TNO

Power-2-Fuel Cost Analysis

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POWER-2-FUEL
COST ANALYSIS

This costanalysis is developed by TNO. A summary of the output of this analysis is included in the Voltachem whitepaper E-Fuels; towards a more sustainable future for truck transport, shipping and aviation.


RENEWABLE ENERGIES
NUCLEAR FUELS
FOSSIL FUELS

CONTENT

-01-

Introduction

The Climate Agreement and the associated CO_2-reduction goals will have a major impact on mobility and associated sectors such as the chemical sector (e.g. refineries) and all connected value chains. All stakeholders involved in these sectors have to achieve a significant CO_2 emission reduction. Part of this required reduction will be absorbed by increasing electrification (e.g. of passenger cars). However, it is expected that heavy transport such as long-distance road transport, shipping and aviation cannot be electrified so easily. Instead, they may continue to be powered by combustion engines, which are fuelled by (an increasing share of) renewable fuels. Such (close to) climate-neutral fuels will have to be produced, stored and distributed for these transport modes. This report studies the costs involved in these energy chains as input to a wider assessment of the feasibility of various synthetically produced renewable fuels as a means to reduce CO_2 emissions in the transport sector.

Ongoing research on e-fuels or power-to-fuels (co-financed by the Ministry of Economic Affairs' Top Consortia Surcharge for Knowledge and Innovation (TKIs)) shows that multiple types of e-fuels could potentially be applied in the future. For aviation, it is quite clear that kerosene, produced from biomass or from electricity and CO_2, will remain the dominant fuel. However, for other modalities the favourable e-fuel types are not so evident looking at indicators regarding environmental impact (i.e. pollutant emissions and GHG emissions), practical applicability and safety. Potential e-fuel types considered here are green hydrogen, e-methanol, e-diesel, e-ammonia and e-methane.

In order to further determine potentially favourable e-fuel types, additional information is required. SmartPort has asked TNO to provide additional analysis regarding the costs of production, distribution and vehicle/vessel adaptation for candidate e-fuels for long-distance road transport and shipping. This report presents the results of the additional cost analysis. The cost modelling is a projection for 2030. A summary of the output of this analysis is included in the Voltachem whitepaper "E-fuels: towards a more sustainable future for truck transport, shipping and aviation".

-02-

Costs of production of various e-fuels

For the transport modalities regarded in this study green hydrogen and the following e-fuels were selected:

- Green hydrogen
- E-Methanol
- E-diesel
- E-ammonia
- E-LNG

For the production of each e-fuel different processes are possible. The process that has been considered for the cost analysis of each e-fuel is described in short below. Green hydrogen is used as a basic feedstock for every e-fuel.

To achieve a fair cost comparison, the costs of green electricity and CO_2 were taken as a common basis for the analysis. These parameters were varied in the sensitivity analysis. The costs are a projection for 2030.

2.1 Production processes

The following production processes were used as a basis for the cost analysis:

Green hydrogen

Green hydrogen (H_2) is made from green electricity and H_2O (water). The water is split into H_2 (hydrogen) and O2 (oxygen) by using a PEM electrolyser. An efficiency of the PEM electrolyser of 64% was used. The resulting hydrogen has a pressure of 30 bar. Hydrogen can be produced at moments of low electricity prices, to reduce the costs of electricity, that form the main share of hydrogen production costs. In the case of intermittent production, buffering or storage is needed.

E-Methanol

E-Methanol (CH_3OH) is produced from green hydrogen, CO_2 and electricity. Though usually methanol is produced from syngas instead of CO_2, CO_2 hydrogenation was chosen to realise circularity, which can be achieved by acquiring CO_2 from biomass or DAC (direct air capture). For the analysis a gas phase conversion was regarded; a liquid phase conversion is also possible but requires more energy [1]. More details on the gas phase conversion process and related efficiencies can be found in [1].

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. For the synthesis, a Fisher-Tropsch process is regarded, with an efficiency of 69 % [3]. An alternative to the Fischer-Tropsch process is methanol to diesel synthesis [2].

E-ammonia

Feedstock for e-ammonia (NH_3) is green hydrogen and nitrogen, which is produced by air separation. Synthesis of hydrogen and nitrogen takes place in a Haber-Bosch reactor with a yield of 70%.

E-LNG

E-LNG (Liquid Natural Gas, CH4) is produced from green hydrogen and CO_2 by methanation of CO_2 and hydrogen. For application in transport, the produced methane is liquefied.

2.2 Cost and sensitivity analysis

A cost analysis was made, based on the production processes described above . The costs of e-fuels are highly dependent on the cost of CO_2 (in case of e-methane, e-methanol and e-diesel) and electricity (all assessed e-fuels). In a base case scenario cost levels were set at €30/MWh for electricity and €40 per ton of CO_2 . The resulting production costs per GJ are shown in Figure 1.

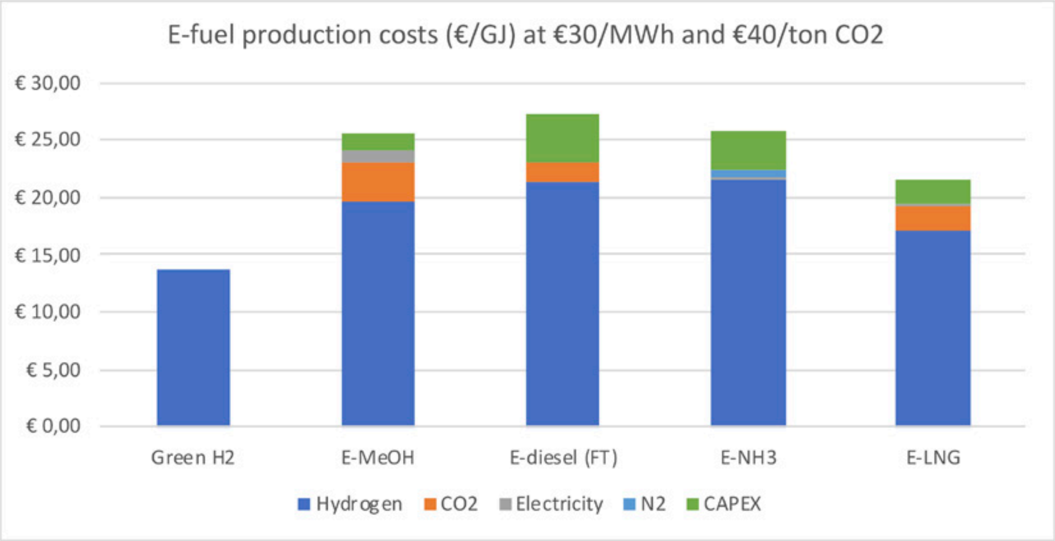

Figure 1 Production cost levels for hydrogen and the assessed e-fuels at €30/MWh for electricity and €40 per ton of CO_2.

Costs for hydrogen (and thus electricity) have the largest share in overall production costs. The costs of hydrogen are significantly lower than those of e-fuels, followed by e-LNG. Specifically these two, however, require compression or liquefaction for application in transport, leading to higher costs for distribution, storage and vehicle, as will be shown in the next chapter.

E-methanol, e-diesel and e-LNG production require significant amounts of CO_2., which is emitted when these e-fuels are burned in an engine. To acquire circularity, the CO_2 for production has to be captured from a circular source (e.g. by direct air capture, DAC) to obtain a net-zero emission situation. This can lead to high costs for CO_2. In 2030, DAC will not yet be applied on a large scale. Instead, CO_2 from point sources (like a steel or cement production facility, or a natural gas power plant) will be used. In the case of DAC costs for CO_2 will highly depend on electricity prices. For CO_2 from point sources an ETS fee is applied. The sensitivity of production costs for electricity prices and CO_2 costs is shown in Figure 2.

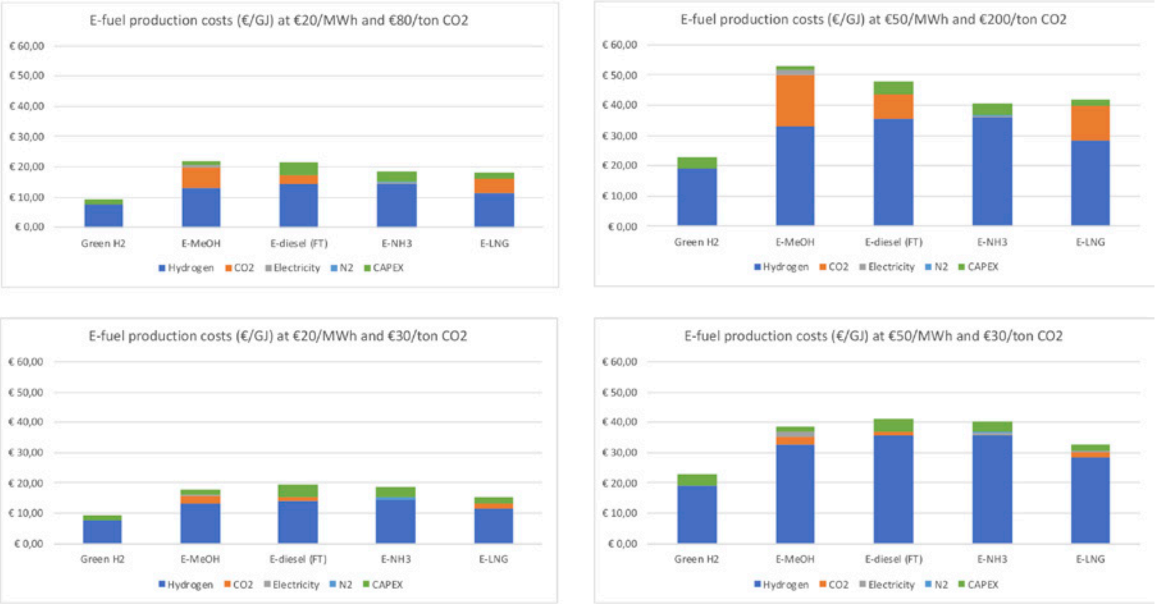

Figure 2 Production costs at different price levels for electricity and CO_2. High CO_2 costs are associated with direct air capture and therefore dependent on electricity costs.

The figure shows the sensitivity of e-methanol, e-diesel and e-LNG clearly, while hydrogen and e-ammonia are only sensitive to the costs of electricity. At very high CO_2 prices e-ammonia has lower production costs than the carbon e-fuels.

2.3 Conclusions production costs

In the base case, with cost levels of €30/MWh for electricity and €40 per ton of CO_2, hydrogen can be produced at €14/GJ, and cost levels of e-fuels range from €22/GJ for e-LNG to €27/GJ for e-diesel. Production costs are highly sensitive to the costs of electricity, and carbon e-fuels are also sensitive to the costs of CO_2. When circularity of CO_2 is required, CO_2 for production has to be captured from a circular source (e.g. by DAC) to obtain a net-zero emission situation, which can lead to high costs for CO_2. Costs for hydrogen (largely dependent on the costs of electricity) have the largest share in overall production costs, even in the case when costs for CO_2 are at a level of €200/ton.

-03-

Costs of distribution and storage of various e-fuels

Next to the costs of production, we have analysed the distribution costs of transporting the fuels from the manufacturing location to the tanks of the vehicles and vessels. This includes e.g. the costs for the fuel stations and the bunker ships. The distribution costs of fuels for road transport are much higher than those of fuels for the other modalities. This is due to the need for a large number of fuel stations, with a relatively small throughput. Moreover, these stations will in most cases be supplied by tanker trucks. The distribution of fuels for shipping and aviation is much more efficient because large quantities of fuel can be supplied to a relatively small number of bunker locations. The supply can usually be organized via more efficient tanker vessels or even pipelines.

3.1 Road transport

For the distribution of fuels for road transport, the transportation costs are estimated by analysing the quantity of fuel which can be transported by typical tanker trucks. These quantities are shown in the table below. It shows the quantity in mass (tonnes of fuel) and energy (GJ) and also the ratio of the number of tank truck trips needed to transport the same amount of energy in comparison to the diesel fuel reference. For example, the amount of hydrogen per tanker truck in terms of mass is very low compared to other fuel types. Because of the relatively high energy density of hydrogen (GJ/ton), the difference between the amount of energy in a hydrogen tanker truck and in a tanker truck for diesel or one of the alternative fuels is much smaller. The distribution costs are based on compressed H_2, because that is the most likely option up to 2030 and currently assessed by fuel distributors.

Table 1. Typical volumes and energy content of fuels transported by tanker trucks

	Tanker truck		ratio of tank trucks with diesel reference
	ton	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

In the table below, the transportation and fuel station cost per GJ energy is calculated for the e-fuel options. The transportation costs are based on the tanker truck size, the distance to the fuel station and the costs per km. For all fuels the same distance is taken, namely 200 km for the return trips. At this point, it is still unknown what the precise production locations will be, and thus what the average distance is for the case of the Netherlands. The distribution costs have been checked and reviewed as follows:

- Oostdam (2019) extensively investigated the distribution and fuel station costs for H_2, including a comparison with pipeline H_2 transport.
- LNG distribution costs have been checked with Robert Goevaers (consultant / LNG platform).
- H_2 and LNG distribution costs have been checked with Bas Hollemans (consultant fuel distribution).

Based on the input of the consultants, we increased transportation costs by adding a fixed amount of EUR 250 per fuel delivery as fixed overhead for man hours, primarily to cover man hours of the truck driver for loading/unloading (including waiting time). This comes on top of the km costs.

Table 2.Calculation of distribution costs for e-fuels for road transport.

	Green H_2 700 bar	**E-methanol**	**E-diesel (FT)**	**E-NH_3 cooled**	**E-LNG**
Tanker truck load [ton]	1	16	16	16	16
Distance [km]	200	200	200	200	200
Truck transport [€/km]	3	1.25	1.1	1.5	2
Tank truck transport [€/kg]	0.800	0.028	0.026	0.031	0.038
Fuel station [€/kg]	0.50	0.04	0.04	0.075	0.20
Specific fuel energy [MJ/kg]	121	19.9	42.7	18.6	50
Transportation [€/GJ]	6.6	1.4	0.6	1.7	0.8
Fuel station [€/GJ]	4.1	2.0	0.9	4.0	4.0
Total [€/GJ]	10.7	3.4	1.6	5.7	4.8

3.2 Inland and maritime shipping

For both inland and maritime shipping, it is assumed for this analysis that the fuel distribution will be done via bunker ships. The distribution costs are based on compressed H_2 (700 bar) for inland shipping and on cryogenic, liquid H_2 for short-sea shipping. The distribution costs are calculated by taking typical bunker quantities per fuel type, the costs of the bunker ship per day, and the number of deliveries per day as the basis. This calculation is presented in the table below for inland ships. The bunker quantities vary from 3 ton per bunkering for H_2 to 40 ton per bunkering for methanol and NH_3. This is primarily based on the needed bunker space onboard the ship. The bunker ship costs are estimated to be 2200 EUR/day for diesel and methanol, and 3000 EUR/day for the other fuels, based on cost figures of typical cargo ships.

Table 3. Distribution costs of e-fuels for inland shipping

		Green H_2 700 bar	E-methanol	E-diesel (FT)	E-NH_3	E-LNG
Typical bunker quantity	ton	3	40	25	40	20
Typical bunker quantity	GJ	363	908	1138	744	1000
Bunker ship deliveries per day	per day	4	4	4	4	4
Bunker ship costs per day	€/day	3000	2200	2200	3000	3000
Distribution costs	€/ton	250	14	22	19	38
	€/GJ	2.07	0.61	0.48	1.01	0.75

For sea vessels, the same calculation is presented in the table below. The bunker quantities vary from 50 ton per bunkering for H_2 to 800 ton per bunkering event for methanol and NH_3. H_2 will, in this case, be supplied as a liquid, cryogenic H_2. The bunker ship costs per day are estimated to be 10,000 EUR/day for diesel and methanol, and 15,000 EUR/day for NH_3, LNG and liquid H_2.

Table 4. Distribution costs of E-fuels for maritime shipping

		Green H_2 liquid	E-methanol	E-diesel (FT)	E-NH_3	E-LNG
Typical bunker quantity	ton	50	800	500	800	400
Typical bunker quantity	GJ	6,050	18,160	22,750	14,880	20,000
Bunker ship deliveries per day	per day	3	3	3	3	3
Bunker ship costs per day	€/day	15,000	10,000	10,000	15,000	15,000
Distribution costs	€/ton	100	4	7	6	13
	€/GJ	0.83	0.18	0.15	0.34	0.25


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-04-

Vehicles and vessels costs

4.1 Reference vehicles / vessels

In order to determine the additional vehicle cost compared to a conventional truck or vessel, associated with the application of the studied alternative fuels, a combination of experiences from earlier projects, as well as calculations based on specific costs of engines, fuel cell systems and fuel storage tanks are used.

A series of reference vehicles/vessels has been determined, in order to determine the additional vehicle/vessel costs per fuel type and to execute the economic TCO calculation. Engine size and operational parameters are presented in the table below. Further assumptions include:

- The reference truck drives about 150,000 km per year, about 600 km per day, typical long-distance application.
- The vessels are based on reference ships defined in Verbeek (2013). However, the high speed and resulting high average engine load of the inland and short-sea vessels assumed in that study have been reduced to about 45% - 50% average engine power. In several later studies it appeared that this is a more realistic average load. The inland vessels are assumed to be in service 20 hours per day, so with a double crew. The remaining 4 hours is waiting time at cargo terminals.

Table 5. Reference vehicles / vessel (diesel fuel)

Reference vehicles	**Engine**	**Time/day**	**Time/year**		**Fuel consumption**	
	kW	hrs	days	hrs	ton/day	ton/year
Long haul truck	315	10	250	2,500	0.210	53
Inland ship	1,125	20	300	6,000	2.4	720
Short-sea vessel	5,500	24	250	6,000	22.0	5,500
Deep-sea vessel	30,000	24	350	8,400	60.0	30,000

4.2 Vehicle and vessel costs with alternative fuels

Generally, vehicles and vessels running on alternative fuels are more expensive than those using diesel fuel. This is due to the larger and more expensive fuel tanks and also the more complex engines or fuel cells, compared to regular diesel engines. The cost increase associated with the use of alternative E-fuels is summarised in the table below. The cost increase includes the driveline, engine modifications or fuel cell, and the fuel storage tank. For all applications, the costs increase, as presented in the table below, is based on new vehicles and new ships. For retrofitting, there are additional costs such as removal of the existing engines and modifications to upholstery or hull to make place for larger fuel tanks. These costs will usually vary strongly on a case by case basis.

Table 6. Additional vehicle costs (€) for new vehicles/vessels on E-fuel in comparison to diesel reference

	Green H_2 700 bar	**E-methanol**	**E-diesel**	**E-NH_3**	**E-LNG**
Long haul truck	225,000	7,500	0	20,000	20,000
Inland ship	3,000,000	200,000	0	50,000	1,000,000
Short-sea vessel	13,400,000	1,000,000	0	3,000,000	5,200,000
Deep-sea vessel		3,800,000	0	12,300,000	21,700,000

Some general notes:

For H_2, in all cases, a fuel cell energy converter is chosen as the basis. For all other E-fuels, the internal combustion engine is chosen as the basis. All fossil or bio-based equivalents of efuels, except for e-NH_3, have been demonstrated in combustion engines in various sizes. LNG and methanol have been demonstrated in practical applications. Ammonia has only been demonstrated in, not always very practical, lab engines. The combustion characteristics of ammonia are far from ideal. Nevertheless, MAN announced that they could develop an ammonia engine for about EUR 5 million. It is concluded that ammonia needs substantial development, and market readiness by 2030 is uncertain, and depends on the availability of large development funds. It should be noted that the use of hydrogen in a combustion engine is also a realistic option, which deserves further evaluation.

Long Haul trucks:

- E-LNG: current vehicle price is about EUR 30,000 higher than a comparable diesel truck. For 2030, a EUR 20,000 cost increase is assumed.
- E-ammonia: same cost increase as for e-methane assumed. The engine modification is probably more complex, but on the other hand, lower tank costs are expected, since it can be a simple pressurized (about 10 bar) tank, rather than a cryogenic tank as is needed with e-methane.
- E-methanol: EUR 7,500: the tank costs are comparable with diesel (both atmospheric tanks) and the engine modification is similar to E-methane. The costs are based on the diesel pilot principle because that would be best for engine efficiency. With spark ignition, the Otto cycle engine, the additional costs will be lower.

Hydrogen fuel-cell driveline for Long Haul trucks:

Both the fuel cell system and the storage tank are much more expensive than for the diesel truck. Oostdam (2019) extensively investigated the costs of fuel cell trucks (see the two tables below). The first table shows the costs ranges of components of fuel-cell drivelines, while the second table compares several sources for the complete truck costs. From the second table, it can be concluded that the price variations are large and that, in general, they remain high compared to a regular diesel truck. Roland Berger (2017) is far more optimistic about cost reductions than the other sources. For 2030 they project a price of EUR 127,000, EUR 41,000 above a standard diesel truck. The other price projections are at least about EUR 70,000 above the diesel reference truck and that is for the far future (2040-2050). The current price of a diesel reference truck ranges from about EUR 85,000 – 100,000.

For this study, for 2030, the fuel cell truck price is taken as the average of Oostdam (modest scenario), Roland Berger (2017) and Moultak (2017). This is EUR 223,000. The diesel reference is taken as EUR 100,000.

Table 7. Uncertainty in cost projections for fuel cell truck components. Source Oostdam (2019).

	Unit	Possible range	Change (20%)	Δ TCO [€/km]
Hydrogen price	€/kg	3,00 to 10,00	1,40	0,105
Fuelling speed	kg/min	1,5 to 7	1,10	0,009
Capacity of fuel tank	kg	40 to 40	2	0
Powertrain efficiency	%	45 to 59	2,8	0,044
Fuel cell system	€/kW	800 to 2.200	280	0,046
Fuel tank	€/kg	400 to 1.000	120	0,007
Total electric components cost	**€**	**12.000 to 23.000**	**2.200**	**0,004**

Table 8. Price projections of several sources for trucks with H_2 fuel cell driveline

Reference	Current price (EUR)	Future price (EUR)	Year
Oostdam (2019)	442,000	258,000 - 335,000	Depending on uptake
Roland Berger (2017)	334,000	127,000	2030
Nikola Motors (2019)	375,000 $	Not specified	
Moultak (2017)	300,000	207,000	2030
Hunter (2019)	492,000	184,000	2040
Vijayagopol (2019)	316,000	175,000	2050
Assumption for TCO		**223,000**	

Inland ship:

- E-methane: until now the cost increase for a ship running on liquid methane (or LNG) is assumed to be about EUR 1.5 million. For 2030, a cost reduction to EUR 1.0 million is assumed, also based on some earlier ambitions for cost reductions: in the PROMINENT project this was estimated at 30%.
- E-ammonia: for ammonia a 25% lower cost increase than e-methane is estimated, since the storage tank is much simpler than for e-methane. Engine modification might be somewhat more complex, but is expected to be a relatively small part of the cost increase. It should be noted that, in practice, ammonia engines of this size have not been presented yet.
- E-methanol: EUR 250,000: engine modification is comparable to e-methane, but the tank is much simpler.
- Hydrogen fuel cell: in Abma, 2019 (Gouwenaar report), the fuel cell driveline costs were calculated at about EUR 2.85 million, about EUR 2 million above the diesel driveline. This is a smaller ship than the reference ship, so for the reference ship, this is adjusted to a EUR 2.5 million cost increase.

Maritime ships (short-sea and deep-sea):

- The vessel cost increase is based on a publication by MKC (2019), which used input from Brynolf (2014) and Lindstad (2015) for the costs of methanol and LNG fuelled ships. This was converted to engine and fuel storage costs, per kW power and per GJ storage capacity respectively. See also the table below.
- The energy storage for the short-sea and deep-see vessels is 49105 GJ and 179,340 GJ respectively. This is for a range of 44 and 60 days (15% margin) respectively. For H_2 an eight times smaller storage capacity is chosen for the short-sea vessel. H_2 is not considered as an option for the deep-sea vessel, because of limited range.

Table 9. Engine and fuel storage specific costs to calculate the additional costs with alternative e-fuels for maritime ships.

Fuel	Engine costs (Euro/kW)	Storage costs (Euro/GJ)
MGO	636	27
Methanol	655	45
LNG	923	100
H_2	2000 (fuel cell)	1180

-05-

Consequences for operation

5.1 Energy use per km

The efficiency of diesel combustion engines from the same size range can vary in practice by ±2% (percentage points and about 10% relative bandwidth). This is mostly dependent on engine optimization and the so-called NOx-BSFC trade-off. When NOx requirements become more stringent, fuel consumption goes up somewhat. Another effect is variation in internal engine friction and also the general quality of the optimization. With the newest engines, such as Euro VI truck engines and Stage V inland ship engines, it can be seen that efficiency increases. This is due to the good NOx after-treatment. The engines are optimized internally for low fuel consumption and high NOx, and SCR after-treatment brings down the NOx within the requirements.

With alternative fuels, quite similar engine efficiencies are seen, provided that the diesel cycle combustion principle is used (so-called dual-fuel or diesel pilot engines). With natural gas, the efficiency is sometimes a few percentage points lower, but at the same time in research engines with natural gas or methanol, a few percentage points higher efficiencies are shown.

For diesel engines, the engine efficiency varies from some 40% to about 47% dependent on the engine size (see table below). For fuel cell systems, the efficiency was checked with several suppliers in the past. Those were Ballard and Nedstack. The efficiency is quite dependent on the load point. According to the latest information, the fuel cell system efficiency varies from some 49% at 50% load to about 45% at full load, for new systems. However, it can lose some 10% efficiency over the lifetime. On top of that, there is an energy loss for the electric motor driving the wheels or propeller, and for power control. This loss, which can total some 8%, is higher than the efficiency loss of a mechanical driveline. The dependency on load makes it also a CAPEX-OPEX trade-off. If you are willing to pay for a large power fuel cell, the efficiency will increase. Taking all these factors into account, and the fact that we are not doing a detailed design of a powertrain for the reference vehicles, it can be concluded that it is rather uncertain whether the efficiency of the fuel cell powertrains is higher or lower than the efficiency of the powertrains with combustion engines. For this study, therefore, it is assumed that the powertrain efficiency remains the same for all alternative E-fuels considered. Due to this, the energy use per km will be identical for all fuels. It should be noted, that several sources present higher fuel cell efficiencies. For example, Oostdam (2019) gives an overview of four sources in which the efficiency ranges from 50% to 60%. Probably, these efficiencies do not include auxiliary and electric conversion losses and losses due to aging. Due to this, we stick to the somewhat lower efficiencies listed in the table below.

Table 10. Used efficiency for combustion engines and fuel cell powertrains

2030	Diesel & other combustion engines	H_2 Fuel cell system (+ electric motor)
Long Haul truck	42%	42%
Inland ship	42%	45%
Short-Sea ship	45%	45%
Deep-Sea ship	47%	Not considered

5.2 Bunkering frequency

Typical tank/bunker quantities for the modalities are listed in the table below.

Table 11. Typical bunker quantities and storage tank size. Several sources a.o. Verbeek (2013).

	Typical bunker quantity		Typical storage tank size		Max range
	ton diesel	GJ	ton 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

The volume or space requirement to store the fuel necessary for the normal operation of the vehicle is dependent on the energy density of the fuel and the efficiency of the powertrain. The powertrain efficiencies for the different fuels and also for the fuel cells are however considered to be equal. See also the previous paragraph. In the table below, the specific volumes and space requirements are given for the e-fuels in comparison to e-diesel. The first column is the net volume requirement which is directly based on the energy content in MJ/dm3. The second column is the 'packaging factor', which can vary from 1 to 2.5. This is primarily based on the fact that (cylindrical) pressurized tanks require much more space than an atmospheric tank (for diesel or methanol) which can be formed in any desired shape (rectangular shape, or odd shape following the ship hull for example). Also, insulation for cooled or cryogenic tanks will add some volume.

Table 12. Volume and space requirements of E-fuels onboard of 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-methane	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

In practice, the tank or bunker size in GJ will often be reduced with the use of alternative e-fuels, since the required volume for an equivalent range is not available onboard the vehicle. For vessels, the bunkering quantities are usually lower than the storage volume. So for vessels, we would expect the bunkering frequency to increase for e-methanol, e-methane and cooled ammonia with up to 50%.

H_2 is another story. It is expected (and confirmed by feedback from stakeholders and earlier case studies) that daily refuelling is necessary instead of weekly or even two-weekly refuelling. This means that the bunkering frequency increases by a factor 4 to 12. To achieve daily refuelling, the H_2 tank pressure should be 700 bar, rather than 500 or 350 bar.

For short-sea shipping, the maximum range with H_2 (either compressed or liquid stored) is expected to be about 3 days. This means that, for deep-sea shipping with normal range (autonomy) requirements of 30-60 days, H_2 is hardly feasible unless you would build refuelling stations on mid-sea.
The consequences for operation can be summarised as follows:

- Long haul truck: compressed H_2 fuel (700 bar) would require daily instead of weekly re-fuelling with diesel fuel. For LNG, methanol and ammonia, one should expect 1.5 to 2 times more re-fuelling events.
- Inland shipping: around 50% more bunkering events with LNG, methanol and ammonia compared to (e-)diesel. Daily bunkering with compressed H_2 (700 bar), compared to weekly bunkering with diesel fuel.
- Short-sea shipping: Inland shipping: around 50% more bunkering events with LNG, methanol and ammonia compared to (e-)diesel. A range of some 3 days with liquid (cryogenic) H_2, compared to some 4 weeks with diesel fuel. One day range with compressed H_2 (700 bar).
- Deep-sea shipping: Bunker tank size will be increased for LNG, methanol or ammonia, such that range requirements, up to 60 days, will be met with those fuels. H_2 is not an option.

5.3 Lifetime

The normal lifetime of diesel engines is presented in the table below. Also, with alternative fuels, this lifetime is not expected to change significantly. Reported lifetimes of different types of natural gas engines have usually been very good. For example, engines suffer less from suit-build with natural gas due to the lower amount of particulate formation. Also with methanol a similar positive effect is expected. With NH_3, the impact on operational lifetime is still unknown. NH_3 is quite aggressive and acid which may lead to corrosion and engine lubricant degradation. So, there might be increased maintenance but after time, the industry may find solutions for this.

Table 13. Typical lifetime of diesel engines

	diesel engine (hours)
Long haul truck	25,000
Inland ship	40,000 – 80,000
Short-sea vessel	80,000 – 100,000
Deep-sea vessel	> 100,000

For PEM fuel cells, the expected lifetime is around 25,000 to 30,000 hours. So this would fall short compared to combustion engines for the shipping segment. Over time other fuel cell systems may be developed with a substantially longer lifetime. The TCO-CAPEX costs of fuel cell vehicles/vessels are based on a fuel cell lifetime of 15 years. This is 90,000 hours for the inland vessel and the short-sea vessel. This means that two replacements of refurbishments of the fuel cell systems are needed within the 15 years lifetime.

5.4 Pollutant emissions

The projection of vehicle/vessel emissions is based on combustion engines for all fuels except for H_2, which is assumed to be used in a fuel cell energy convertor with zero tailpipe emissions. It is also based on the newest emission requirements for combustion engines, which are:

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

The emissions projection is summarised in the table below. Only with H_2 fuel in combination with fuel cells zero (pollutant) emissions are accomplished. Zero emissions are primarily important for urban areas. In that sense, it could be important for distribution trucks, but this is less important for long haul trucks. Also for specific ships, such as port vessels and workboats zero-emission can be important. Especially for shipping, all synthetic fuels will lead to substantial reduction in pollutant emissions, due to the absence of potentially polluting components such as sulphur , heavy hydrocarbons such as poly-aromatics, tar, etcetera. Due to that, especially the SOx and PM emissions will be much lower (e.g. 80% to 99% lower). NOx emissions will become lower due to the entering into force of the IMO Tier III legislation. Basically, the relatively stringent legislation, and as a result of that, the application of exhaust after-treatment (such as particle filters and SCR deNOx catalysts for diesel trucks) reduces the differences in emission behavior between the different fuels. Overall, zero-emission is generally not possible since for most e-fuels there will always be some pollutant emissions such as NOx and PM.

Table 14. Emission projection with different fuels, based on EURO VI for trucks, Stage V for inland ships and Tier III for the maritime vessel. Fossil diesel fuel for 2020 onwards

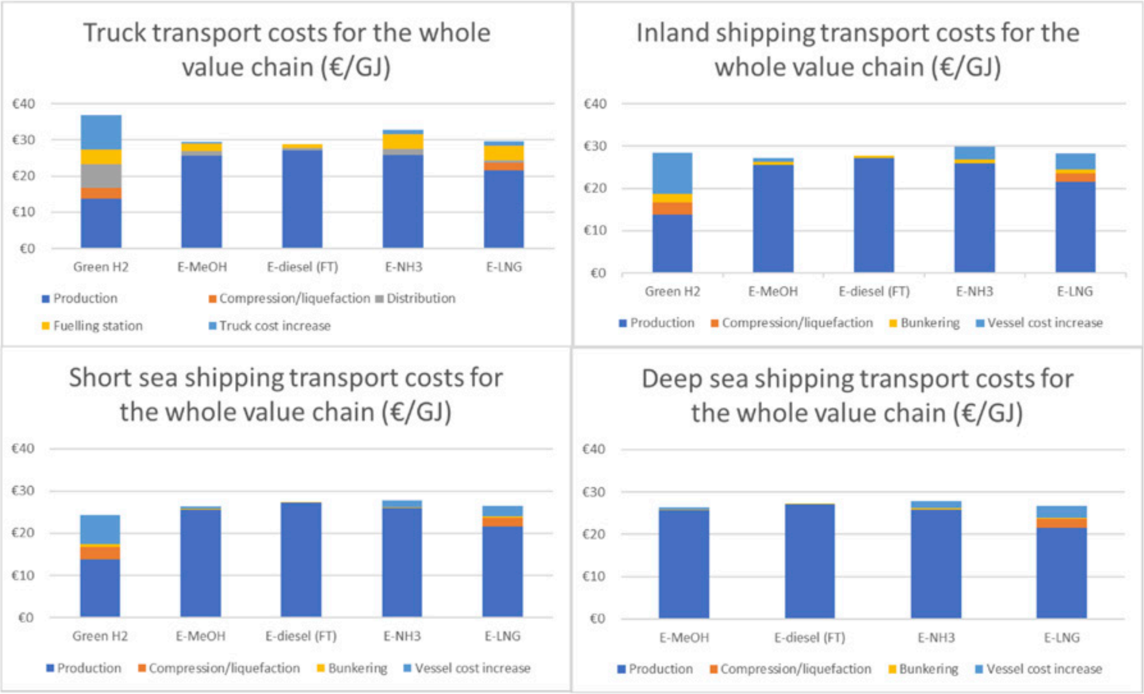
	Emission	**Current fossil diesel**	**Green H_2 fuel cells**	**E-MeOH**	**E-diesel (FT)**	**E-NH_3**	**E-LNG**
Trucks and inland ships	NOx	low	zero	low	low	low	low
	PM	low	zero	low	low	low	low
	SOx	low	zero	low	low	low	low
Maritime vessels	NOx	medium	zero	medium	medium	medium	medium
	PM	medium	zero	low	low	low	low
	SOx	medium	zero	low	low	low	low

-06-

Conclusions

In this part of the ongoing P2Fuels project, TNO studied the fuel production costs and the fuel distribution and application costs for five P2X fuels, namely compressed H_2 (700bar), e-methanol, e-diesel, e-ammonia and e-LNG. The study includes four transport modalities and a number of scenarios with variation in the assumed costs of electricity and CO_2.

In the figure below, the costs for fuel production, fuel distribution and vehicle are combined in one figure per modality. This is done for a base case scenario for 2030, with electricity costs of €30/MWh and CO_2 costs of €40 per ton. NB: for the vehicle costs only the cost increase compared to the diesel versions of truck and ships, is taken into account .



Truck transport costs for the whole value chain (€/GJ)

Inland shipping transport costs for the whole value chain (€/GJ)

Short sea shipping transport costs for the whole value chain (€/GJ)

Deep sea shipping transport costs for the whole value chain (€/GJ)

Figure 3. 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/ton. Projection for 2030, includes fuel production and distribution costs and vehicle & ship costs calculated back to EUR/GJ taking into account powertrain efficiency .

From the analysis, the following conclusions are drawn for the base scenario with electricity costs of €30/MWh and ETS costs of €40/ton (Figure 3):

- Overall the cost differences between the fuels are relatively small. H_2 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, H_2 is the most expensive option. H_2 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 shipping and deep-sea shipping, e-methanol, e-diesel and e-LNG appear the most attractive options, but the estimated cost difference with H_2 and NH_3 are small and probably within the uncertainty range of the calculations.
- For short-sea, in those cases where it is possible (e.g. short distances, ferries) H_2 is economically the most attractive option. For inland shipping, H_2 is also an interesting option for short distances.

For the sensitivity analysis four scenarios were defined:
- Low electricity costs (€20/MWh) and low CO_2 costs (€30/ton)
- High electricity costs (€50/MWh) and low CO_2 costs (€30/ton)
- High electricity costs (€50/MWh) and high CO_2 costs (€200/ton, correlation with electricity price for direct air capture)
- Low electricity costs (€20/MWh) and high CO_2 costs (€80/ton, correlation with electricity price for direct air capture)

The results for the value chain costs per modality are shown in Figure 4 to Figure 7 . From the sensitivity analysis the following conclusions can be drawn:
- For all transport modalities, e-methanol is most sensitive to high CO_2 costs, more than e-diesel and e-LNG.
- Hydrogen is less sensitive to an increase in electricity costs, due to its higher production efficiency.
- In the scenario with high costs for electricity and CO_2, hydrogen is the most attractive option for all transport modes (except for deep-sea, where it is not applicable), followed by e-ammonia. E-ammonia, however, is (currently) considered as unsafe for truck transport.

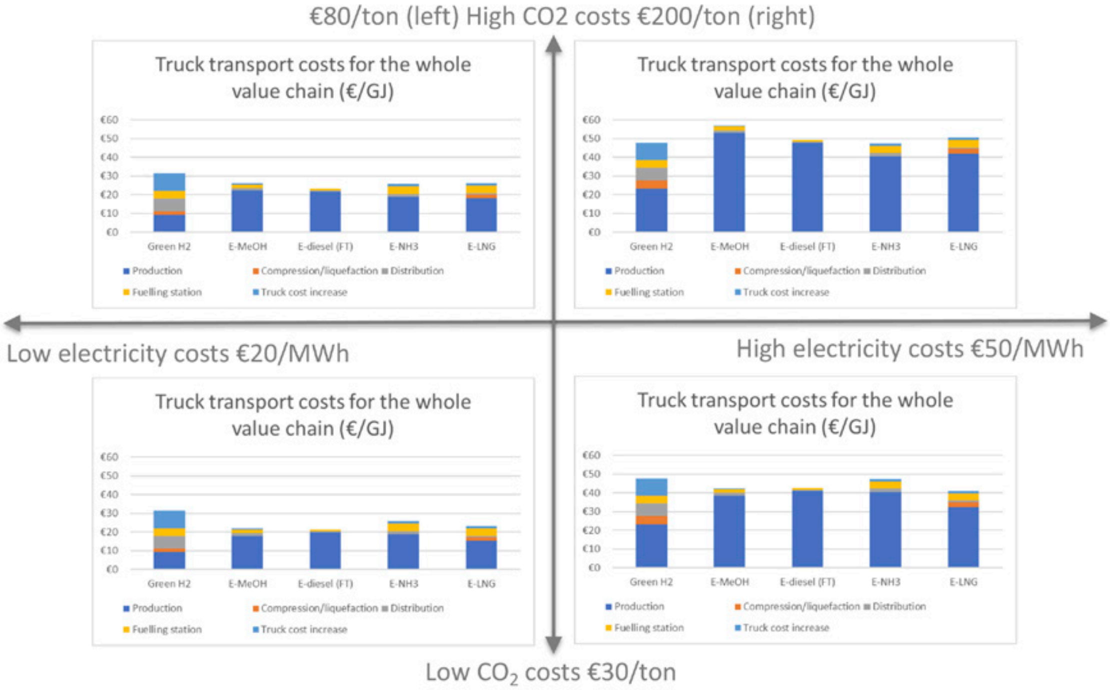


Figure 4. Value chain costs for truck transport in four scenarios.

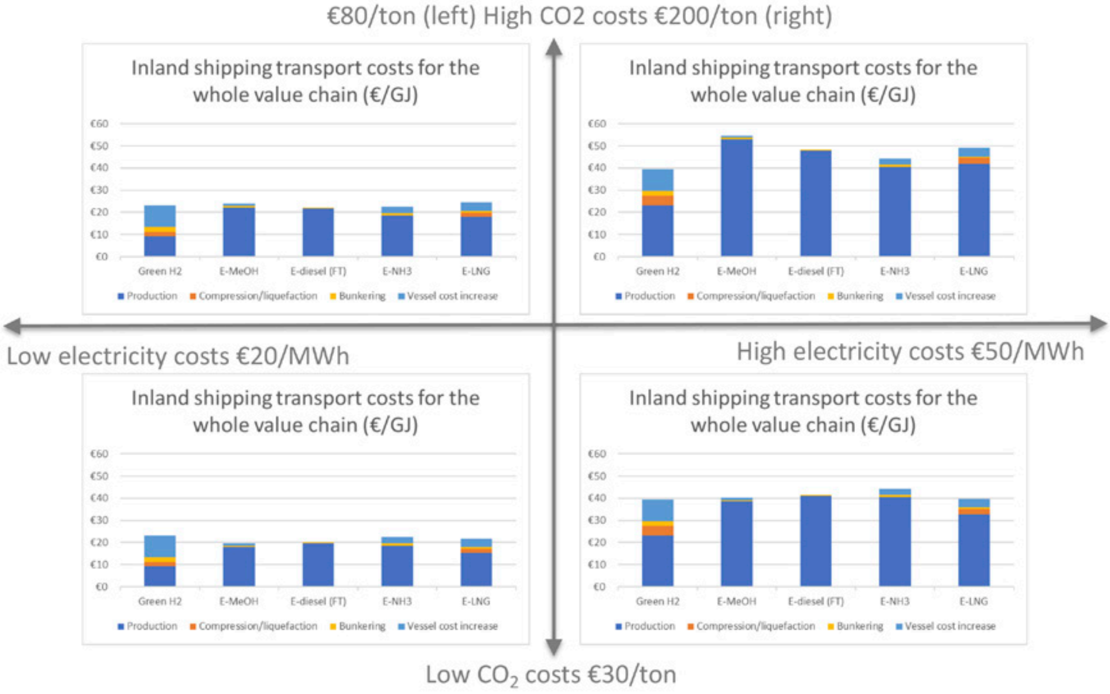


Figure 5. Value chain costs for inland shipping in four scenarios.

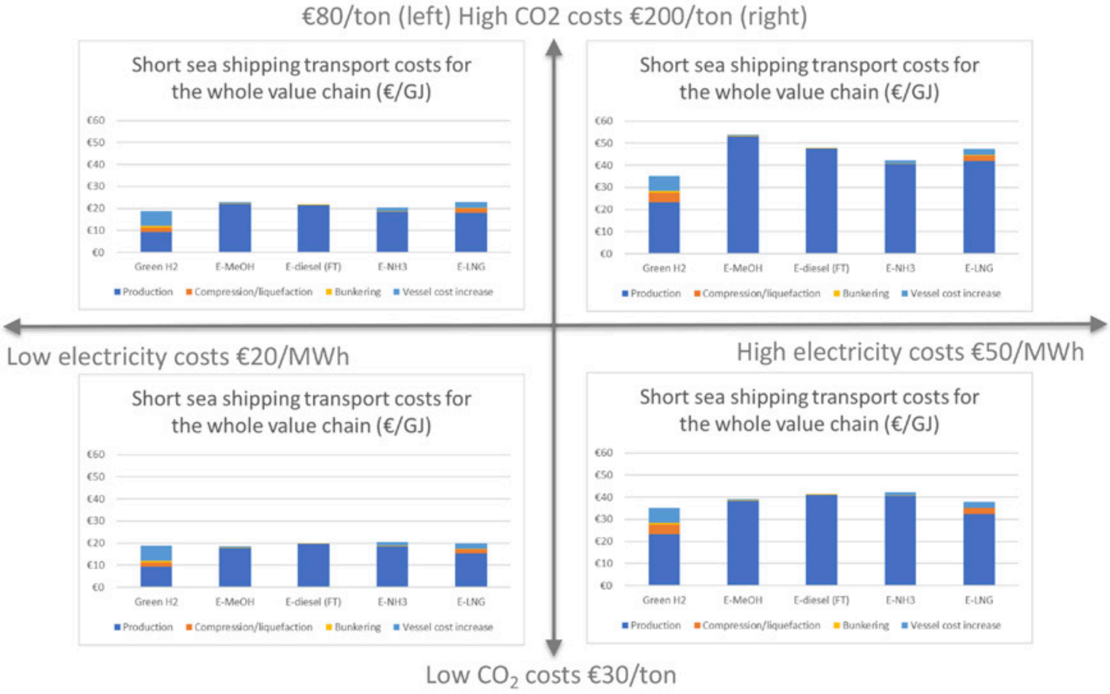


Figure 6. Value chain costs for short-sea shipping in four scenarios.

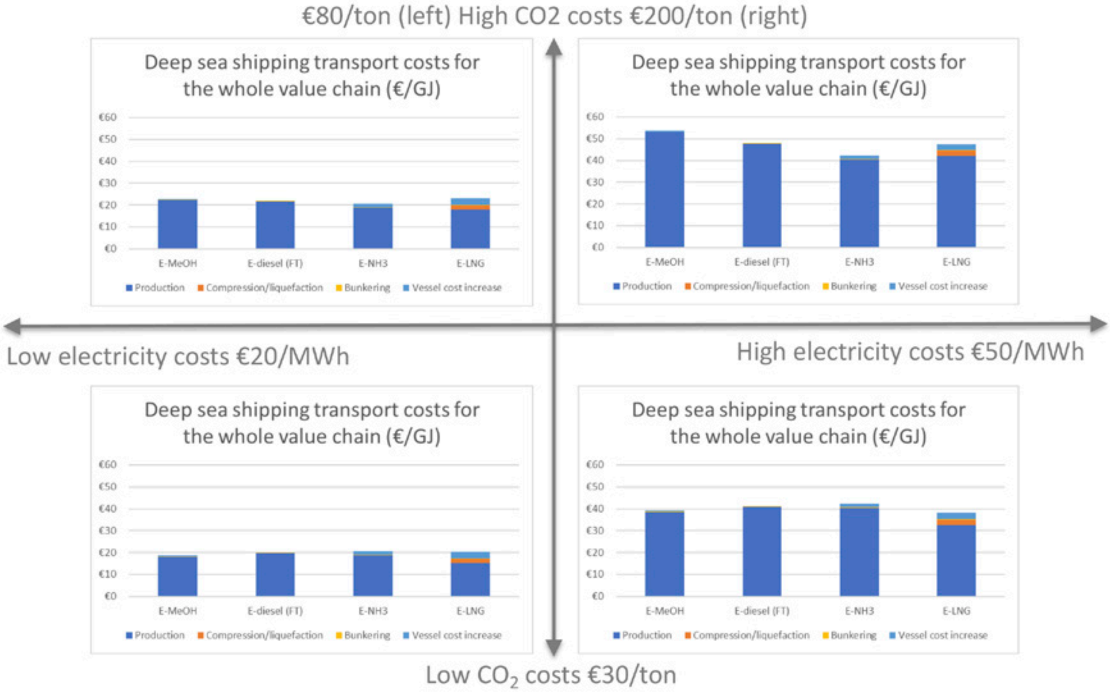


Figure 7. Value chain costs for deep-sea shipping in four scenarios.

Overall we can conclude that, though green hydrogen has by far the lowest production costs per GJ, for the whole value chain it has higher costs than most e-fuels in the base case, except for short-sea shipping. Because the outcomes of the cost comparisons are highly variable per scenario, no clear winner can be nominated.

Footnotes

1. In practice this efficiency is not realised yet; a presumption was made that there will be an improvement in technology over time and efficiency is assumed to be 64% by 2030.
2. CAPEX, OPEX, feedstock use and efficiencies were based on TNO models and literature, see references [1] to [5].
3. Costs for CO_2 include the following elements:
   - Feedstock costs. Costs for feedstock consist of cost for production or capturing (CCU or DAC) of CO_2, costs for delivery and margins for suppliers based on market dynamics (supply versus demand). Capture from point sources has significantly lower costs than direct air capture, see [3] for cost indications
   - In the future: ETS and CO_2 tax when applicable, dependent on future regulation and the way in which suppliers of CO_2 pass these costs to their customers.
4. Based on TNO energy market modelling and forecasting.
5. In 2030 direct air capture will not yet be widely applied; cost level is therefore based on ETS cost development. We presume that in 2030 ETS will apply somewhere in the value chain (e.g. at the fuel producing or emitting party).
6. PEM: Proton-Exchange Membrane fuel cells, also known as Polymer Electrolyte Membrane fuel cells
7. truck and inland ship fossil diesel also have an ultra-low sulphur content
8. Specific catalyst to reduce NOx emissions. Customary for diesel engines.
9. Since only additional costs for vehicle and ship were taken into account, this analysis is suitable for comparing e-fuels, but not for comparing it with fossil fuels.
10. Refer to section 5.1. The efficiencies of combustion engines on different fuels and also fuel cell systems are however considered equal, since the information does not clearly indicate that one is better than the other. This varies based on the precise engine types and level of optimization
11. NB: maxima of y-axes are not equal to keep figure readable.

-07-

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