E-FUELS: TOWARDS A MORE SUSTAINABLE FUTURE FOR TRUCK TRANSPORT, SHIPPING AND AVIATION

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MANAGEMENT SUMMARY

Mobility needs to become sustainable
To realise the targets of the Paris Climate Agreement, drastically greener modes of transport are needed. Smart mobility concepts, more efficient engines, battery electric vehicles and biofuels are often mentioned as applications. Electric vehicles can be considered the preferred solution for short distances and light vehicles (e.g. passenger cars, urban mobility concepts). Truck transport, shipping and aviation, meanwhile, are currently lagging behind when it comes to contributions to sustainable mobility. These modes of transport require energy carriers with a higher energy density, for which e-fuels and green hydrogen can be the solution. This whitepaper therefore focuses on the potential of e-fuels for three modes of transport: long-haul road transport, shipping (inland and short/long distances over sea) and aviation.

E-fuels offer an opportunity to reduce carbon emissions
E-fuels are produced from electricity, water and carbon dioxide or nitrogen. When using electricity from renewable sources and circular carbon dioxide (e.g. from biomass or direct capture from the air), net emissions are near zero. The e-fuels analysed in this whitepaper are hydrogen, e-methanol, e-diesel, e-ammonia, e-LNG and e-kerosene.

In terms of costs, the differences between the various e-fuels turn out to be relatively small. Hydrogen is the most economical fuel to produce, but higher distribution and powertrain costs level out this advantage.
The costs of producing e-LNG, e-methanol and e-diesel are sensitive to varying CO_2 costs, and all e-fuels are sensitive to electricity costs.

The overall analysis of the different e-fuels in this whitepaper has led to three conclusions.

1. For *truck transport*, hydrogen is only applicable for shorter distances. Compared to e-fuels, hydrogen is only attractive when the costs of electricity and CO_2 are high or when the costs of infrastructure and vehicles have declined significantly. In all other cases, e-methanol, e-diesel and e-LNG are the most attractive options. E-ammonia is currently considered unsafe for road transport.

2. For *shipping*, cost differences between the various e-fuels are small. Hydrogen is an interesting option for short distances and ferries, especially when CO_2 costs are high. E-ammonia is also interesting in the case of high CO_2 costs, particularly for deep sea shipping (sea transport over long distances). E-methanol, e-diesel and e-LNG are interesting options, especially when CO_2 costs are low.

3. For *aviation*, only e-kerosene can be regarded as a feasible e-fuel. All fuels deviating significantly from kerosene, are unacceptable due to a too high loss of passenger and load capacity and large investments in completely new airplane and engine designs.

A drastic transition in fuel production is required
To enable the desired transition towards sustainable mobility in heavy, long-distance applications, a drastic increase in e-fuel production and associated infrastructure is needed. In the Netherlands, a fuel demand of 960 petajoule (PJ) is forecasted for 2050 in relation to the international transport modes analysed in this study. It would take more than 2000 PJ of electricity and quite some surface space to produce these fuels. In the case of e-methanol, for example, a land surface equalling 60% of Maasvlakte 2 would be needed for electrolysis, CO_2 capture and chemical synthesis for producing these amounts. Given these predicted requirements, the importation of electricity, hydrogen or e-fuels will probably become a necessity.

A collaborative effort by all stakeholders can accelerate the adoption of e-fuels in mobility
Close cooperation between stakeholders and the creation of alliances will be of vital importance for a successful transition to e-fuels. The application of these fuels in transportation will require steps forward in R&D, production, infrastructure for distribution and fuelling, vehicle adaptation and supporting legal frameworks and regulations. A roadmap for the deployment of e-fuels for transport in the Netherlands is shown in Figure 2. Roadmaps for other countries would look similar.

E-fuels will only become a viable option if all stakeholders take the following steps:

- *Governments* should promote e-fuels over fossil fuels, e.g. through CO_2 taxes and blending requirements. At the EU level, the production and use of e-fuels should be further stimulated through policy instruments such as the Renewable Energy Directive, as well as for shipping and aviation. Governments should create clarity on long-term policies and the legal landscape. They should accelerate the development of production and application techniques and social acceptance.

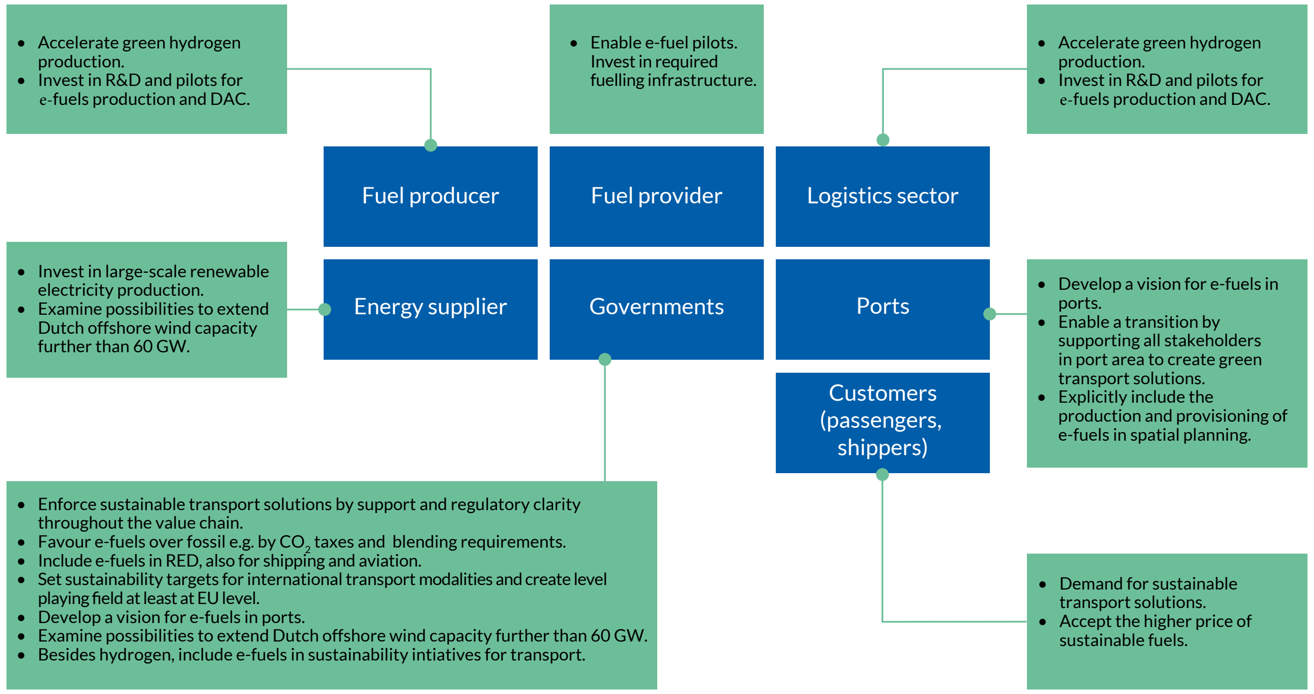
- *Logistics service providers* and their *customers* and *partners* must be willing to accept a higher price of sustainable fuels compared to current fossil price levels.

- *Energy providers* should invest in large-scale renewable electricity production.

- ***Fuel producers*** and ***fuel providers*** must be prepared to invest in the production of e-fuels and the associated infrastructure, even though there is still a lot of uncertainty regarding the demand for e-fuels for transport.

- ***Ports*** should explicitly include the production and provisioning of e-fuels in their spatial planning, taking into account synergies with the sustainable transition of the chemical industrial complexes around these ports, and enable stakeholders in the port region to create green transport solutions together.

Now that the opportunities that e-fuels offer are clear when it comes to making transport more sustainable, it's time for action. ***Ports, governments, end-markets, the logistics sector, the fuel-producing industry and the energy sector all need to unite forces to pave the way for the adoption of e-fuels.*** Steps are needed at the global, EU, national and regional levels. Actions that are required from each stakeholder (in regard to the Dutch situation in specific) are depicted below (Figure 1):



- Accelerate green hydrogen production.
- Invest in R&D and pilots for e-fuels production and DAC.

- Enable e-fuel pilots. Invest in required fuelling infrastructure.

- Accelerate green hydrogen production.
- Invest in R&D and pilots for e-fuels production and DAC.

- Invest in large-scale renewable electricity production.
- Examine possibilities to extend Dutch offshore wind capacity further than 60 GW.

- Develop a vision for e-fuels in ports.
- Enable a transition by supporting all stakeholders in port area to create green transport solutions.
- Explicitly include the production and provisioning of e-fuels in spatial planning.

- Enforce sustainable transport solutions by support and regulatory clarity throughout the value chain.
- Favour e-fuels over fossil e.g. by CO_2 taxes and blending requirements.
- Include e-fuels in RED, also for shipping and aviation.
- Set sustainability targets for international transport modalities and create level playing field at least at EU level.
- Develop a vision for e-fuels in ports.
- Examine possibilities to extend Dutch offshore wind capacity further than 60 GW.
- Besides hydrogen, include e-fuels in sustainability intiatives for transport.

- Demand for sustainable transport solutions.
- Accept the higher price of sustainable fuels.

Figure 1: The transition to sustainable mobility will require action from all involved stakeholders. The needed efforts are summarised here.

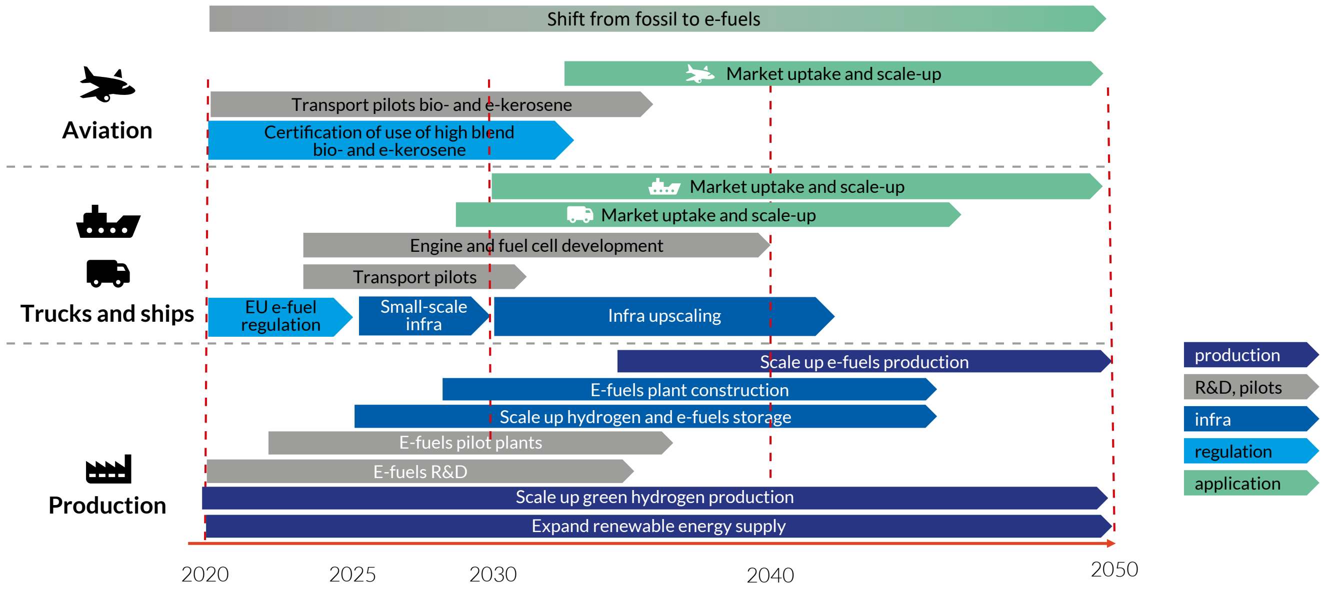


Figure 2: Steps to be taken for the transition from conventional to e-fuel based mobility in a roadmap for the Netherlands. Roadmaps for other countries will look more or less the same.

Contents

This whitepaper is the result of a ***cooperative project*** between stakeholders from the logistics sector, industry and knowledge institutes. Stakeholders expressed a need for a clear vision on innovation in the field of e-fuels and answers to a variety of questions: What will the preferred e-fuels be for the different transport modalities? What steps should be taken to accelerate the adoption of hydrogen and e-fuels and the innovation and implementation of production plants, vehicle technology and infrastructure? The following partners participated in the project:

26 representatives from the Dutch transport and logistics industry and the energy and chemicals sector participated in a ***market consultation***. They were asked to present their vision on e-fuels, the opportunities they see for their company, the business drivers behind these opportunities and the barriers to overcome in order to pave the way for the large-scale implementation of e-fuel technologies. This consultation provided valuable insights for this whitepaper. The project was coordinated by the Shared Innovation Programme VoltaChem.

The whitepaper discusses:
- why e-fuels offer an opportunity to reduce carbon emissions
- which e-fuels are suitable for which modalities and what the necessary technological developments are
- what the future costs throughout the value chain of the various e-fuels could be
- what the requirements for renewable energy production and land use are when it comes to realising the large-scale implementation of e-fuel production
- how the uptake of e-fuels can be accelerated by stakeholders and an adoption roadmap to get there

MOBILITY NEEDS TO BECOME MORE SUSTAINABLE

Europe is taking up the challenge to curb global warming by drastically reducing the emissions of CO_2 and other greenhouse gases. Whilst most sectors have achieved a reduction in CO_2 emissions in the last decades, the transport sector is lagging behind [1].

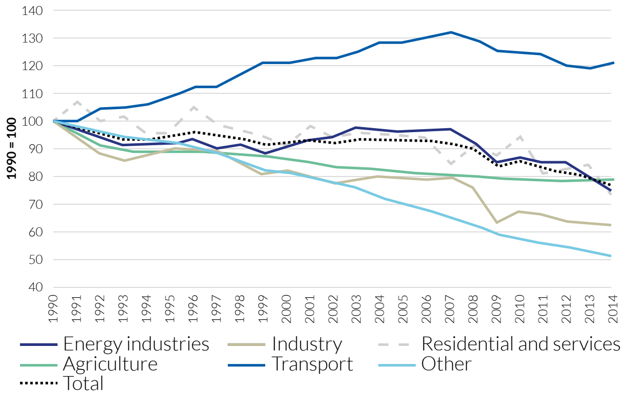


Figure 3: European greenhouse gas (GHG) emissions per sector (transport includes international aviation, excludes international shipping). Source: [1]

Currently, the transport sector is responsible for 23% of global CO_2 emissions [2]. Road transport accounts for almost three quarters of these emissions and aviation and deep-sea shipping for more than a tenth each.

In order to meet the proposed targets of the Paris Climate Agreement, CO_2 emissions from transport will have to be reduced by approximately 95% by 2050 compared to 1990 levels. Multiple strategies are available to reduce CO_2 emissions from transport, i.e.:

- lowering the amount (or at least curbing the growth) of distance travelled per capita (e.g. smart mobility, working from home or local sourcing)
- increasing the energy efficiency of vehicles and vessels operated using fossil energy carriers
- introducing energy carriers with lower ecological (e.g. CO_2) footprints, including certain biofuels, electricity, hydrogen and/or e-fuels

If only the first two strategies are applied, the aforementioned Paris Agreement targets will not be met. Alternative energy carriers with (near) zero CO_2 emissions will therefore have to be deployed.

Battery electric propulsion can generally be considered the preferred solution for short-distance and light vehicles (e.g. urban mobility, passenger vehicles, etc.) because of their significantly higher energy efficiency. However, batteries have a limited energy density compared to liquid and gaseous fuels such as biofuels, (compressed) hydrogen and e-fuels. Batteries are therefore not suitable for modes of transport that require high amounts of energy to be stored onboard: vessels and vehicles that have higher power demands (e.g. because of their weight) or that have higher mileages and/or limited possibilities for refuelling. For these modes of transport, the solutions include biofuels, (compressed) hydrogen and e-fuels.

The amount of energy used by such modes (e.g. long-haul road transport, shipping and aviation) is approximately half of the global energy use for transport [3]. In countries like the Netherlands in particular (with a large sea port and a big international airport), the demand for fuels which are suitable for heavy and/or long distance applications is expected to remain high.

Although the production of biofuels may be less energy intensive than the production of e-fuels, the amount of available sustainable biofuels is likely to be insufficient for fuelling all modes that require high energy densities [4], [5].

This whitepaper therefore focuses on the potential of hydrogen and e-fuels in the following three transport modes: long-haul road transport, shipping (inland, short-sea (i.e. short distances) and deep-sea shipping) and aviation.[1] There is still much uncertainty regarding what the innovation trajectory of e-fuels should look like and what is needed for such innovations to take shape. The aim of this paper is therefore to provide an overview of technical facts and potential costs and a roadmap for innovation as a basis for further action which is required of relevant actors.

> **“The transport sector is responsible for 23% of global CO_2 emissions”**

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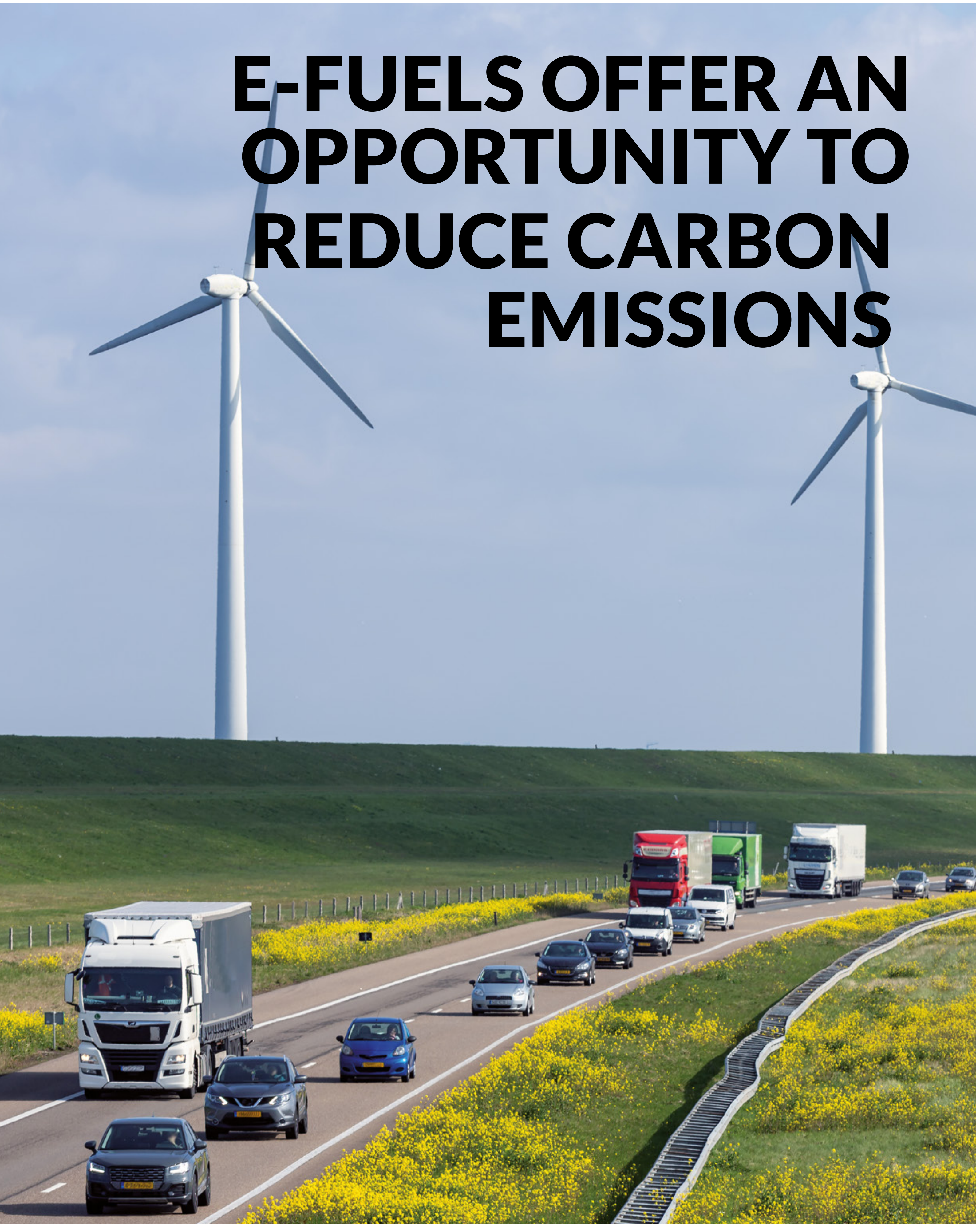
[1] Rail is not within the scope of this study. However, e-fuels can also play a role in rail transport.

E-FUELS OFFER AN OPPORTUNITY TO REDUCE CARBON EMISSIONS



E-fuels are synthetic fuels which can be produced on the basis of electricity (from renewable sources), water and carbon dioxide or nitrogen. Figure 4 shows a simplified schematic representation of the production routes for the e-fuels on which this whitepaper focuses. For various e-fuels (e.g. methanol), a number of synthetic production routes are available or under development, which are not included in this figure for reasons of clarity.

The production processes described below were used as a basis for the analysis.

Green hydrogen
Green hydrogen (H_2) is made from H_2O (water) using green electricity. The water is electrocatalytically split into H_2 (hydrogen) and O_2 (oxygen) by a device called an electrolyser. One example of this device, expected to have significant market penetration in the coming decades, is the Polymer Electrolyte Membrane (PEM) electrolyser. Water electrolysis has the potential to reach efficiencies of 64%.[2] This value was used as the benchmark performance in this study. The resulting hydrogen from a PEM electrolyser has a pressure of 30 bar. As electricity costs are known to contribute significantly to hydrogen production costs, periods of low electricity prices (e.g. during periods of excess production) can be utilised to minimise production costs. Buffering or storage is needed in the case of intermittent production.

E-methanol
E-methanol (CH_3OH) is produced from green hydrogen, CO_2 and electricity. Though methanol is usually produced from syngas[3] instead of CO_2, the hydrogenation of CO_2 was chosen in order to realise circularity. The circularity of CO_2 can be achieved by capturing it from biomass or through direct air capture (DAC). For this study, a gas phase conversion was focused on; a liquid phase conversion is also possible but this requires more energy [6]. More details on the gas phase conversion process and related efficiencies can be found in [6].

E-diesel
E-diesel ($C_{12}H_{24}$, ranging from $C_{10}H_{20}$ to $C_{15}H_{28}$) is also produced from green hydrogen and CO_2. A Fischer-Tropsch process is required for the synthesis, with an efficiency of 69% [7]. An alternative to the Fischer-Tropsch process is methanol-to-diesel synthesis [8].

E-ammonia
Feedstock for e-ammonia (NH_3) consists of green hydrogen and nitrogen, produced by air separation. The synthesis of hydrogen and nitrogen takes place in a Haber-Bosch reactor with a yield of 70% [9].

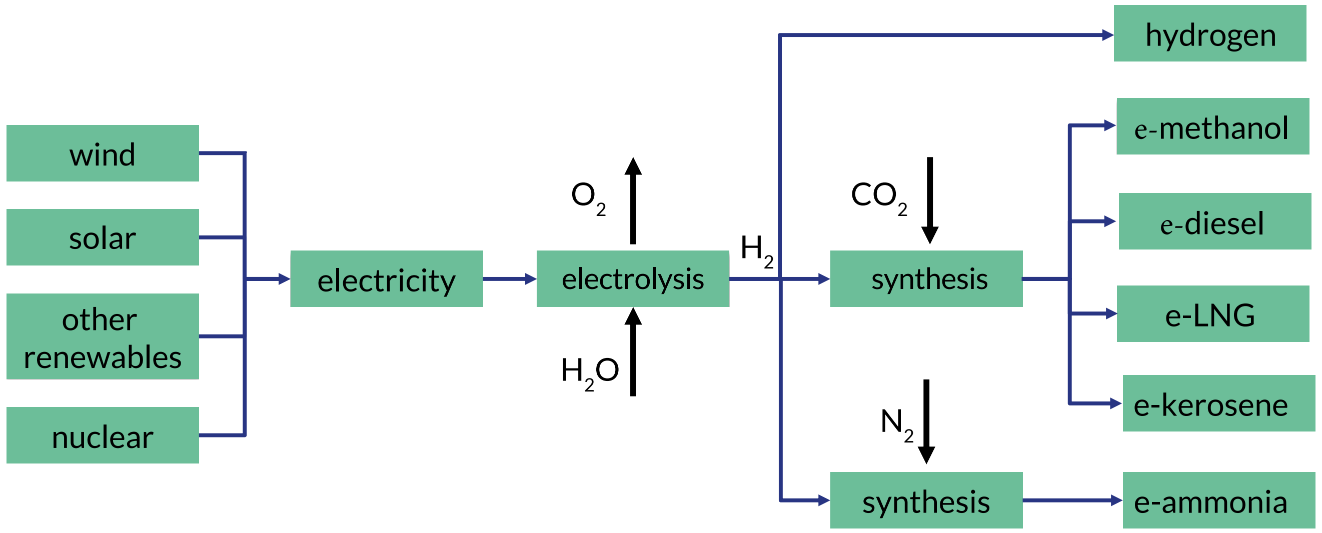


Figure 4: Schematic representation of the production routes of hydrogen and the most relevant e-fuels.

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[2] In practice, this efficiency has not yet been realised; for this study, it is presumed that there will be an improvement in technology over time.

[3] Syngas (synthesis gas) is a fuel gas mixture containing carbon monoxide, carbon dioxide and hydrogen.

E-LNG

E-LNG (Liquified Natural Gas, predominantly CH_4) is produced from green hydrogen and CO_2 via the Sabatier reaction [10]. The methane produced is liquified for application in transport.

E-kerosene

E-kerosene ($C_{12}H_{26}$, ranging from C_{11} to C_{14}) can be produced from green hydrogen, CO_2 and Fischer-Tropsch synthesis. An alternative pathway is using e-methanol as a basis and upgrading it to kerosene [11].

Besides the e-fuels in this study, others are being developed. Some of the most relevant are described in the textbox below. There are also alternative storage options for hydrogen in which the hydrogen is bound in a chemical structure in liquids (e.g. LOHC, Liquid Organic Hydrogen Carriers) or solids (e.g. metal hydrides, see text box below).

In this study, fuel cells are assumed to be the energy convertor for hydrogen, while Internal Combustion Engines (ICE) are assumed to be used for e-fuels.

For the selection of the most suitable e-fuels for the selected transport modes, three Key Performance Indicators (KPIs) have been defined (Figure 5). Based on these KPIs, the analysis of the different e-fuels is summarised below.

> **“LOHC allows the storage of hydrogen at ambient conditions”**

Oxygenated fuels

Within the e-fuels landscape, a number of other synthetic options are also being considered. Of particular recent interest are the products Dimethylether (DME) and Oxymethylene Dimethylethers (OME). These ethers can conventionally be produced from methanol. If the methanol is sourced from a power-to-fuels platform, renewable DME and OME can be produced.

Aside from somewhat lower CO_2 emissions per unit of energy compared to e.g. diesel, the actual combustion properties of these synthetic fuels are inherently ‘cleaner’ as a consequence of their purity and chemical composition (so-called oxygenated fuels). This means that there are typically significant reductions to SO_x, NO_x and PM emissions [12], which is especially relevant for marine applications (e.g. in marine boundary layer chemistry) and increasingly stringent regulations in such application environments [13]. However, the application of exhaust after-treatment and particulate filters on conventionally-fuelled engines greatly reduces the environmental benefits of more inherently clean fuels such as DME and OME.

OME1 is already commercially available and is typically used as a solvent, whereas OME3-5 has advantages over OME1 and DME in regard to energy density as well as its liquid state under standard conditions. Furthermore, it has a superior fuel rating in regard to its cetane number. In regard to industrialisation, DME is more advanced than OME, with a number of pilot plant activities underway [14]. Conversely, there is only one current plant in industrial operation for the production of OME3-5.

Liquid Organic Hydrogen Carriers

A longer-term option for the higher energy density storage of green hydrogen is the use of so-called Liquid Organic Hydrogen Carriers (LOHC) [15], [16]. This technology allows the storage of hydrogen at ambient conditions and is based on the hydrogenation (for storage) and dehydrogenation (for hydrogen release) of suitable organic molecules (normally liquids, e.g. tolene-cyclohexane, dibenzyltoluene, etc.). LOHC is an umbrella term for a variety of different organic liquids, including methanol, formic acid and – perhaps most notably in the field – N-Ethylcarbazole. Advantages (e.g. over liquification/compression of hydrogen) include inexpensive, secure and easily manageable substances. In theory, LOHCs also potentially offer improved long-term energy storage (e.g. without suffering from boil-off losses) and the on-demand delivery of stored hydrogen in an easily transportable form. One strong proponent of this technology which is currently gathering interest in the marketplace is the SME Hydrogenious [17].

For use in transportation, a chemical plant or reformer is needed onboard the vehicle in order to extract the hydrogen from the carrier. In terms of energy density, these options fall under a similar range to liquid hydrogen.

Practical application and safety	Environmental impact	Economics
• Vehicle modifications • Impact on infrastructure • Impact on operations • Safety	• Pollutant emissions: NOx, PM, SOx • GHG emissions	• Production costs of fuel • Storage & distribution costs • Vehicle costs • Powertrain efficiency

Figure 5: Key Performance Indicators for a selection of the most suitable e-fuels.

Practical application and safety

A transition from fossil fuels to hydrogen and e-fuels may have a large impact on vehicles, infrastructure and logistics. New engines and tanks for vehicles may be required; distribution and tank infrastructure is not yet present for a number of e-fuels, and the application of e-fuels has consequences for operations. Safety in the use of hydrogen and e-fuels is also important. For the Practical application and safety KPI, the following elements are therefore being considered:

- Impact on vehicles
- Impact on infrastructure for distribution and storage
- Impact on operations
- Safety

The costs of fuelling infrastructure and vehicle modifications are represented in the results for the Economics KPI.

Impact on vehicles

Depending on the respective energy densities and physical states, vehicles and vessels running on e-fuels may need larger and more expensive fuel tanks (e.g. to handle compressed gases) and more complex engines or fuel cells instead of regular engines.

For most modalities, the current benchmark energy convertor is the internal combustion engine (ICE). Despite its complexity, the (larger) ICE is quite efficient (40-50% from fuel to mechanical energy) and robust and the production costs are low (between €200-500/kW).

All of the e-fuels discussed in this study have been demonstrated or used in combustion engines, although only for diesel and LNG does this concern normal series production models. The application of fuel cells is also possible.[4] Fuel cell electric vehicle (FCEV) powertrains are currently only available for use with pure hydrogen, and prices are in the range of €2500-3500/kW (> 200 kW size). The KPI analysis in this study is based on ICEs for e-fuels and the use of fuel cells for hydrogen.

For e-diesel and e-LNG, existing engines can be used. E-methanol can enter the market fairly easily as existing and competitive technologies for engines can be used. For e-ammonia[5] and hydrogen, substantial to very large development efforts are needed and some uncertainties remain. These kinds of developments will only take place if manufacturers are assured that the overall energy system is feasible and suitable for a large market share of their products so that their investments will be paid back.

For the storage of hydrogen and e-fuels in the vehicle, the energy density and specific energy of the fuels are relevant. The ways in which the fuels are stored also impacts the complexity of storage.

In Figure 6, a qualitative assessment is made for the form of fuel storage onboard the vehicle based on the following criteria: space and weight, safety and costs of the fuel tank. Red-coloured cells are not feasible due to energy density. Ships sailing on hydrogen are considered a possibility only if hydrogen is bunkered every one to three days. This automatically limits the use of hydrogen to inland and short-sea shipping (e.g. in applications with limited range requirements). For aviation, all fuels deviating significantly from (synthetic) kerosene are unacceptable due to too high loss of passenger and load capacity and large investments in complete new airplane and engine designs. E-LNG may be feasible, but the fuel tanks have to be concentrated in the central cargo compartment and not in the wings, which poses a big disadvantage.[6]

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[4] For the use of e-fuels with fuel cells, a reformer needs to be added to produce hydrogen. With e.g. high-temperature SOFC, the reformer function can be integrated into a combined-cycle, pressurised fuel cell system. These kinds of systems can also have a much higher energy conversion efficiency (50%-70%), although these systems are currently only modelled. The development effort to get to a prototype is extensive.

[5] The combustion of ammonia in an ICE is quite difficult due to the very low flame speed. In lab demonstrations up to now, a second fuel was used (either hydrogen or something else) to properly burn the ammonia. The hydrogen can be produced from the ammonia onboard the vehicle. Market readiness by 2030 is uncertain.

[6] It should not be expected that current aviation fleets will adapt to e-LNG use within the next decade.

Storage in vehicle	green hydrogen	e-methanol	e-diesel (FT)	e-ammonia	e-kerosine	e-LNG
Distribution & long-haul trucks	compressed or cryogene	standard liquid	standard liquid	compressed (± 10 bar)	n.a.	cryogene (or compressed)
Inland shipping	compressed or cryogene	standard liquid	standard liquid	compressed (±10 bar) or cooled (ca -33°)	n.a.	cryogene
Short-sea shipping	cryogene	standard liquid	standard liquid	cooled (ca -33°)	n.a.	cryogene
Deep-sea shipping	–	standard liquid	standard liquid	cooled (ca -33°)	n.a.	cryogene
Aviation	–	–		–	standard	cryogene

■ Easy ■ Quite feasible ■ Feasible ■ Not impossible ■ Impossible

Figure 6: Form and suitability of the storage of different fuels for different modalities.

The energy density and specific energy both impact the volume and mass of the storage of e-fuels in the vehicle. The weight of the tank impacts the mass of the fuel storage. High energy density and/or specific energy and low tank weight are particularly important factors for modalities for which load volume or mass are critical. In Figure 7, the specific energy and energy density of the fuels with (middle) and without (left) tank weight are presented.

Compressed hydrogen – and to a lesser extent, cryogenic hydrogen, e-LNG and e-ammonia – require heavy tanks to contain the fuel.

Besides the mass and volume of the tank, the shape of the fuel tank is also important. Pressurised and cryogenic tanks are cylindrical and (in the case of cryogenics) insulated. Due to this, significant onboard space (e.g. trunk space) is lost. In Table 1 and in Figure 7 (right picture), a packaging factor per fuel is introduced for ships. This packaging factor varies from 1 for a liquid fuel at ambient conditions to 2.5 for a high-pressure pipe bundle (e.g. as is used for hydrogen). The last column shows the resulting space requirement factor compared to diesel fuel. The first three fuels - e-methanol, cryo-e-LNG and cooled e-ammonia - have an overall volume factor between 2.3 and 3.4. These are acceptable factors for truck transport and ships, allowing a truck or ship to maintain its normal operations without very frequent refuelling events or unacceptable cargo loss. For aviation, this is a different story as both mass as well as volume are very much limited. A plane can devote up to 30% of its take-off weight to fuel. Doubling this fuel weight and tripling its volume would effectively reduce the passenger/cargo mass and volume by around 50%. For short-range planes, it would be less dramatic, but the losses are still too high to consider this a realistic option. The table also shows why batteries are not applicable for long-distance transport and why hydrogen could become an option only for shorter distances.

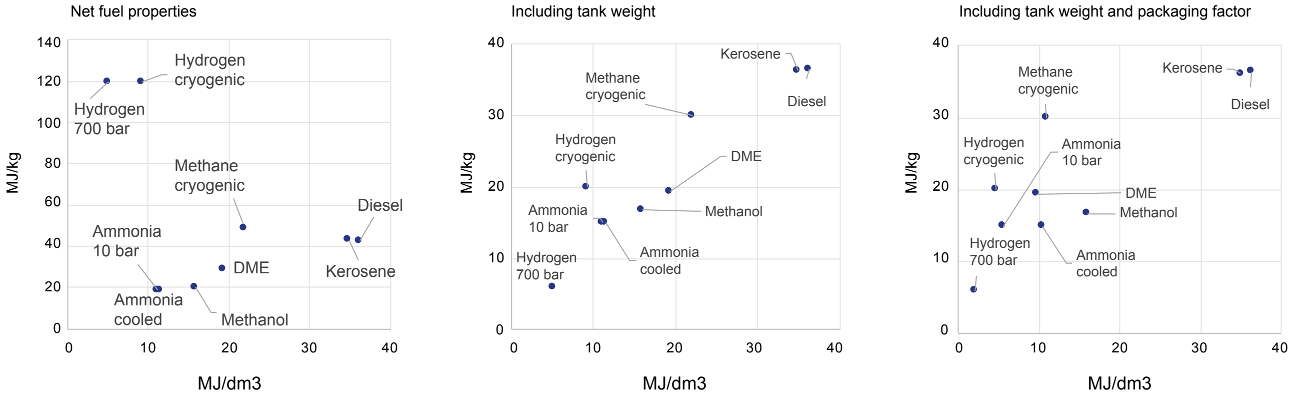

Figure 7: Energy density and specific energy of fuels with and without the tank weight and volume.

From a storage perspective, liquid fuels are the most feasible. E-ammonia requires a larger storage volume than liquid fuels and needs to be compressed to approximately 10 bar or cooled to -30°C in order to make it a reasonable fuel option. E-LNG requires about the same space as cooled e-ammonia but the tank and fuel supply system are more expensive than for ammonia.

For aviation, a high-energy-density fuel is required and modifications to planes have to be avoided. E-kerosene is therefore regarded as the only viable e-fuel for aviation.

Impact on infrastructure
Fuels need to be distributed from the production location to fuelling/bunkering stations and/or the tanks of the vehicles and vessels. The options for distribution are transport by pipeline, by tanker truck or by bunkering ship. An overview of distribution options for the different fuels is presented in Figure 9.

For e-diesel and e-kerosene, existing infrastructure can be used. For e-LNG, existing infrastructure has to be expanded (e.g. in terms of capacity). For e-methanol (liquid) and e-ammonia (compressed or cryogenic), new tank infrastructure will be required.

Table 1: Volume and space requirements of e-fuels onboard ships in comparison to standard diesel fuel. Packaging factors based on feedback from ship owners and own calculations.

	Volume factor based on MJ/dm³	Packaging factor ship	Space requirement
E-diesel	1.0	1.0	1.0
E-methanol	2.3	1	2.3
E-LNG	1.6	2	3.2
E-ammonia (cooled)	3.1	1.1	3.4
E-ammonia (10 bar)	3.2	2	6.4
Hydrogen (cryogenic)	3.8	2	7.7
Hydrogen @700 bar	6.3	2.5	15.7
Battery	50	2	100

	Impact on vehicle costs
Hydrogen	Fuel cell or new engine; costly tank: high pressure or cryogenic
E-methanol	Some modifications on engine and tank
E-diesel	No modification
E-ammonia	New engine type or fuel cell; significant impact on tank
E-LNG	Some modifications on engine; expensive tank
E-kerosine	No modification

■ No impact ■ Small impact ■ Medium impact ■ Significant impact

Figure 8: Overview of the impact and feasibility of hydrogen and e-fuel applications for vehicles.

Distribution / transport via	green hydrogen	e-methanol	e-diesel (FT)	e-ammonia	e-kerosine	e-LNG
Pipeline	compressed			compressed		compressed
Tanker truck	compressed or cryogene	standard liquid	standard liquid	compressed (±10 bar)	-	cryogene
Inland ship	compressed or cryogene	standard liquid	standard liquid	cooled (ca -33°)	-	cryogene
Short-sea ship	cryogene	standard liquid	standard liquid	cooled (ca -33°)		cryogene
Deep-sea ship	cryogene	standard liquid	standard liquid	cooled (ca -33°)	-	cryogene

■ Easy ■ Quite feasible ■ Feasible

Figure 9: Overview of distribution options for e-fuels.

Hydrogen will require a completely new distribution system, including distribution infrastructure (pipelines[7] or tanker trucks and bunker ships). For hydrogen with expected demand from other sectors (e.g. in industry), the combined use of new infrastructure will be possible. The need for compression or liquefaction (in the case of hydrogen, e-ammonia and e-LNG) makes infrastructure more complex as compared to infrastructure for liquids.

The distribution of fuels for road transport will be more extensive than for other modalities due to the need for many fuel stations with a relatively small throughput. Moreover, these stations will be supplied/refilled by tanker trucks in most cases. The quantity of fuel that can be transported by typical tanker trucks varies with the energy density of the fuels. Table 2 shows the quantity in terms of mass (tonnes of fuel) and energy (GJ) and the ratio of the number of tanker truck trips needed to transport the same amount of energy in comparison to the diesel fuel reference. Though hydrogen distribution as a compressed gas is the most likely option up to 2030, it is clear that this will strongly intensify efforts regarding the fuel supply.

The distribution of fuels for shipping and aviation is much more efficient than for road transport because large quantities of fuel can be supplied to a relatively small number of bunker locations (e.g. at strategic port/harbour locations). This supply can usually be organised via more efficient tanker vessels or pipelines.

Impact on operations

The use of hydrogen or e-fuels will have an impact on the necessary frequency of refuelling or bunkering. Depending on the specific fuel in question, it is expected that the frequency will increase (e.g. compared to diesel[8]) in relation to the engine/powertrain efficiency, the energy density of the fuel and the tank size.

For diesel engines, engine efficiency varies from 40% to 47% and is dependent on engine size. Provided that the diesel cycle combustion principle is maintained (i.e. so-called dual-fuel or diesel pilot engines), similar efficiencies are expected when e-fuels are employed. For new systems, fuel cell system efficiency varies from 49% at 50% load to about 45% at full load. However, 10% efficiency is expected to be lost over the lifetime of the cell. On top of that, there is an energy loss for the electric motor which drives the wheels or propeller and for power control. This loss, which can total approximately 8%, is greater than the efficiency loss for a mechanical driveline. For this study, it is assumed that the powertrain efficiency is equal for conventional diesel, hydrogen and e-fuels. Thus, the energy use per km will be identical for all fuels.

The energy densities and consequences for the space requirements of a tank with a comparable energy content are presented in Figure 7 and Table 1 (see pages 12 and 13).

Table 2: Typical volumes and energy content of fuels transported by tanker trucks.

	Tanker truck		**Ratio of tanker trucks to diesel reference**
	Tonne	**GJ**	
E-diesel	16	683	1.0
Hydrogen (compressed)	1	120	5.7
Hydrogen (cryogenic)	4	480	1.4
E-methanol	16	315	2.2
E-ammonia (compressed)	16	298	2.3
E-LNG	16	784	0.9

Table 3: Typical bunker quantities and storage tank size for conventional fuels.

	Typical bunker quantity		**Typical storage tank size**		**Max. range**
	tonne diesel	GJ	tonne diesel	GJ	Days
Long-haul truck	0.8	34	1.0	43	5
Inland ship	25	1,070	50	2,135	14
Short-sea vessel	500	21,500	1,150	49,100	30
Deep-sea vessel	2,000	86,000	4,200	180,000	60

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[7] In the future, the reuse of existing natural gas infrastructure for hydrogen distribution may become an option.
[8] This does not apply to kerosene. As kerosene is assumed to be the only realistic option for aviation, it has been left out here.

For some of the investigated e-fuels and hydrogen, a larger storage tank than for diesel will be needed to store the equivalent amount of energy. In practice, the tank or bunker size in GJ will often be reduced through the use of alternative e-fuels as the required volume for an equivalent range is not available onboard the vehicle. Based on diesel, typical tank and bunker quantities for the different modalities are listed in Table 3.

The consequences for operations can be summarised as follows:

- Long-haul trucks: compressed hydrogen fuel (700 bar) would require daily instead of weekly refuelling (as is currently the case with diesel fuel). For e-methanol, e-LNG and e-ammonia, one should expect 1.5 to 2 times as many refuelling events.
- Inland shipping: approx. 50% more bunkering events with e-methanol, e-LNG and e-ammonia compared to (e-)diesel. Daily bunkering with compressed hydrogen (700 bar), compared to weekly bunkering with diesel fuel.
- Short-sea shipping: will require approx. 50% more bunkering events with e-methanol, e-LNG and e-ammonia as compared to diesel. A range of 4 days with liquid (cryogenic) hydrogen, compared to 4 weeks with diesel. 1-day range with compressed hydrogen (700 bar).
- Deep-sea shipping: bunker tank size will be increased for e-methanol, e-LNG and e-ammonia, such that range requirements (up to 60 days) can be met with these fuels. Hydrogen is not considered an option.

Safety

All e-fuels in this study have additional safety concerns compared to diesel. These concerns are related to the easier formation of ignitable mixtures with air, the lower flash point temperatures and the toxicity of inhaling vapours, ingestion or contact with the skin.

Ammonia is a gas at ambient temperature and is toxic when inhaled. This probably makes it too unsafe for road transport. If it were to escape from a tank, e.g. in a garage or a tunnel, it would become quite hazardous. For shipping, sufficient safety measures for ammonia as a fuel can probably be taken. In [18], safety analyses are shown for a maritime vessel and compared with LNG as a fuel.

Concerns regarding methanol are related to its toxicity when in contact with the skin or eyes or when ingested. In this sense, it is probably similar to gasoline or benzene [19]. Another safety concern is its invisible flame, although this is also an advantage in certain conditions. Methanol was applied in cars in California in the eighties in so-called Flexible Fuel Vehicles, later replaced by ethanol. Methanol is already being applied as a fuel for shipping [20].

LNG and hydrogen also have additional safety issues because they are gases and can easily form ignitable mixtures. Hydrogen burns at low concentrations in air (>4%) and with a very low energy input. An advantage of LNG is that it is lighter than air and diffuses quickly into the surrounding atmosphere. The same is true for hydrogen but allowing its escape into the surrounding environment is not advised given its very high combustibility.

Environmental impact

For the Environmental impact KPI, pollutants (NO_x, PM) and CO_2 emissions are examined. This analysis discusses the WTW (well-to-wheel) CO_2 emissions of the selected e-fuels, while only TTW (tank-to-wheel) emissions are addressed for pollutant emissions. We assume that only electricity from renewable sources (e.g. offshore wind energy) is utilised.

The projection of vehicle and vessel emissions is based on combustion engines for all fuels except for hydrogen, which is assumed to be used in a fuel cell energy convertor with zero tailpipe emissions. The newest pollutant emission requirements for combustion engines are taken into account. These are:

- Trucks: Euro VI (2014 onwards)
- Inland vessels: Stage V (2019/2020 onwards)
- Maritime vessels: Tier III NO_x (2021) and fuel sulphur requirements from 2021 onwards

Table 4 summarises the projected pollutant emissions. Only with hydrogen in combination with fuel cells are zero pollutant emissions accomplished. Zero pollutant emissions are primarily important for urban areas. In that sense, it could be important for distribution trucks, but is less important for long-haul trucks. For specific ships, such as port vessels and workboats, zero emission can also be important.

For road transport and inland shipping, e-fuels (except for H_2) will not lead to a substantial reduction in pollutant emissions because the legislation on emissions is already very stringent and requires SCR catalysts and particulate filters for diesel engines. For sea shipping, the use of e-fuels will lead to a substantial reduction in pollutant emissions compared to fossil fuels due to the inherent purity of the synthetic fuel. The absence of sulphur-containing compounds[9] and, in the case of e-diesel, the lack of problematic poly-aromatics and tars etc. will lead to reductions in SO_x and PM emissions (e.g. 70% to 99% lower).

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[9] Truck and inland ship fossil diesels also have an ultra-low sulphur content.

NO_x emissions from marine vessels will become lower due to the entry into force of the IMO Tier III legislation. As a consequence of this relatively stringent legislation, the application of exhaust after-treatments (e.g. particle filters and SCR deNO_x[10] catalysts, similar to what is used for diesel trucks) will increasingly be implemented, leading to reductions in the differences in emission profiles between the different fuels. Overall, zero pollutant emissions are generally not possible and are not anticipated given the inherent nature of combustion in ICEs. For most e-fuels, pollutant emissions in the form of NO_x and PM are therefore to be expected. Near-zero emissions could be possible if methanol and ammonia fuel cells were to become mature and be scaled-up and implemented after 2030.[11]

For the assessment of the CO_2 emissions of synthetic fuels based on renewable energy, a distinction needs to be made between carbon-based and non-carbon-based fuels. Hydrogen and e-ammonia are free of carbon and therefore have no (tank-to-wheel) CO_2 emissions when combusted.[12] If all energy used for their production is from renewable sources and no greenhouse gas emissions occur in the production process, their well-to-tank emissions are also zero, resulting in zero well-to-wheel emissions.

Carbon-based e-fuels (e-methanol, e-diesel, e-LNG and e-kerosene) need a CO_2 source for production[13] and cause CO_2 exhaust emissions when combusted. Whether these exhaust emissions are attributed as tank-to-wheel emissions in the transport sector is a matter of definition, determined by applicable regulations.

If the CO_2 used for the production of e-fuels is obtained through direct air capture or biomass combustion, if all energy used in the process is obtained from renewable sources and if the production process does not emit other greenhouse gases, it is evident that the well-to-wheel CO_2 emissions of such e-fuels will be zero. As a first step towards circularity, however, the CO_2 used for producing synthetic fuels will be captured from fossil point sources, e.g. from power plants or industrial processes. In a European Commission document [21] explaining the principles for calculating the lifecycle GHG intensity of novel transport fuels in relation to the Fuel Quality Directive (FQD), it is stated that the carbon content of the fuel is not counted as an emission during its combustion when it comes to carbon containing fuels produced from CO_2 that would otherwise be released into the air. This means that the tank-to-wheel emissions of carbon-containing e-fuels count as zero, similar to the case for biofuels. As their production also emits no greenhouse gases or very low levels of them, the overall well-to-wheel emissions attributed to e-fuels under the FQD will generally be very small.

The GHG emission reduction impact of e-fuels should generally be viewed as a system level impact for the combined system of the industrial activity of which the CO_2 emissions are captured and utilised (CCU) and the transport activity in which the e-fuel is used. The industry that supplies the CO_2 will generally be part of the EU-ETS. As the FQD attributes the emission benefits of e-fuels entirely to the transport sector, the supply of CO_2 as a feedstock for e-fuels should not be considered a CO_2 emission reduction measure under the EU-ETS in order to avoid carbon leakage or double-counting of the reduction. This is consistent with the current treatment of CCU under the EU-ETS [22][14], but the way in which CCU options should be treated under EU-ETS is under debate and could change in the future.

Table 4: Emission projection for different fuels based on EURO VI for trucks, Stage V for inland ships and Tier III for maritime vessels. Medium emissions (for maritime vessels) will still be within Tier III requirements in practice.

	Emission	Current fossil diesel	Green hydrogen fuel cells	E-MeOH	E-diesel (FT)	E-NH_3	E-LNG
Trucks and inland ships	NO_x	Low	Zero	Low	Low	Low	Low
	PM	Low	Zero	Low	Low	Low	Low
	SO_x	Low	Zero	Low	Low	Low	Low
Maritime vessels	NO_x	Medium	Zero	Medium	Medium	Medium	Medium
	PM	Medium	Zero	Low	Low	Low	Low
	SO_x	Medium	Zero	Low	Low	Low	Low

The fact that the industry that supplies the CO_2 as feedstock for the production of e-fuels still needs to buy emission allowances for this CO_2 means that this industry does not have a direct incentive to invest in CCU for e-fuels. The incentive to produce e-fuels will then mainly have to come from the fact that they are rewarded or even mandated to some extent under the FQD and RED II (Renewable Energy Directive). In the context of CO_2 regulations for vehicles, tailpipe emissions are regulated (as with the European CO_2 regulation for heavy duty road vehicles) so that vehicles running on e-fuels are defined as having the same CO_2 emissions as vehicles running on the fossil-based equivalents of the same fuels. This regulation therefore does not provide additional incentives for the transition to e-fuels.

Economics

For the Economics KPI, the costs throughout the value chain are relevant, including hydrogen and e-fuel production costs, costs of compression or liquefaction (where needed) and distribution to fuelling stations, costs of fuelling stations and extra investments in vehicles.

In this whitepaper, only the results of the cost analysis are presented. An extensive analysis and the assumptions on which the analysis is based can be found in [23]. The costs are a projection for 2030. As there is a lot of uncertainty on many factors in the analysis, including technology development, optimal production routes and efficiencies, the cost figures only give an indication of the cost levels and their structure.

The costs of production are highly dependent on the costs of electricity and CO_2. The costs of CO_2 include the following elements:

- Feedstock costs. The costs of feedstock consist of the costs of production or the capturing (CCU or DAC) of CO_2, the costs of delivery and the margins for suppliers based on market dynamics (supply versus demand).
- In the future: ETS[15] and CO_2 tax when applicable, dependent on future regulation and the ways in which suppliers of CO_2 pass these costs on to their customers.

Since the cost levels of electricity and CO_2 are uncertain for 2030, a base case scenario with electricity costs of €30/MWh and CO_2 costs of €40/tonne is used. A sensitivity analysis is subsequently presented.

Figure 11 presents the value chain costs for trucks and different shipping modalities. Aviation is left out of the economics analysis as kerosene is regarded as the only viable e-fuel for aviation.

Table 5: Environmental impact KPI scores for the different e-fuels.

	Polutant emissions	CO_2 emissions
Hydrogen	Zero emission	Zero WTW & TTW CO_2 emissions
E-Ammonia	Combustion engines: stringent legislation leads to equal emissions of all e-fuels	Zero WTW & TTW CO_2 emissions
E-Methanol		Zero WTW CO_2 emissions if all CO_2 is circular When CO_2 for e-fuels is derived from fossil sources, the FQD / RED II also consider WTW CO_2 emissions as zero to very low, which is formally only correct as long as CCU is not considered as CO_2 reduction measure under EU-ETS.
E-Diesel (FT)		
E-LNG		
E-Kerosene (FT)		

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[10] Specific catalyst to reduce NO_x emissions. Customary for diesel engines.

[11] Methanol fuel cells are now used for small applications and ammonia fuel cell technology has a very low TRL. At this moment, however, ammonia can be converted to hydrogen in a fuel reformer, which can be used in a fuel cell. The conversion of ammonia in the fuel reformer can result in some pollutant emissions.

[12] NB: That does not mean that other carbon-based emissions do not occur elsewhere in their value chains.

[13] Dependent on the production process, syngas or CO may also be used.

[14] See e.g. Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects final report, https://www.cedelft.eu/en/publications/download/2739

[15] Road transport and shipping are currently not included in EU ETS; this only applies to aviation (see [24]). When DAC is applied, net emissions are (near) zero for the value chain, and it is to be expected that possible future ETS costs and emission taxes will not apply in the case of DAC.

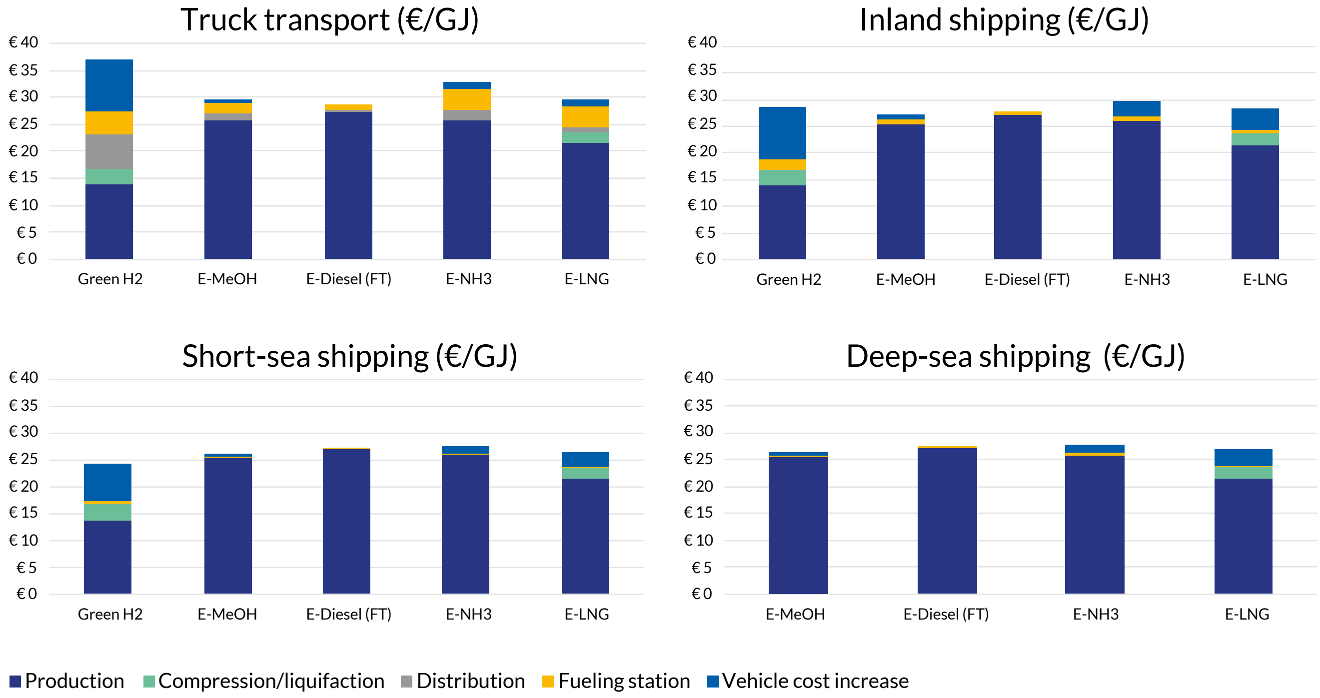

Figure 11: Costs per GJ fuel energy for different e-fuels and four transport modalities. Based on electricity costs of €30/MWh and CO_2 costs of €40/tonne. Projection for 2030, includes fuel production and distribution costs and additional vehicle/ship costs calculated back to €/GJ and taking into account powertrain efficiency.[16,17]

For this base scenario with electricity costs of €30/MWh and CO_2 costs of €40/tonne, the following conclusions have been drawn:

- Overall, the cost differences between the e-fuels are relatively small. Hydrogen is more economical to produce (in €/GJ), but this advantage is lost when the distribution costs and increased powertrain costs are included.
- For truck transport, hydrogen is the most expensive option. Hydrogen could become an attractive option if solutions can be found for the high distribution costs (e.g. via pipeline distribution) and the high vehicle costs (e.g. through cost reductions for fuel cells through innovation or economies of scale). It is expected that this might take place well after 2030.
- For truck transport, inland and deep-sea shipping, e-methanol, e-diesel and e-LNG appear to be the most attractive options, but the estimated cost differences between hydrogen and e-ammonia are small and probably fall within the uncertainty range of the calculations.
- For short-sea mobility, hydrogen is the most attractive option economically in the cases where it is possible (e.g. short distance ferries). For inland shipping, hydrogen is also an interesting option for short distances.

The costs of hydrogen and e-fuels are, however, sensitive to the cost of CO_2 (in the case of e-LNG, e-methanol and e-diesel) and electricity (all assessed e-fuels) (Figure 12). As CO_2 is emitted when carbon-based fuels undergo combustion in the engine, the CO_2 for production has to be captured from a circular source (e.g. by direct air capture) to generate a (nearly) net-zero emission situation. This can lead to high costs of CO_2. When the costs of electricity and CO_2 are high, hydrogen is the least expensive option for all transport modes (except for deep sea, where it is not applicable), followed by e-ammonia. E-ammonia, however, is (currently) considered unsafe for road transport. For all transport modalities, e-methanol is the most sensitive to high CO_2 costs, more so than e-diesel and e-LNG.

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[16] However, the efficiencies of combustion engines regarding different fuels and also fuel cell systems are considered equal as the information does not clearly indicate that one is better than the other. This varies based on the precise engine types and level of optimisation.

[17] This analysis is intended for comparing the costs of e-fuels to one another and not for comparing these with the costs of fossil fuels.

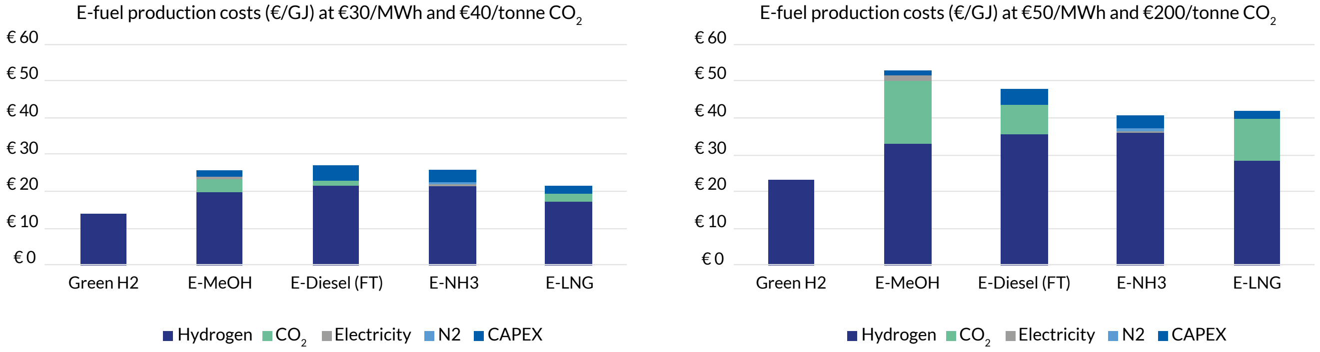

Figure 12: E-fuel production costs are highly sensitive to the costs of green electricity and CO_2. Left figure costs are €30/MWh for green electricity and €40/tonne CO_2; on the right, €50/MWh and €200/tonne CO_2.

For the Economics KPI, it can be concluded that although green hydrogen has by far the lowest production costs per GJ, it has higher costs for the whole value chain than most e-fuels in the base case (except for short-sea shipping). Because the outcomes of the cost comparisons are highly variable and dependent on electricity and CO_2 costs, no clear winner can be determined.

Summary of Key Findings

From this analysis based on KPIs, four conclusions can be drawn:

- For trucks, hydrogen is considered applicable only for use in short-distance transport. Compared to e-fuels, it is only attractive when the costs of electricity and CO_2 are high or when the costs of infrastructure and vehicles have declined significantly.
- In all other cases, e-methanol, e-diesel and e-LNG are the most attractive options. E-ammonia is currently considered unsafe for road transport use.
- For shipping, the cost differences between e-fuels are small. Hydrogen is an interesting option where applicable (short distances and ferries), especially in the case of high CO_2 costs. E-ammonia is also interesting if CO_2 costs are high, particularly for deep-sea shipping. E-methanol, e-diesel and e-LNG are interesting options, especially when CO_2 costs are low.
- For aviation, e-kerosene is regarded as the only viable e-fuel option.

	🚚	🚢	✈
Hydrogen	For short distances, in case of high electricity and CO_2 costs		
E-methanol	Feasible		
E-diesel			
E-LNG			
E-ammonia	Unsafe	In case of high CO_2 cost	
E-kerosene			Only feasible option

Figure 13: Conclusions on the applicability of hydrogen and e-fuels for trucks, shipping and aviation.

A DRASTIC TRANSITION IN FUEL PRODUCTION IS REQUIRED

The production of e-fuels will lead to a large demand for electricity from renewable sources, water and CO_2. In this section, a case study of the Netherlands is presented in order to analyse the impact that the production of e-fuels will have on the demand for electricity and feedstock and on the space required for the production of e-fuels. The Netherlands, with the Port of Rotterdam and Amsterdam International Airport Schiphol as its main ports, plays an important role as a logistical hub for European and worldwide transport. Europe's largest refineries are located in the Rotterdam port area. Background information on this analysis can be found in [25].

This section assesses the required size of installations in the Netherlands if the future sustainable fuel production is to meet the projected future demand from inland consumption and bunkering for international transport, determined under the assumption that ships and aeroplanes will continue their habits of bunkering in the Dutch main ports.

For the Netherlands, the total energy demand for national and international mobility is forecasted to be > 1200 PJ/annum, representing the highest demand on a sectoral basis (Figure 14 and Figure 15). For 2050, a fuel demand of 960 PJ is forecasted for international transport modes, approximately covering the modalities in this study.

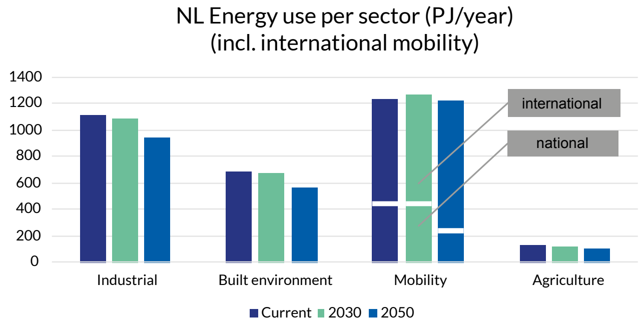

Figure 14: Energy use in the Netherlands per sector, including bunkered fuels for international transport. Energy demand forecast by TNO, based on EBN [26] (figures 2019), Klimaatakkoord [27] (figures 2030), Net voor de Toekomst scenario "Regie Nationaal" from CE Delft [28] (figures 2050). For figures on national and international mobility NEV 2017 [29], CBS, and EU Reference scenario 2016 [5] were used.

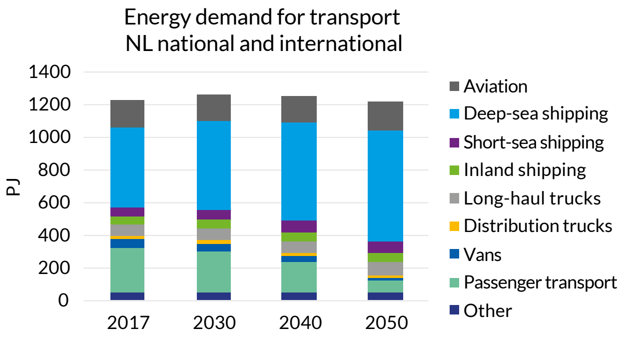

Figure 15: Energy demand in NL for national and international transport (fuelled/bunkered in NL)[18]

To determine the required capacities and the space needed for installations for fuel production, an example is described in which this 960 PJ of fuels is produced in the form of e-methanol.[19] To produce this amount of e-fuels, more than 2000 PJ of electricity is required.[20] Currently, the maximum Dutch offshore wind capacity is estimated at 900 PJ [30]. This means that importation will become necessary in the form of electricity, hydrogen or e-fuels. However, scenarios are possible in which much more energy can be produced on the Dutch continental shelf (see text box).

A transition from Dutch refinery clusters to e-fuels production will have a large impact not only on energy demand but also on infrastructure. If all required e-fuels were produced in the Netherlands as e-methanol, this would require a capacity of 68 GW water electrolysers, 58 methanol plants with a capacity of 2 ktonne/day each and a feedstock of > 70 Mtonne CO_2/annum, which would require extensive DAC installations and probably a seawater desalination plant (since electrolysis requires significant volumes of water). For comparison: current Dutch CO_2 emissions are approx. 160 Mtonne/annum. The 58 methanol plants would represent an annual production capacity of 42.3 Mtonne of e-methanol, equating to approx. 50% of current global methanol production. The storage capacity for bunker fuels would have to be scaled up as methanol has a significantly lower volumetric energy density than fossil fuels.

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[18] Based on data from NEV 2017 [29], CBS, and EU Reference scenario 2016 [5].

[19] E-methanol is taken as an example; other e-fuels are also possible. For aviation, the production of e-kerosene will be necessary.

[20] A production efficiency of 45% is assumed. Only electricity needed for the production of hydrogen and methanol is included. Excluded is the electricity needed for CO_2 capture, hydrogen and fuel distribution and storage, etc.

How much electricity can be produced from offshore wind?
A number of parameters determine the amount of electricity that can be produced from offshore wind on the Dutch continental shelf:

- the energy density of windmills in MW/km^2
- the capacity factor (the energy production in terms of % of the maximum capacity of windmills)
- the percentage of the Dutch continental shelf that is used for offshore wind

Developments will lead to an increase in energy densities and capacity factors. For example, the Gemini wind parks have an energy density of almost 9 MW/km^2, compared to 4-6 MW/km^2 applied in [30]. Technical developments, like better designs of rotor blades and higher towers, will result in higher capacity factors.

The share of the Dutch continental shelf that can be used for offshore wind depends on regulation and political choices. Areas are used for military exercise, shipping, fisheries and nature. The multi-purpose use of areas may lead to a larger area for offshore wind. Because the depth of the Dutch North Sea is less than 55 metres, the whole area is suitable for offshore wind.

Example: if 28% of the Dutch continental shelf were to be used for offshore wind, with an average energy density of 7.5 MW/km^2 and a capacity factor of 55%, this would result in an installed capacity of 120 GW and 578 TWh or 2081 PJ electric energy delivered per year.

The Rotterdam port area would be a logical place for e-fuels production in the Netherlands:

- A large share of fuel bunkering takes place in the Port of Rotterdam. The transportation of fuels will thus be minimised.
- The Maasvlakte is a landing place for offshore wind energy. Direct use of electricity from offshore wind makes further transportation unnecessary and will thus alleviate the grid.
- Storage and transport facilities are in place, though expansion will be needed.

The production of e-methanol will require a significant amount of space for hydrogen plants, methanol production plants and DAC.[21] For the scenario described above, with 960 PJ of fuels produced, approx. 600 ha of land area will be required, representing approx. 60% of Maasvlakte 2. About two-thirds of the total required space will be used to obtain CO_2 from the air with a DAC plant[22], so reduction of the footprint of such a plant or the transportation of CO_2 from other regions is crucial for e-methanol production in the Rotterdam area.[23] The CO_2 demand is also reduced when the CO_2 of the purge gas from the e-methanol plant can be used as feedstock. The production of e-fuels other than e-methanol would require less space for DAC because less CO_2 feedstock is needed for e-diesel and e-LNG than for e-methanol. E-ammonia and hydrogen have no CO_2 needs at all, reducing the space requirements for production significantly.

> **“The Rotterdam port area would be a logical place for e-fuels production in the Netherlands”**

🟪	1400 - 1800	Oude havens
🟧	1800 - 1900	Oude handelsterreinen
🟥	1920 - 1940	1e en 2e Petroleumhaven, Merwehaven, Waalhaven
🟪	1946 - 1960	Botlek, Eemhaven
🟦	1960 - 1970	Europoort
🟩	1970 - Heden	Maasvlakte
🟨	2008+	Maasvlakte 2

Figure 16: Impact on space requirements when 960 PJ of e-methanol per year is produced at Maasvlakte 2. Above is a picture of Maasvlakte 2. The bottom picture shows the Rotterdam port area, in which the yellow part is Maasvlakte 2; picture source: [32].

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[21] Compared to land use for the production of biomass for biofuels, the space requirements for e-fuels plants are, of course, very limited.

[22] It is assumed that 30 Mtonne of CO_2 will be used from CO_2 capture from power plants and industrial processes as a first step towards circular e-fuels. For fully circular e-fuel production, more CO_2 has to be transported to Rotterdam from other regions with DAC plants. The space required for DAC is estimated at 10 hectares for a Mt CO_2 production per year.

[23] Other reasons to produce CO_2 in other regions than at Maasvlakte 2 are the lack of space at Maasvlakte 2 (a large part of the land at Maasvlakte 2 has already been reserved for other activities) and the high price of land at Maasvlakte 2 [31].

COLLABORATION IS NEEDED TO ACCELERATE THE ADOPTION OF E-FUELS IN MOBILITY

It should be stated that e-fuels offer an opportunity for the transport sector to become more sustainable and to deliver its contribution to the climate goals. E-fuels, based on energy and feedstock from renewable sources, offer scope to de-fossilise (in particular) the heavy and long-distance segments of the transport sector whilst still fulfilling the mobility needs of passenger and freight transport. It will, however, require a drastic transition in fuel production and the effort of all stakeholders. Together with stakeholders throughout the value chain, the interests of stakeholders and the barriers preventing the adoption of e-fuels have been identified and a roadmap for innovation has been set up.

Interests of stakeholders

There are a significant number of stakeholders in the potential value chain, whose interests must be taken into consideration if the transition to hydrogen and e-fuels is to be realised successfully in the transport sector. The main stakeholders and their interests in hydrogen/e-fuels for mobility are summarised below (Figure 17):

A common interest of all commercial stakeholders is financial viability, e.g. generating a profit for commercial operations while keeping travel and transport affordable for customers. Currently, e-fuels would have to compete in the marketplace with fossil fuels that have far lower inherent production costs. Incentives from governments to favour green fuels over fossil fuels are therefore a precondition for the adoption of e-fuels. Also, customers may have to accept increased costs for sustainable transport solutions, which implies a challenging behavioural change.

For *fuel producers*, e-fuels offer an opportunity to develop new Product Market Combinations (PMCs) by delivering new products (e-fuels) to the transport market. This role can be fulfilled by current (fossil) fuel producers, by chemical companies or by parties at industrial clusters in new circular business models. To avoid over-investment in production capacity, fuel producers have an interest in predictable, reliable market demand from fuel providers. Producing 'green' e-fuels can help them achieve their sustainability goals.

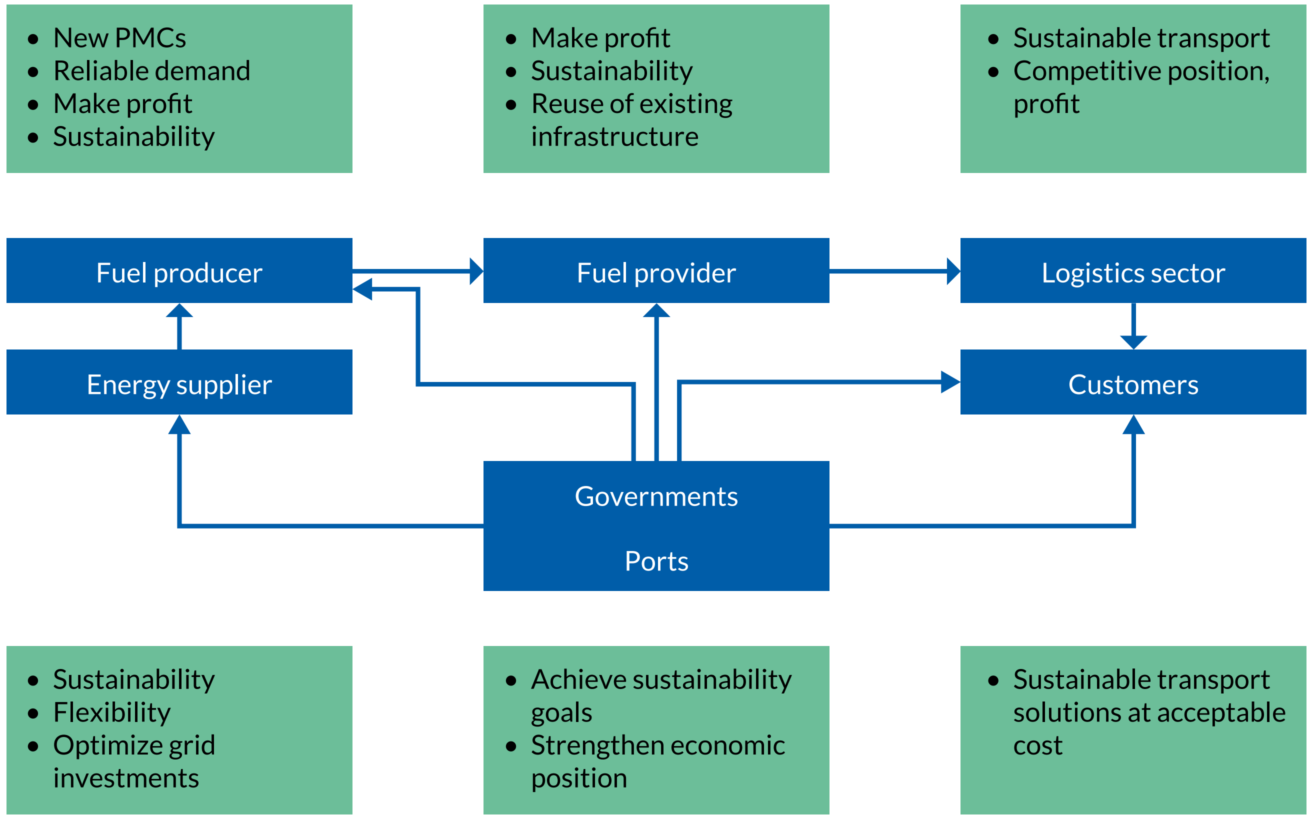

Figure 17: Main stakeholders and their interests in e-fuels for mobility.

Fuel providers have an interest in reusing existing infrastructure to minimise the need for investments in new infrastructure. As infrastructure for diesel and kerosene is already in place (although potentially not at the volume required), fuel providers could probably favour e-diesel and e-kerosene over other e-fuels. The development of hydrogen infrastructure by third parties will make hydrogen more attractive.[24] Infrastructure costs for e-methanol are lower than for e-ammonia and e-LNG. Though fuel providers have a large interest in current fossil fuel provisioning, it is inevitable that they become fellow travellers in the transition to sustainable fuels.

For the ***logistics sector***, it is important to fulfil the demands of their customers, who ask for sustainable transport solutions with end-to-end transparency at acceptable costs. Besides e-fuels costs, investments in vehicles will also impact the price of sustainable logistic solutions.

For ***energy suppliers***, the production of e-fuels will have a large impact on the demand for electricity from renewable sources. Investments in large-scale renewable energy supplies (e.g. offshore wind parks) are needed. As the supply patterns of renewable sources such as wind and solar are volatile, the energy sector has an interest in flexible demand. Hydrogen production can meet this need for flexibility. The capacity of the electricity grid will have to be extended significantly, which will require large investments. The production of hydrogen and e-fuels in ports will minimise grid investments for e-fuel production as ports are logical landing places for offshore wind.

Governments at a regional, national and international level and ports will need to achieve sustainability goals, and hence have an interest in making transport more sustainable. They therefore need to enable all stakeholders throughout the value chain - from fuel storage providers to logistic companies - to transition from fossil fuels to more sustainable fuels like e-fuels, such as by creating incentives and/or obligations or by offering other mechanisms of support. Meanwhile, governments and ports will want to strengthen the economic position of the region or country. E-fuels offer opportunities but represent a challenge too due to all of the costs associated with production and the uncertainties and risks associated with the transition.

Besides these stakeholders, many other parties are important to the development and adoption of e-fuels, like suppliers of electrolysers, feedstock providers of CO_2 and nitrogen, storage providers for storing hydrogen and e-fuels, providers of tank infrastructure and suppliers of vehicles, engines, fuel cells and tanks.

Overcoming the barriers

In order to accelerate the adoption of hydrogen and e-fuels, an intensification of the innovation and implementation of e-fuel production, vehicle technology and infrastructure should take place. To achieve this, several barriers will need to be overcome. The table below describes the barriers that were named during the market consultation in this study. Suggestions on how to overcome these barriers are also provided.

Table 6: Barriers for the adoption of e-fuels.

	Barriers	How to overcome
Economic	• High cost of e-fuels • Uncertainty regarding the future development of renewable electricity and CO_2 feedstock costs • Depreciation of existing assets; new infrastructure needed	• Invest in R&D for more efficient production routes and reduced CAPEX of electrolysers • Accept that sustainable fuels are more expensive than current fossil cost levels • Develop and apply financial constructions and long-term contracts to mitigate the uncertainty of future energy and feedstock costs • Make use of volatile electricity prices by applying the flexible production of hydrogen • Share infrastructure with other sectors where possible, e.g. for hydrogen and methanol. Reuse fossil infrastructure, e.g. for storage
Technical	• Optimal production routes of e-fuels not clear yet • Not enough CO_2 from circular sources available • Engine and fuel cell developments needed	• Invest in R&D and pilots to develop and optimise production routes • Use CO_2 from point sources and biomass during transition; in the meantime, develop DAC technology for large-scale application • Invest in the development of engines and fuel cells
Organisational	• A system perspective and cooperation by all stakeholders is needed • Dependent on electricity import (e.g. from neighbouring countries or even from other continents) • Strong emphasis on current policies on BEV and hydrogen, which are not suitable for long-distance transport	• Create alliances with all stakeholders and make long-term commitments • Examine the possibilities to extend Dutch offshore wind capacity beyond 60 GW • Create awareness of the potential of e-fuels and include e-fuels in future policies
Regulatory	• Fossil fuels and CO_2 emissions are too inexpensive, preventing companies from choosing more sustainable alternatives • Certification of e-fuels has not yet been arranged • Uncertainty about future tax regimes for vehicles and fuels • No global level playing field for sustainability in transport; worldwide goals are needed	• Favour e-fuels over fossil, e.g. through CO_2 taxes and blending requirements and stronger support for e-fuels in further iterations of the Renewable Energy Directive (e.g. also for shipping and aviation) • Support pilots and the commercial deployment of sustainable initiatives • Arrange regulatory certainty and predictability through the certification of e-fuels and by creating clarity about future taxes • Create a level playing field at least at an EU level

Many of these barriers cannot be overcome by individual stakeholders alone. Stakeholders are dependent on one another and cooperation is of major importance to overcoming these barriers. In some cases, especially in the field of regulation and emission target setting, there is a dependency on other EU member states or even on worldwide cooperation.

A roadmap for innovation

Close cooperation between stakeholders and the creation of alliances is of vital importance for a successful transition to e-fuels. The application of e-fuels in transport requires steps in R&D, production, regulation, infrastructure for e-fuel distribution and fuelling and the adaptation of vehicles. A roadmap for the deployment of e-fuels for transport in the Netherlands is shown in Figure 18. A roadmap would look similar for countries other than the Netherlands.

While biofuels and hydrogen are already being piloted and applied on a small scale, e-fuels are still in their infancy. Since the availability of biomass in the Netherlands is very limited, it is assumed that hydrogen and e-fuels will cover the lion's share[25] of sustainable fuel demand for transport in the long term.

To produce e-fuels, sufficient amounts of electricity from renewable sources will need to be available. Since hydrogen is a feedstock for all e-fuels, hydrogen production needs to be scaled up extensively. Production processes for e-fuels require R&D in order to find efficient production routes and reduce costs. Synergy with the chemical industry can be realised by the joint development of production processes and DAC. Though it is not yet clear which e-fuels will be adopted for trucks and ships, the production of e-methanol is a relatively safe choice to start with

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[24] In the Netherlands, Gasunie has plans for the development of a national hydrogen backbone. Four hydrogen fuelling stations are also operational and the extension to twenty fuelling stations is planned.

[25] An alternative would be to import biomass for the production of biofuels or to import biofuels.

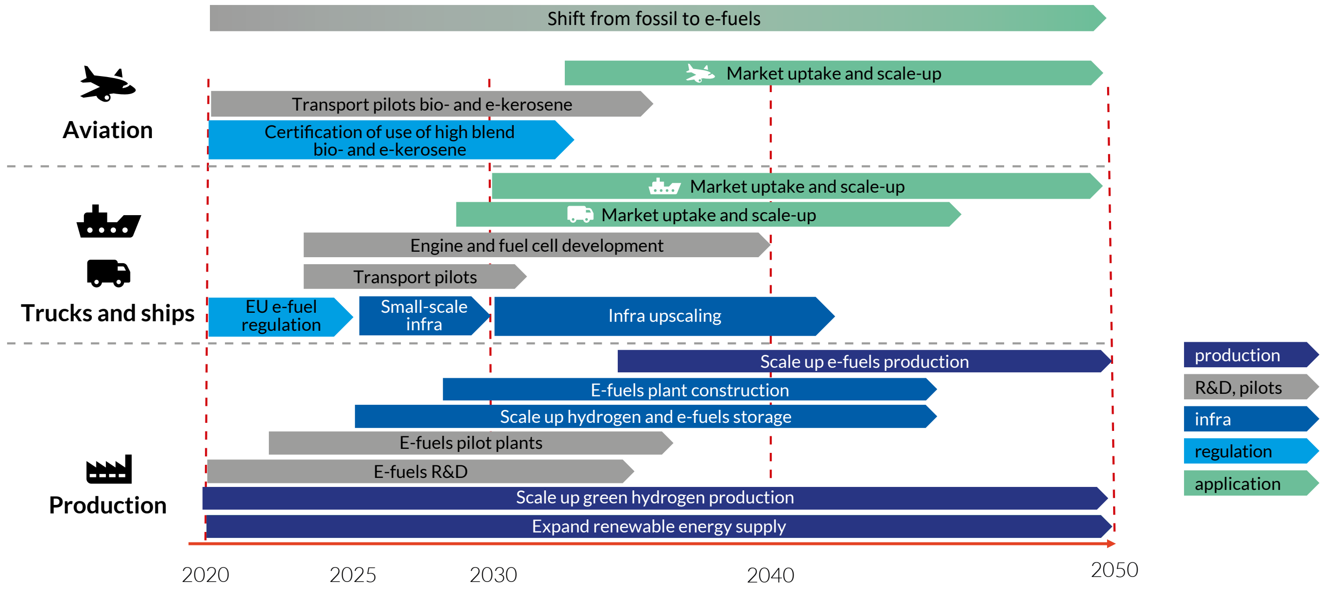


Figure 18: A roadmap for e-fuels in transportation in the Netherlands.

because it can also be used as a feedstock for e-diesel and e-kerosene and is a platform for a variety of chemical sector applications. E-diesel is also a rather secure option as aside from a production capacity increase, infrastructure and standards are in place and no vehicle modifications would be required.

Call to action

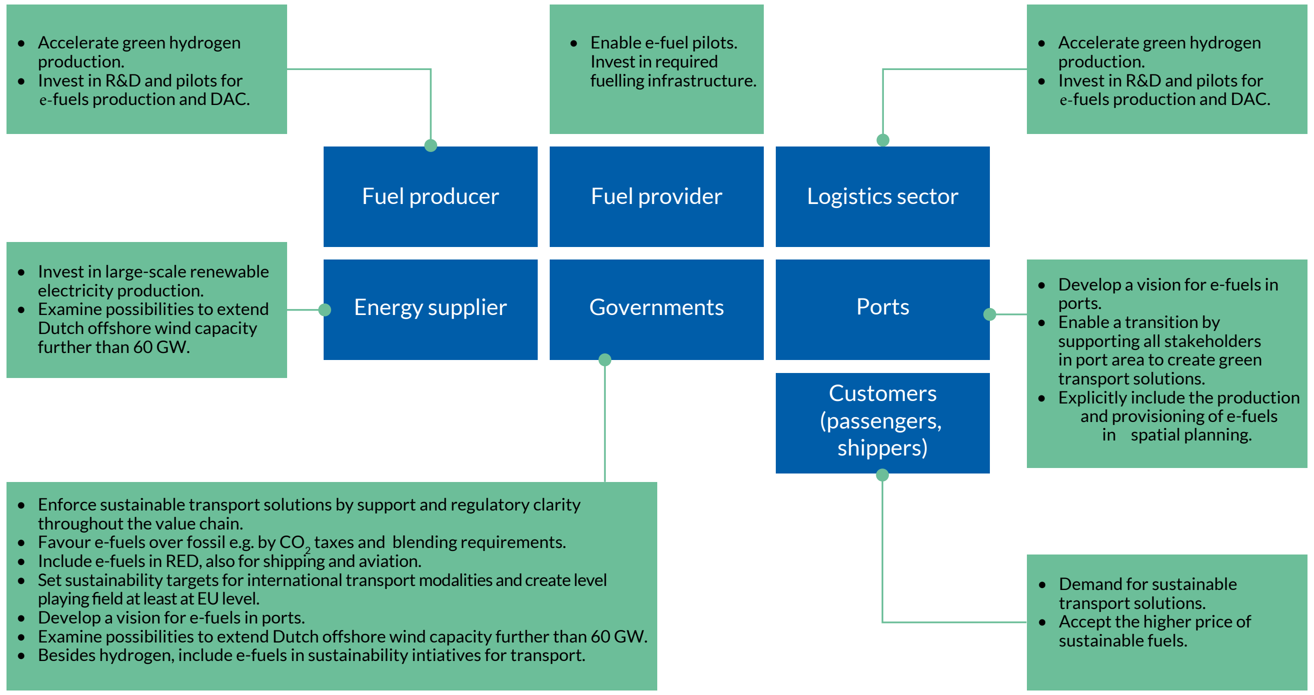
Now that the opportunities that e-fuels offer in making transport more sustainable are clear, it is time for action. Given the above roadmap, e-fuels will only become a viable option if:

- *Governments* favour e-fuels over fossil e.g. through CO_2 taxes and blending requirements, and support the use of e-fuels in the Renewable Energy Directive, as well as for shipping and aviation; create clarity on long-term policies and the legal landscape and accelerate the development of production and application techniques and social acceptance.
- *Logistics service providers* and their *customers* and partners accept the higher price of sustainable fuels compared to current fossil price levels.
- *Energy providers* invest in large-scale renewable electricity production.
- *Fuel producers* and *fuel providers* are prepared to invest in the production of e-fuels and the associated infrastructure even though there is still a lot of uncertainty in regard to e-fuels for transport.
- *Ports* explicitly include the production and provisioning of e-fuels in their spatial planning and enable stakeholders in the port region to create green transport solutions together.

Ports, governments, end-markets, the logistics sector, the fuel-producing industry and the energy sector need to join forces to pave the way for the adoption of e-fuels. Actions that are needed for each stakeholder are shown in Figure 19. Actions are needed at the global, EU, national and regional levels. For the Netherlands, the following steps are recommended:

- *Governments and ports: develop a vision on the role of e-fuels in Dutch ports*. Ports are the logical location for landing offshore wind, e-fuel production and bunkering infrastructure. Ports therefore have a large potential for the creation of green supply chains. As ports are of great importance to the Dutch economy and have the potential to facilitate the transition to sustainability for long-distance transportation, it is of major importance that a vision on the future role of e-fuels in ports be developed.

- *All stakeholders: pave the way for a future with e-fuels.* Though it is not yet clear which e-fuels will become dominant (especially for trucks and ships), it is obvious that such a future requires a large amount of green electricity, hydrogen production, e-fuel production capacity, government stimulation and vehicle development, etc. In order to be ready for this, all stakeholders should now start preparing themselves and should initiate developments. Meanwhile, cost developments for renewable electricity, CO_2 and e-fuels production should be monitored in order to be able to make final choices on e-fuels and to take specific actions for the development of these e-fuels.



- Accelerate green hydrogen production.
- Invest in R&D and pilots for e-fuels production and DAC.

- Enable e-fuel pilots. Invest in required fuelling infrastructure.

- Accelerate green hydrogen production.
- Invest in R&D and pilots for e-fuels production and DAC.

- Invest in large-scale renewable electricity production.
- Examine possibilities to extend Dutch offshore wind capacity further than 60 GW.

- Develop a vision for e-fuels in ports.
- Enable a transition by supporting all stakeholders in port area to create green transport solutions.
- Explicitly include the production and provisioning of e-fuels in spatial planning.

- Enforce sustainable transport solutions by support and regulatory clarity throughout the value chain.
- Favour e-fuels over fossil e.g. by CO_2 taxes and blending requirements.
- Include e-fuels in RED, also for shipping and aviation.
- Set sustainability targets for international transport modalities and create level playing field at least at EU level.
- Develop a vision for e-fuels in ports.
- Examine possibilities to extend Dutch offshore wind capacity further than 60 GW.
- Besides hydrogen, include e-fuels in sustainability intiatives for transport.

- Demand for sustainable transport solutions.
- Accept the higher price of sustainable fuels.

Figure 19: Call-to-action for stakeholders.

- *Logistics sector and industry: initiate pilots* to identify research questions and examine the feasibility of potential solutions. The logistics sector would be a natural instigator, but partners throughout the value chain should cooperate. The focus of R&D should be on technologies that have the potential to create breakthroughs in the reduction of costs at various steps of the value chain of e-fuels for transport applications. A technological lead for Dutch companies provides competitive advantages in the global market and increases the chances of developing an e-fuel industry in (the port regions of) the Netherlands.

> **“Stakeholders need to join forces to pave the way for the adoption of e-fuels”**

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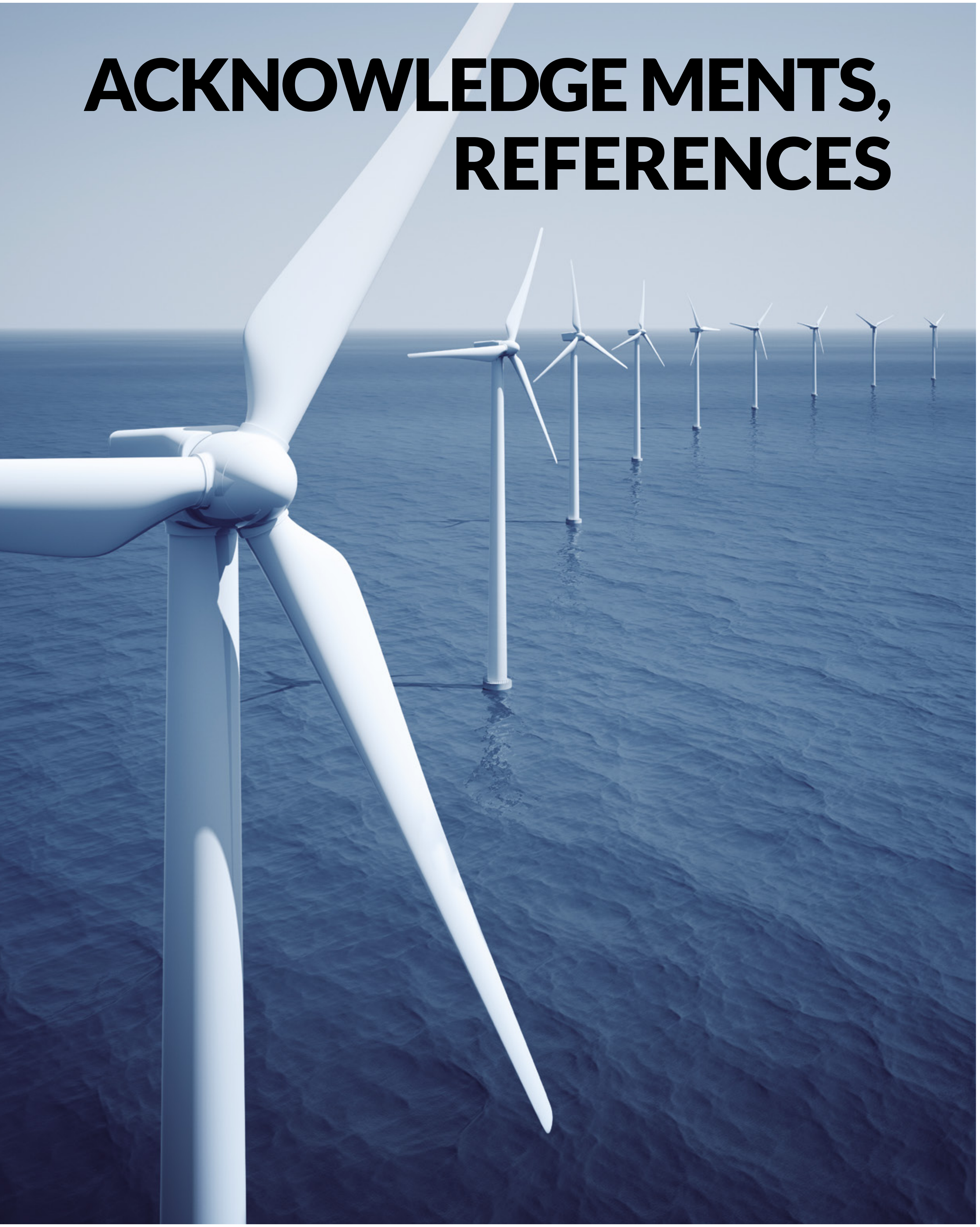

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