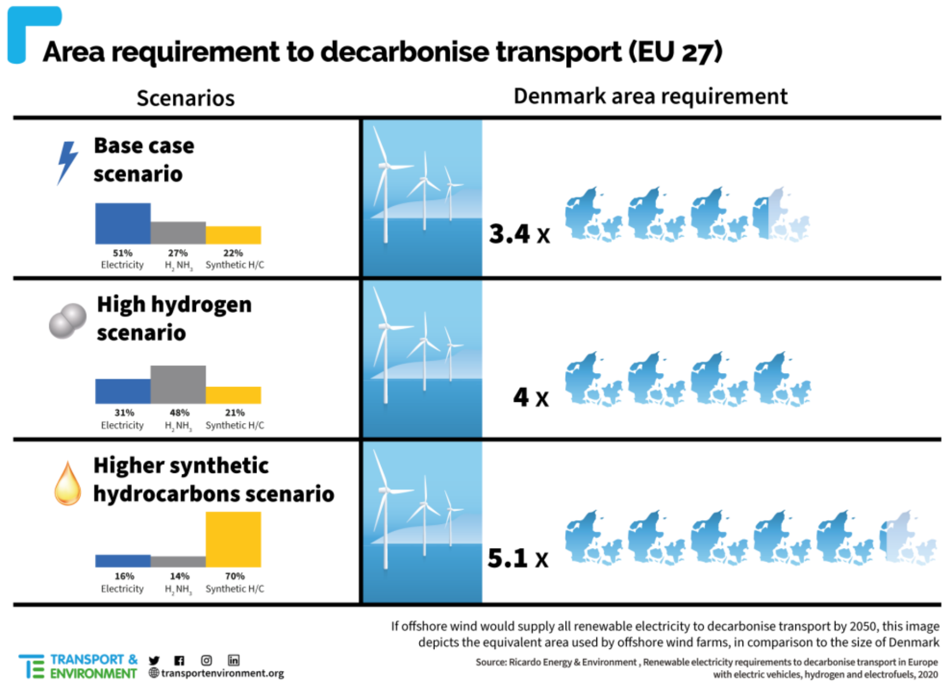
Blue hydrogen, low carbon? It depends ...

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.[17] The wide range in the estimates of lifecycle emissions of blue hydrogen – between 30 and 99 g CO_2/kWh – shows the level of uncertainty about the low-carbon status of blue hydrogen. Therefore, blue hydrogen is not a realistic long-term solution to achieving full decarbonisation.

4.2. Land use: size matters

In comparison to fossil fuel generation, solar and wind plants require significantly more space per unit of electricity produced. While less land-intensive than crop biofuels, the land required in 2050 for the additional renewable electricity generation needed is significant. The image below helps to bring the renewable electricity demands of the three scenarios and their corresponding land use to life. Delivering the energy needed for the base case scenario will require an area equivalent to 3.4 times the size of Denmark, if offshore wind would supply all of the additional electricity needed to decarbonise the transport sector. The 'higher hydrogen' scenario will require 4 times and 'higher synthetic hydrocarbon' scenario even 5.1 times the area of Denmark.

[17] For more details, see the Ricardo Energy & Environment, section 7.3. 'Environmental risks with blue hydrogen'.



4.3. Water demand for electrofuels : significant but manageable, when compared to biofuels and nuclear and fossil power plants

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 compared relative to the water use involved in producing other fuels. Compared to biofuels made from food or feed crops, the water demand for renewable electricity and electrolysis is far lower. Concretely, 9 litres of water is used for every kilogram of hydrogen produced. Or 0.07 litres of purified water per 1 MJ of energy stored in the hydrogen, compared to between 33 and 476 litres for first generation biofuels. Compared to nuclear and fossil power plants, electrolysis only uses a tiny fraction of the water that these generators mostly use for the purpose of cooling. The total water volume required to produce the electrofuels for the transport sector by 2050 will amount to 270 billion litres. Fossil and nuclear power plants in the EU use about 68,000 billion litres of water.

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

As is the case in other large industrial projects and especially in cases where the local environment is arid, any electrofuel facility should undergo a local water availability assessment and ensure that the necessary wastewater treatment facilities are available.

4.4. Air quality: Electrofuels offer limited benefits

Battery electric vehicles and ships charged with renewable electricity are the only technologies able to reduce air pollutants to zero. Hydrogen can also improve the air quality, when used in a fuel cell.

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, nitrous oxide (N_2O) emissions can be generated by SCR systems, 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 of these three 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 of 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

The main takeaway of this briefing and the underpinning study is that the decarbonisation of transport cannot be planned one transport mode at a time. For example, the decision whether or not to enable electrofuels in road transport has far-reaching implications, not only for the other transport modes but even for the decarbonisation of other sectors of the EU economy. The EU's plans for a Strategy for Energy System Integration and the forthcoming Sustainable and Smart Mobility Strategy are to be welcomed in that respect. Clearly, planning for the most efficient decarbonisation of transport will pay off in the long run. Nevertheless, the scale of the challenge and the amount of renewables needed remain enormous. The land use involved offers a sobering fact. As mentioned in the introduction, there are no silver bullets. Lowering the energy demand in the transport sector by promoting public transport, shared vehicle use, modal shift, logistics efficiency and reducing air travel can help to reduce the scale of the challenge.

Our findings should help inform decision-making on a wide range of European policies that will set the course for the decarbonisation of transport: higher targets for renewable transport fuels in the Renewable Energy Directive and the role of electrofuels in road transport, the CO_2 standards for cars and the role of carbon-neutral fuels therein, gradually phasing out the internal combustion engine under the EU vehicle CO_2 standards as well as the Euro standards on tailpipe emissions, the level of ambition for the 2030 targets in CO_2 standards for vans and trucks, examining an operational standard promoting efficiency for ships under the FuelEU maritime initiative, setting ambitious targets for recharging and refueling infrastructure under the reviewing Alternative Fuels Infrastructure Directive, the design of a fuel mandate for aviation fuel suppliers, ...

Further information

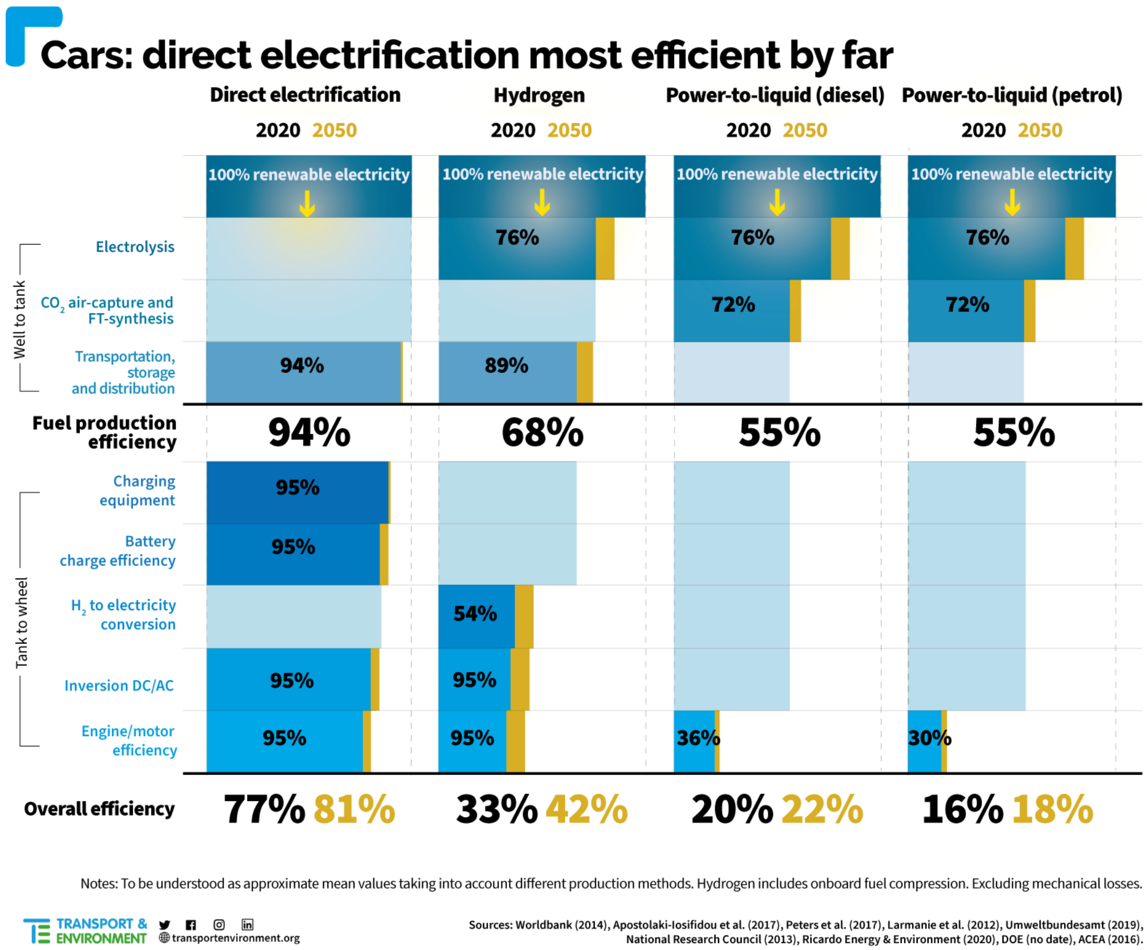
Geert Decock
Electricity and Energy Manager
Transport & Environment
geert.dc@transportenvironment.org
Mobile: +32(0) 484 629 491

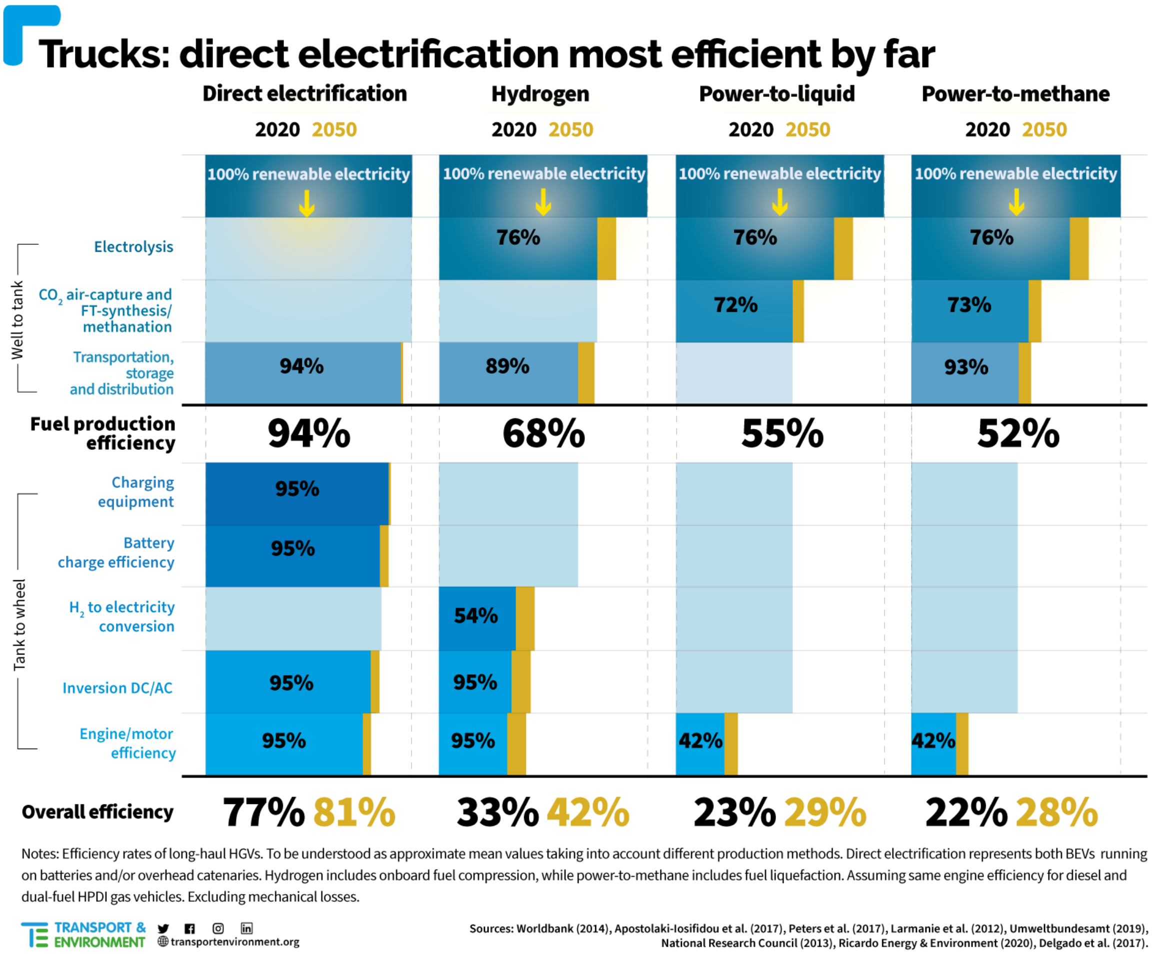
ANNEX I: Scenario assumptions for all transport modes

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
Direct electrification
Hydrogen
Power-to-liquid
Power-to-methane
2020 2050
100% renewable electricity
Well to tank
Electrolysis
CO2 air-capture and FT-synthesis/ methanation
Transportation, storage and distribution
Fuel production efficiency
Tank to wheel
Charging equipment
Battery charge efficiency
H2 to electricity conversion
Inversion DC/AC
Engine/motor efficiency
Overall efficiency
76%
72%
73%
94%
89%
93%
94%
68%
55%
52%
95%
54%
42%
77% 81%
33% 42%
23% 29%
22% 28%
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.
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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[18]		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[19]	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-

[18] 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.

[19] 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.

				societies/improving-efficiency
Fossil kerosine	Engine efficiency for planes	39%	43%	National Academies of Sciences, 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/default/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 and FT-synthesis	72%	72%	Ricardo Energy & Environment (2020).
	Engine efficiency for ships (synthetic methanol)	51%	51%	Anantharaman et al. (2015) and Wärtsilä (2020).