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Review of electrofuel feasibility—prospects for road, ocean, and air transport

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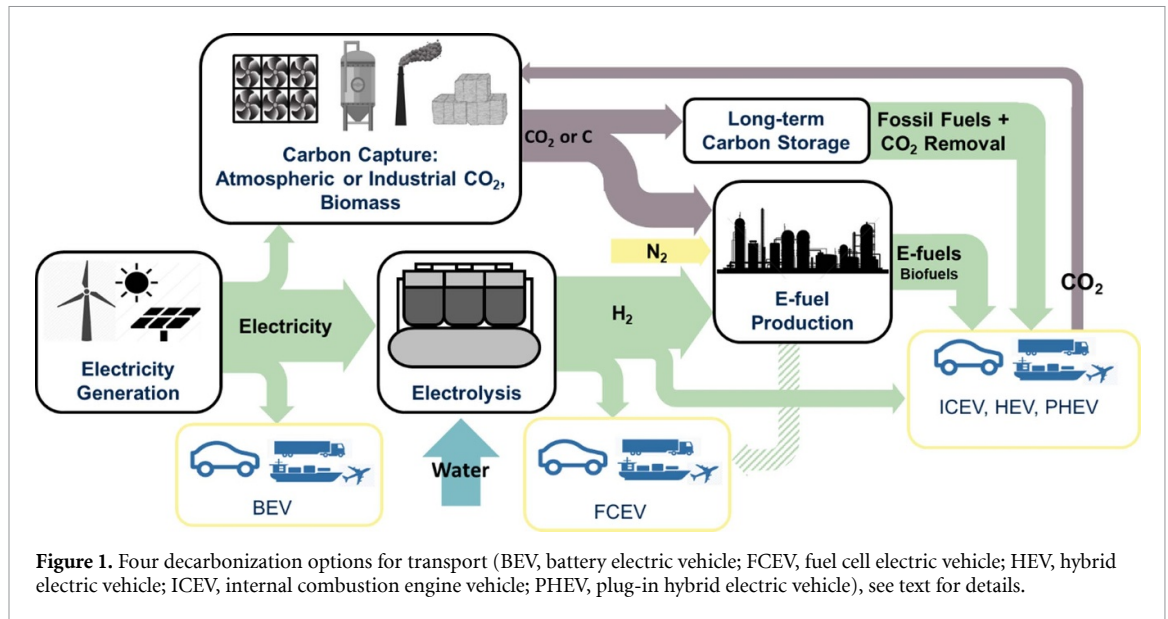
Abstract

To meet climate targets the emissions of greenhouse gases from transport need to be reduced considerably. Electrofuels (e-fuels) produced from low-CO₂ electricity, water, and carbon (or nitrogen) are potential low-climate-impact transportation fuels. The purpose of this review is to provide a technoeconomic assessment of the feasibility and potential of e-fuels for road, ocean, and air transport. The assessment is based on a review of publications discussing e-fuels for one or more transport modes. For each transport mode, (a) e-fuel options are mapped, (b) cost per transport unit (e.g. vehicle km) and carbon abatement costs are estimated and compared to conventional options, (c) prospects and challenges are highlighted, and (d) policy context is described. Carbon abatement costs for e-fuels (considering vehicle cost, fuel production and distribution cost) are estimated to be in the range 110–1250 € tonne^{−1} CO₂ with e-gasoline and e-diesel at the high end of the range. The investigated combined biofuel and e-fuels production pathways (based on forest residues and waste) are more cost-competitive than the stand-alone e-fuel production pathways, but the global availability of sustainable biomass is limited making these pathways more constrained. While the potential for e-fuels to decarbonize the transport sector has been discussed extensively in the literature, many uncertainties in terms of production costs, vehicle costs and environmental performance remain. It is too early to rule out or strongly promote particular e-fuels for different transport modes. For e-fuels to play a significant role in transportation, their attractiveness relative to other transport options needs to be improved. Incentives will be needed for e-fuels to be cost-effective and increased clarity on how e-fuels are linked to existing policies is needed.

1. Introduction

To contribute to climate targets the transport sector needs to reduce its emissions of greenhouse gases (GHGs) considerably. Transport (including road, rail, air, and ocean) is responsible for approximately 24% of global fossil fuel CO₂ emissions and these emissions are expected to increase without additional measures [1]. Internal combustion engine vehicles (ICEVs) comprised about 99% of the existing global light-duty vehicle (LDV) fleet and 97% of new LDV sales in 2019 [2]. As with road transport, fossil fuels dominate ocean transport and aviation. The introduction of alternative transportation options is required to decarbonize the transport sector.

As illustrated in figure 1, transport has four options for large-scale decarbonization. All are based on the availability of low, or zero-, CO₂ electricity. The four options are: (a) renewable electricity with battery-electric propulsion, (b) renewable hydrogen in fuel cells or internal combustion engines (ICEs),



(c) renewable carbon-based fuels (or ammonia) in fuel cells or ICEs, and (d) continued use of fossil fuels combined either with onboard carbon capture and storage (e.g. onboard ships [3]) or with carbon removal, e.g. direct air capture (DAC) or storage from bioenergy (figure 1). Plug-in hybrid electric vehicles (PHEVs) are a combination of options 1 and 2, 3 or 4.

The first three options can potentially be carbon neutral if they are accomplished using renewable energy as the primary energy source. However, this is not generally the case currently when the whole life cycle is considered. The most attractive option for a given application depends on the specific vehicle performance requirements, future vehicle technology and energy costs, and the necessary supporting infrastructure [4]. Compensation of emissions using carbon capture and storage from bioenergy or direct-air capture is a fundamentally different approach and may face societal and regulatory resistance due to questions about its sustainability, e.g. its capacity to sequester CO₂ over long time scales and continued reliance on fossil fuels for transport.

Electrofuels (e-fuels), one group of potential renewable fuels, are produced by combining hydrogen (produced from electricity) and carbon (typically CO₂) or nitrogen (N₂) to form various fuels. CO₂ can be obtained from biofuel production or captured from the air or point sources (e.g. fossil or biomass-based heat and power plants). Nitrogen is captured from air. Marketable by-products such as high-purity oxygen and heat are also generated. We refer to e-fuels produced when hydrogen is added directly into a biofuel production facility (hence avoiding the costs of carbon capture) as bio-electrofuels or bio-e-fuels. We refer to e-fuels produced using CO₂ captured from point sources (biogenic or fossil) or captured from the atmosphere as stand-alone e-fuels. Depending on the specific production technology, a range of liquid and gaseous e-fuels can be synthesized, including electro-methane, electro-methanol, electro-gasoline, electro-diesel, electro-jet fuel, and electro-ammonia. Electrofuels are in this paper hereafter denoted e-fuels, e-diesel, e-methanol, bio-e-fuels, bio-e-methanol and so on. In the text e-fuels generally include bio-e-fuels except when a distinction between the two is needed, for those cases the terms stand-alone e-fuels production and bio-e-fuels are used.

The main appeal of e-fuels is that many are backward-compatible with existing vehicles, ships, and aircraft and with the existing liquid fuel distribution and retail delivery systems. E-diesel, e-gasoline, and e-jet fuel are 'drop-in' fuels which can be fully fungible with conventional fuels. Given the long lifetimes of the existing vehicle, ship, and aircraft fleets and the urgency of addressing climate change the use of drop-in e-fuels might be a required element in a portfolio of actions to reduce transportation GHG emissions. Other renewable transportation fuels generally require new or adapted vehicles and infrastructure.

The main drawbacks for e-fuels are the low energy conversion efficiencies from electricity to energy at the wheels and the high production costs compared to fossil and biomass-based counterparts [5–7]. These drawbacks, combined with recent dramatic strides in electric vehicle technology (mainly battery cost and performance) and concern that e-fuels may contribute to fossil-fuel dependence lock-in, have led to considerable uncertainty in the future availability of e-fuels [7].

From a technical perspective, e-fuels are of interest for all transport modes, but, as also shown in this review, are of special interest in medium to long-distance ocean transport, aviation, and heavy-duty road

transport or other road applications where liquid fuels with high energy density are difficult to substitute by electrification through battery-electric propulsion [8, 9]. The limited global biomass supply potential for sustainable biofuels, which could also support these transport modes, also increases the interest in e-fuels [10–12]. In addition, e-fuels could also contribute to balancing intermittent electricity production by providing a use for excess electricity and facilitating its storage and transport (as e-fuel products).

In recent years, there has been increased interest in the concept of e-fuels, for example from different transport related stakeholders and a considerable number of papers have been published exploring e-fuels from different perspectives; some examples include e-fuel production costs (FPCs) [5–7] and environmental impact [6, 13–25]. A few studies are available which examine different fuel options for specific transport modes including e-fuels, such as Dahal *et al* [26] with a focus on the aviation industry (including jet fuel selling price and direct operating cost) and Korberg *et al* [27] with a maritime focus (compares estimates of total cost of ownership for several vessel types). There are also some review papers on e-fuels, e.g. Brynolf *et al* [5] focusing on production costs; and more recently Ababneh and Hameed [28] reviewing the production processes, costs and environmental impacts; and Ince *et al* [29] presenting 79 system-level mathematical modeling and simulation studies of different e-fuel production pathways (including no differentiation in relation to transport mode). Marzi *et al* [30] analyzed the state-of-the-art of e-fuels research by specifically mapping projects on e-fuels production funded by the EU Horizon 2020 Programme and found the largest interest to be in hydrogen. Sherwin [31] conducted and optimized a techno-economic assessment focusing on how e-fuel cost could be minimized.

However, there is still a lack of scientific publications providing the overall perspective and clarifying the feasibility or potential for e-fuels in different transport modes. In addition, relatively few studies include assessments of combined biofuel and e-fuels production. Thus, an overview and mapping of existing studies exploring e-fuels for different transport applications while including also combined biofuel and e-fuels production is called for.

The purpose of this paper is to review and assess the feasibility of e-fuels for different transport modes considering road, ocean, and air transport, partly from a techno-economic perspective. The assessment is based on a literature review using publications discussing e-fuels for one or more transport modes. E-fuel options discussed in the literature for each transport mode are: (a) mapped, (b) the cost per transport unit (e.g. vehicle km) for e-fuels and carbon abatement cost estimated and compared to conventional options, (c) prospects and challenges for different e-fuels are highlighted, and (d) the policy context described.

The method is described in section 2, an overall categorization of the reviewed publications is presented in section 3 and the results of the literature review for e-fuels for different transport modes (road, ocean, and air transport) are presented in sections 4–6. The policy context relevant for e-fuels is presented in section 7. Finally, the findings are summarized and discussed in sections 8 and 9.

2. Method

2.1. Literature review

To assess the feasibility of e-fuels in different transport modes, a literature review covering publications from 2016 to 2020 was carried out. The number of research articles considering e-fuels increased rapidly after 2015. The relevant existing literature (including scientific articles, reports, conference proceedings) was identified based on specific search phrases used in Scopus (for title, abstract and keywords) and from so-called snowballing using the reference lists in the identified papers and other publications found to identify additional publications. Snowballing was included due to the difficulties in finding all relevant scientific publications in the e-fuel area through search phrases (e.g. due to the range of terms used) and since there are a range of relevant recent reports. The literature search was based on the search phrases presented in table 1, combining A and B with either C1 (transport), C2 (road), C3 (ocean), or C4 (air).

Initially, the abstracts of all publications identified using different combinations of search phrases (in total 248, 89, 18 and 31 for all transport modes (*A AND B AND C1*), road (*A AND B AND C2*), ocean (*A AND B AND C3*) and air transport (*A AND B AND C4*), respectively) were screened. The different fuel types mentioned in the title, abstract and keywords were identified to get a first screening of the fuels covered in the studies. Then, including also the publications identified via snowballing (17 publications), those that actually assessed or mentioned the use of e-fuels for one or several specific transport modes were categorized, e.g. the different transport modes indicated to be of interest for e-fuels were identified, see section 3. In total 106 publications were included in the categorization of the considered transport modes after the second screening of abstracts and when needed the full publication (91 when excluding conference proceedings). The remaining publications did not specify a specific transport mode or were in a few cases found irrelevant to include mainly due to insufficient focus on e-fuels as defined in this study.

Table 1. Search phrases used for the literature search made in Scopus.

Search phrase name	Search phrase
A	<i>electrofuel*</i> OR <i>efuel*</i> OR <i>'e-fuel*'</i> OR <i>'electro-fuel*'</i> OR <i>'e-gas'</i> OR <i>'e-methane'</i> OR <i>'e-methanol'</i> OR <i>'e-gasoline'</i> OR <i>'e-diesel'</i> OR <i>'e-kerosene'</i> OR <i>'e-ammonia'</i> OR <i>'e-liquid'</i> OR <i>'electro-methane'</i> OR <i>'electro-methanol'</i> OR <i>'electro-gasoline'</i> OR <i>'electro-diesel'</i> OR <i>'electro-kerosene'</i> OR <i>'electro-ammonia'</i> OR <i>'electro-liquid*'</i> OR <i>electromethane</i> OR <i>electromethanol</i> OR <i>electrogasoline</i> OR <i>electrodiesel</i> OR <i>electrokerosene</i> OR <i>electroammonia</i> OR <i>electroliquid*</i> OR <i>'power-to-methane'</i> OR <i>'power-to-methanol'</i> OR <i>'power-to-gasoline'</i> OR <i>'power-to-diesel'</i> OR <i>'power-to-kerosene'</i> OR <i>'power-to-ammonia'</i> OR <i>'hydrogen-based synthetic fuel*'</i> OR <i>'hydrogen-based fuel*'</i> OR <i>'CO2-derived fuel*'</i> OR <i>'power-to-transport'</i> OR (<i>ptx</i> OR <i>ptl</i> OR <i>ptg</i> OR <i>'power-to-fuel*'</i> OR <i>'power-to-gas'</i> OR <i>'power-to-liquid*'</i> OR <i>'power-to-x'</i>) AND (<i>fuel*</i> OR <i>methane</i> OR <i>methanol</i> OR <i>gasoline</i> OR <i>diesel</i> OR <i>kerosene</i> OR <i>ammonia</i>)) AND NOT <i>*cigar*</i> AND NOT <i>'power fuel cell*'</i>
B	<i>'environmental impact*'</i> OR <i>'climate impact*'</i> OR <i>lca</i> OR <i>'life-cycle assessment*'</i> OR <i>'CO2 emission*'</i> OR <i>'carbon dioxide emission*'</i> OR <i>'carbon emission*'</i> OR <i>'GHG emission*'</i> OR <i>'greenhouse gas emission*'</i> OR <i>cost*</i> OR <i>'techno-econom*'</i>
C1	<i>transport*</i> OR <i>'road transport*'</i> OR <i>'heavy-duty'</i> OR <i>'light-duty'</i> OR <i>cars</i> OR <i>trucks</i> OR <i>vehicle</i> OR <i>hauling</i> OR <i>maritime</i> OR (<i>marine</i> AND <i>fuel*</i>) OR <i>shipping</i> OR <i>'ocean transport'</i> OR <i>'aviation'</i> OR <i>'air transport'</i> OR <i>aircraft</i>
C2	<i>'road transport*'</i> OR <i>'heavy-duty'</i> OR <i>'light-duty'</i> OR <i>cars</i> OR <i>trucks</i> OR <i>vehicle</i> OR <i>hauling</i>
C3	<i>maritime</i> OR (<i>marine</i> AND <i>fuel*</i>) OR <i>shipping</i> OR <i>'ocean transport'</i>
C4	<i>'aviation'</i> OR <i>'air transport'</i> OR <i>aircraft</i>

We mapped the results of the review in terms of number of publications, focus of each publication, and which e-fuels are discussed for different transport applications. Some publications estimate the future volumes of e-fuels used for different transport modes, when so this information is also included.

2.2. Cost estimates

To understand the cost competitiveness of e-fuels in different transport modes, mobility costs, representing the cost per transport unit (e.g. € km⁻¹) as defined by equation (1), were estimated. For the mobility cost estimates, a limited number of data sources were selected based on their completeness in terms of options considered and their applicability for assessing mobility cost around 2030. The mobility cost of different e-fuel based propulsion systems are compared against hydrogen and battery-electric propulsion options. Traditional biofuels are not included in the comparison, but they are expected to have lower production costs than bio-e-fuels for most future cost scenarios (see for example Korberg [32] and Korberg *et al* [27]). FPC estimates representing the situation in 2030 are from Grahn *et al* [6] (see table 2), which are based on an extensive recent literature review of e-FPCs performed in parallel to this study based on the same literature. In the more long-run (2040–250) the electro-FPCs are estimated to be considerably lower [6]. Several factors such as electricity cost, CO₂ cost, biomass cost and other investment cost will have an impact on the e-FPC [5, 6], in a high cost case we consider a higher electricity price (75 € MWh⁻¹), higher biomass cost (~40% increase), higher CO₂ cost (120 € tonne⁻¹ CO₂) and higher other investment cost (three times annualized investment cost of all components). The other investment cost represents the annualized indirect investment costs for the whole plant including for example engineering and construction, fees, and project contingency costs (see Brynolf *et al* [5] for a more detailed elaboration on this factor).

Fuel distribution costs (FDCs) are shown in table 3, LDV costs are from Islam *et al* [33] (see table 4), heavy-duty vehicle (HDV) costs are from Holmgren *et al* [34] (see table 5), ship costs are from Korberg *et al* [27] (see table 6), and aircraft direct operating costs are from Dahal *et al* [26] (see table 7). There are significant differences in how cost estimates are traditionally done for different transport modes. We are not aiming to compare the different transport modes to each other but rather to compare the relative cost of e-fuels options within each transport mode and are therefore using the cost methodologies developed in the reviewed studies as much as possible. The mobility cost is based on the annual vehicle cost (AVC), the FPC and the FDC using a specific yearly transport basis which differs between the transport modes (road transport uses vehicle kilometers traveled per year, ocean transport uses one year of operation, air transport uses passenger kilometers traveled per year):

$$\text{Mobility cost} \left(\frac{\text{€}}{\text{transport unit}} \right) = \frac{\text{AVC} + \text{FPC} + \text{FDC}}{\text{transport unit per year}}. \quad (1)$$

For the FDCs, shown in table 3, there is a difference in the infrastructure cost for different transport modes and also in how it is handled in the studies used for the vehicle cost assessments. Kramer *et al* [35]

Table 2. Fuel production cost estimates for 2030 based on an extensive recent review [6].

Fuel production pathway	Fuel abbreviation	Base fuel cost (€ GJ ⁻¹) [6]	High fuel cost (€ GJ ⁻¹) ^f	Optimistic fuel cost (€ GJ ⁻¹) ^a [6]
Electricity	Elec	13.9	20.8	13.9
Compressed hydrogen	C-H ₂	32.0	53.6	25.9
Liquid hydrogen	L-H ₂	35.5	67.4	27.2
Biomass hydrogenation to methanol (MeOH) ^g	Bio-e-MeOH	33.6	58.3	24.4
Biomass hydrogenation to dimethyl ether (DME)	Bio-e-DME	35.0	60.7	25.4
Biomass hydrogenation to gasoline (e.g. via methanol-to-gasoline, MTG) ^g	Bio-e-gasoline	41.5	70.9	29.3
Biomass hydrogenation to jet (e.g. via methanol-to-jet, MTJ) ^g	Bio-e-jet (MTJ)	50.9	86.5	35.5
Biomass hydrogenation to Fischer–Tropsch (FT) liquids ^g	Bio-e-diesel/jet (FT)	46.4	78.5	33.3
Biomass hydrogenation to compressed methane (CMG) ^g	Bio-e-CMG (syngas)	32.6	56.8	24.3
Biomass hydrogenation to liquid methane (LMG) ^g	Bio-e-LMG (syngas)	35.3	60.6	26.5
Biogas methanation to liquid methane ^g	Bio-e-CMG (biogas)	28.8	48.6	22.3
Biogas methanation to liquid methane (LMG) ^g	Bio-e-LMG (biogas)	31.5	52.5	24.5
CO ₂ hydrogenation to methanol	E-MeOH	41.6	87.0	29.1
CO ₂ hydrogenation to DME	E-DME	44.6	91.2	31.7
CO ₂ hydrogenation to gasoline (e.g. via methanol-to-gasoline, MTG)	E-gasoline	52.0	104.2	36.1
CO ₂ hydrogenation to jet (e.g. via methanol-to-jet, MTJ)	E-jet (MTJ)	63.8	127.4	44.0
CO ₂ hydrogenation to FT liquids	E-diesel/jet (FT)	60.7	123.5	41.7
CO ₂ hydrogenation to compressed methane	E-CMG	40.8	80.3	29.9
CO ₂ hydrogenation to liquid methane	E-LMG	43.5	84.2	32.1
Nitrogen to ammonia	E-NH ₃	41.4	68.5	32.2
Refining crude oil to gasoline	Gasoline	16.9	20.8	13.4 ^d
Refining crude oil to diesel	Diesel	15.8 ^b	22.1 ^d	12.3 ^d
Refining crude oil to kerosene	Kerosene	12.2 ^c	20.8 ^e	6.8 ^e
Refining crude oil to marine gas oil (MGO)	MGO	14.5 ^b	19.6 ^d	10.8 ^d
Refining crude oil to low sulfur heavy fuel oil (HFO)	HFO	10 ^b	14.2 ^d	6.9 ^d

^a Optimistic FPC are based on the long-term cost estimate in Grahn *et al* [6].

^b Median European fuel cost between 2003–05–01–2022–03–21. Marine gas oil prices are approximated with heating gas oil [37].

^c Median U.S. Gulf coast kerosene spot prices between 2003–01–2022–02 (assuming 1 USD = 0.91 Euro) [38].

^d 90th and 10th percentile European fuel cost between 2003–01–05–2022–03–21. Marine gas oil prices are approximated with heating gas oil [37].

^e 90th and 10th percentile U.S. Gulf coast kerosene spot prices between 2003–01–2022–02 (assuming 1 USD = 0.91 Euro) [38].

^f High fuel cost cases are generated from Grahn *et al* [6] assuming electricity price of 75 € MWh⁻¹, ~40% increase in biomass cost (resulting in biomass feedstock cost of 10 M€/PJ and biogas feedstock cost of 1.7 M€/PJ) and CO₂ cost of 120 € tonne⁻¹ CO₂ representing a low cost case for direct-air capture (DAC).

^g The bio-e-fuels are assumed to be produced from forest residues or organic municipal solid waste with addition of renewable electrolytic hydrogen.

assume no cost for existing fuel distribution infrastructure and add only the costs needed for new infrastructure or modification of infrastructure (consequential approach) while Holmgren *et al* [34] consider an infrastructure cost for all alternatives including those able to use existing infrastructure (attributational approach). As noted earlier, these differences mean that the results for different modes should not be directly compared. However, it may also be noted that the FDC for conventional fuels is a minor share

Table 3. Fuel distribution cost estimates (range in parenthesis).

	LDV [35] ^a €/100 km	HDV [34] € GJ ⁻¹	Ocean transport [27] € GJ ⁻¹	Air transport ^d € GJ ⁻¹
Electricity	1.7 (0.5–2.9)	11.6 (10.2–14.8) ^b	11.6 (10.2–14.8) ^c	—
C-H ₂	0.59 (0.39–0.78)	16.3	—	—
L-H ₂	—	—	11.6 (9.05–13.07)	11.6 (9.05–13.07)
MeOH	0 (0.03) ^e	2.4	0.6	—
DME	0.03 (0.02–0.04)	2.1	1.2	—
Diesel, gasoline, jet fuel	0	1.5	0.3	1.3
CMG	0.09 (0.06–0.11)	—	—	—
LMG	—	4.9	4.7 (3.5–5.3)	4.9 (4.1–6.1)
NH ₃	—	—	1.2	—

^a Based on the average infrastructure cost scenario derived from the difference in values in figures 18 and 22 in Kramer *et al* [35] which assigns zero cost for distribution of fossil alternatives as they assume no cost for existing fuel distribution infrastructure and only add the costs needed for new or modified infrastructure.

^b Lower value represents charging only during night, higher value represents fast charging (1.2 MW).

^c Assumption based on cost for HDV.

^d Assumption based on infrastructure for HDV transport and ocean for liquid hydrogen.

^e Assumed to be the same as DME's base case to indicate the potential for a higher infrastructure cost for methanol compared to gasoline based on the lower energy density of methanol.

Table 4. Light-duty vehicle (midsize passenger car) costs in 2030 [33]^a.

	Fuel consumption (MJ/100 km)	Vehicle cost (€)
BEV 300	44 (42–46)	28 400 (28 000–28 900)
C-H ₂ FC 300	99 (93–106)	33 200 (32 700–33 700)
DME ICE ^c	192 (181–205)	32 200 (30 800–36 600)
CMG ICE	218 (205–233)	33 800 (32 700–34 900)
MeOH ICE ^c	218 (205–233)	29 500 (27 300–31 900)
Gasoline ICE ^d	202 (182–227)	29 400 (27 200–31 600)
Diesel ICE	192 (181–205)	31 800 (30 400–33 200)

^a Cost ranges reflect low- and high-technology progress cases for 2030 model year (2025 lab year) vehicles from the Argonne National Laboratory Autonomie Model [38] and BEAN tool [39]. Manufacturing costs are multiplied by a factor of 1.5 to give estimated retail price equivalents. Base costs are averages of the range. 1 USD = 0.91 Euro is used for all conversions.

^b BEV300.

^c DME and methanol drivetrains are not included in Islam *et al* [33] and are assumed to have the same fuel consumption as Diesel ICE and CMG ICE, respectively. Based on Kramer *et al* [35] additional costs of 300 Euro for MeOH ICE compared to gasoline ICE and 3400 Euro for DME ICE compared to diesel were assumed.

^d Conventional SI Turbo.

of the overall costs. No specific distribution cost for air transport fuel was found and it is estimated based on data for road transport (HDV) and ocean transport.

The infrastructure for battery-electric vehicles (BEVs), which is included as a comparison for some applications, is uncertain and depends to a large extent on the amount of fast charging (i.e. charging at high power) at public stations versus charging with low power typically at home. Charging at high power will generally be more expensive than charging at lower power. The cost for fast charging has been estimated by Gnann *et al* [36] to be between 0.05 and 0.3 € kWh⁻¹. The charging cost mainly depends on charging power capacity, utilization of the charger, and acceptance of queuing time.

The AVCs for LDVs are calculated for a midsize passenger car assuming 15 000 km annual driving distance, 5% discount rate, and a lifetime of 17 years. The vehicle costs and fuel consumption given in table 4 were taken from Islam *et al* [33] and the associated BEAN tool [39]. The vehicle costs in table 4 were combined with fuel costs from table 2 to give vehicle plus fuel costs (Euros/km) for different powertrains. The Autonomie model described by Islam *et al* [33] does not include dimethyl ether (DME) or methanol fueled vehicles, estimates in table 4 for these vehicles were based on data from Kramer *et al* [35].

For HDVs 125 000 km annual driving distance, 10% discount rate, lifetime of 7 years, and the data presented in table 5 based on Holmgren *et al* [34] are used to calculate the AVC. The HDV considered here is a type HGV40 (heavy goods vehicle with total maximum weight of 40 tonnes).

Table 5. Data used to estimate heavy-duty vehicle cost in 2030, represented by HGV40.

	Vehicle investment cost (€ km ⁻¹) ^a [34]	Vehicle fuel consumption (kWh km ⁻¹) [34]
Diesel ICE	0.169	2.48
BEV	0.257 (0.196–0.319) ^b	1.19
MeOH ICE	0.169	2.48
DME ICE	0.169	2.48
CMG ICE	0.196	2.93
LMG ICE	0.188 (0.232) ^c	2.93 (2.24) ^c
C-H ₂ FC	0.222	1.71

^a An annual driving distance of 125 000 km, 10% discount rate and lifetime of 7 years is assumed, following Holmgren *et al* [34], when these values are calculated.

^b Base case 800 km range, low case 400 km range, high cost 800 km range and 50% increase in battery cost.

^c Representing more advanced engine concept, high pressure direct injection (HPDI).

Table 6. Data used to estimate ocean transport cost (including propulsion and onboard fuel storage cost)^a.

	Large ferry		Container ship	
	Propulsion system and O&M, k€ yr ^{-1c}	Onboard fuel storage, k€ yr ^{-1b}	Propulsion system and O&M, k€ yr ⁻¹	Onboard fuel storage, k€ yr ⁻¹
HFO, MGO, diesel ICE	200	2	2400	300
Battery-electric (BE)	1000 (600–1300)	4400 (3000–6600)	—	—
MeOH ICE	300	3	2400	500
DME ICE	500	10	3800	1100
LMG ICE	700	30	6900	3800
NH ₃ ICE	700	5	5100	600
L-H ₂ ICE ^b	700	50	8600	6800
MeOH FC ^b	3000 (1100–4300)	50 (50–70)	14 250 (5700–21 500)	500
LMG FC ^b	3200 (1300–4500)	80 (80–100)	18 400 (8600–24 500)	3500
NH ₃ FC ^b	3200 (1300–4400)	80 (80–100)	16 300 (6500–22 400)	600
L-H ₂ FC ^b	2200 (1300–2900)	80 (80–100)	15 200 (10 700–21 000)	6200

^a Based on Korberg *et al* [27]. The large ferry has a yearly fuel consumption of 93.6 TJ yr⁻¹, 51.5 TJ yr⁻¹ and 74.8 TJ yr⁻¹ for ICE, battery-electric and FC while the container ship has a yearly fuel consumption of 1740 TJ yr⁻¹ and 1570 TJ yr⁻¹ for ICE and FC.

^b For fuel cell propulsion systems a battery is also assumed necessary for managing load changes, this is added in the fuel storage cost and is the reason for the higher fuel storage cost indicated. Polymer membrane FC are assumed for liquefied hydrogen and solid oxide fuel cell for methane, methanol and ammonia.

^c O&M are based on a fraction of the onboard and propulsion system cost, see Korberg *et al* [27].

The AVC for ocean transport is calculated for a large ferry with 1260 h of annual operation and 6 h between bunkering, and for a container ship with 5280 h of annual operation and 480 h between bunkering, using data presented in table 6 based on Korberg *et al* [27]. The cost is estimated considering a 5% discount rate (modified from 3% in the original to match assessments in the present review) and a technical lifetime of the propulsion systems. Only the cost of the propulsion systems is considered, not the entire vessel cost. For a more detailed description of the data and assumptions see Korberg *et al* [27].

Direct operating cost (including total financial cost, maintenance cost, crew cost and fuel cost) is typically used to calculate cost for different fuels and aircraft propulsion systems. Cost estimates for a medium-range (MR) and long-range (LR) aircraft are presented in table 7. For more information about the data and assumptions see Dahal *et al* [26].

One key metric in discussions of e-fuels attractiveness versus other options is the carbon or CO₂ abatement cost (expressed in € tonne⁻¹ CO₂). The carbon abatement cost for each transport mode is estimated using equation (2), where Mobility Cost_{Alt.} represents the total cost of mobility for the different e-fuel, bio-e-fuel, and hydrogen alternatives for different transport units (for cars and trucks it is € kilometer⁻¹, for ships it is €/year, and for aircraft it is €/passenger and kilometer) and Mobility Cost_{Conv.} represents the corresponding cost for the conventional fossil alternative for respective transport mode. The GHGs_{Conv.} and GHGs_{Alt.} represent the life cycle GHG emissions associated with the conventional and

Table 7. Data for estimating air transport cost for medium-range (MR) and long-range (LR) aircraft for different fuels, following Dahal *et al* [26].

	Fuel consumption (MJ/passenger/km)		Aircraft direct operation cost excluding fuel cost (€/passenger/km)	
	MR	LR	MR	LR
Jet A-1	0.631	0.884	0.037	0.026
E-jet fuel/ bio-e-jet fuel	0.631	0.889	0.037 (0.038) ^a	0.027 (0.028) ^a
LMG	0.733	0.999	0.040 (0.041) ^a	0.029 (0.030) ^a
L-H ₂	0.743	0.947	0.041 (0.044) ^a	0.029 (0.031) ^a

alternative fuel options respectively (see table 7). Carbon abatement cost have been calculated separately for the base, high and low cases and the conventional alternative is the lowest cost fossil alternative for each transport mode, i.e. gasoline ICE for LHV, diesel for HDV, MGO for large ferry, HFO for container ship and fossil jet fuel for air transport:

$$\text{Carbon abatement cost} \left(\frac{\text{€}}{\text{ton}} \right) = \frac{\text{Mobility cost}_{\text{Alt.}} \left(\frac{\text{€}}{\text{transport unit}} \right) - \text{Mobility cost}_{\text{Conv.}} \left(\frac{\text{€}}{\text{transport unit}} \right)}{\text{GHGs}_{\text{Conv.}} \left(\frac{\text{tonne CO}_2 \text{ eq.}}{\text{transport unit}} \right) - \text{GHGs}_{\text{Alt.}} \left(\frac{\text{tonne CO}_2 \text{ eq.}}{\text{transport unit}} \right)}. \quad (2)$$

For consistency in the life cycle GHG emissions for the e-fuel pathways, data from Prussi *et al* [40] (which is one of the most comprehensive assessments on LCA of e-fuels, in terms of fuel pathways) have been used (see table 8). However, these values are also uncertain and the actual GHG performance depends on the specific fuel pathway and methodological choices, see for example Grahn *et al* [6]. All the bio-e-fuels are assumed to be based on forest residues and/or organic municipal solid waste. These pathways use waste biomass and hence do not have significant land use change impacts [41]. Pathways involving dedicated biomass production may have significant direct or indirect land use change impacts which would need to be considered in assessments of carbon abatement costs.

3. Overview of the reviewed publications

The scientific publications and reports found from the Scopus search and snowballing specifically addressing or mentioning e-fuels for different transport modes (91 publications in total excluding conference proceedings, see section 2) are listed in table 9, indicating the transport modes for which e-fuels are considered. E-fuels for light-duty road transport, heavy-duty road transport, ocean transport and air transport are considered in 52, 52, 22, and 37 publications, respectively, though explored to differing extents (see also figure 2). Several publications consider the use of e-fuels relevant for several transport modes. However, more studies have addressed e-fuels for the road transport sector (often considering both light-duty and HDVs) than aviation and shipping. This could partly be explained by the generally larger number of publications on alternative fuels for road transport than for other transport modes. However, this does not mean that e-fuels are considered a less attractive option for the latter sectors. Rather, the main competing options differ between different transport modes and fewer options exist for LR road-based transport, shipping, and aviation for which there is less potential for battery-electric and hydrogen solutions [45, 46].

Different e-fuels are considered to a varying extent for different transport modes in the publications (as seen in figure 2) and are further discussed for the specific transport modes in section 4–6. E-fuels are most discussed for transport in general without specifying a transport mode (figure 2). Hydrogen, which is not defined as an e-fuel in the present paper and thus not specifically searched for, is however, included for comparison in figure 2.

Several of the identified scientific papers specifically assessed or outlined the potential role of e-fuels in the future transport sector on a national, regional, and/or global level focusing mainly on 2050 [9, 45, 55–57, 62, 66, 67, 79, 88, 91, 93, 107]. E-fuels are introduced in road transport, primarily heavy-duty, in 10 (75%) of these studies [9, 45, 55–57, 62, 66, 79, 91, 93], in aviation in 7 studies [45, 55, 57, 62, 67, 91, 93], and in shipping in 5 studies [9, 45, 55, 62, 91]. Lehtveer *et al* [9], Connolly *et al* [62], and Blanco *et al* [45] conclude that e-fuels are mainly attractive for reducing GHG emissions in the transport sector when carbon capture and storage/sequestration (CCS) technologies are not available at large scale, while Lester *et al* [91] concluded that their future role depends on the biomass potential.

Table 8. Fuel life cycle GHG emissions for the fuels included in the assessment of carbon abatement costs mainly based on Prussi *et al* [40] in gCO₂-eq./MJ final fuel (using GWP100, CH₄ = 25, N₂O = 298).

	LDV	HDV	Ocean transport ^o (gCO ₂ -eq./MJ final fuel)	Air transport
Electricity	0	0	0	—
Compressed hydrogen (C-H ₂) ^a	9.5	9.5	—	—
Liquid hydrogen (L-H ₂) ^b	3.6	3.6	3.6	3.6
Biomass hydrogenation to methanol (Bio-e-MeOH) ^{c,d}	6.16	6.16	6.16	—
Biomass hydrogenation to DME (Bio-e-DME) ^{c,e}	6.07	6.07	6.07	—
Biomass hydrogenation to gasoline (Bio-e-gasoline) ^{c,f}	5.28	5.28	—	—
Biomass hydrogenation to jet (Bio-e-jet (MTJ)) ^{c,f}	—	—	—	5.28
Biomass hydrogenation to FT liquids (Bio-e-diesel/jet (FT)) ^{c,g}	5.28	5.28	5.28	5.28
Biomass hydrogenation to compressed methane (Bio-e-CMG, from syngas) ^{c,h}	11.73	—	—	—
Biomass hydrogenation to liquid methane, (Bio-e-LMG, from syngas) ^{c,h}	15.98	15.98	35.73 (15.98 ^p)	15.98
Biogas methanation to compressed methane (Bio-e-CMG, from biogas) ^{c,i}	10.21	—	—	—
Biogas methanation to liquid methane (Bio-e-LMG, from biogas) ^{c,i}	10.21	10.21	29.96 (10.21 ^p)	—
CO ₂ hydrogenation to methanol (e-MeOH) ^j	1.78	1.78	1.78	—
CO ₂ hydrogenation to DME (e-DME) ^k	1.70	1.70	1.70	—
CO ₂ hydrogenation to gasoline (e-gasoline) ^f	0.9	0.9	—	—
CO ₂ hydrogenation to jet (e-jet) ^f	—	—	—	0.9
CO ₂ hydrogenation to FT-liquids (e-diesel/e-jet) ^l	0.9	0.9	0.9	0.9
CO ₂ hydrogenation to compressed methane (e-CMG)	2.42	—	—	—
CO ₂ hydrogenation to liquid methane (e-LMG) ^m	6.67	6.67	26.42 (6.67 ^p)	—
Nitrogen to ammonia (e-NH ₃) ⁿ	—	—	10	—
Conventional fossil alternative	90.5, 92.1 ^q	92.1	92.6, 89.6 ^r	81

Process pathways in the footnotes are from Prussi *et al* [40] except where other information is given. The bio-e-fuel pathways included are assumed to be produced from waste flows such as forest residues and organic municipal solid waste with addition of renewable electrolytic hydrogen.

^a WDEL1/C-H₂.

^b WDEL1/LH2 (data represent road transport but are assumed here to be similar for ocean and air transport), the larger emissions associated with WDEL1 used for C-H₂ is due to H₂ compression and dispensing at retail sites where average European electricity mix (EU-mix, LV) is assumed. For liquefaction wind electricity is assumed.

^c Data is lacking for the combined biomass to hydrogenation fuels in Prussi *et al* [40]. A rough estimate has therefore been made taking the average data between corresponding biofuel and e-fuel production.

^d Represented by the average of the following process pathways (REME1a + WWME1a)/2.

^e Average of the following process pathways (REDE1a + WWDE1a)/2.

^f Prussi *et al* [40] does not have data for the Methanol-to-Gasoline or Methanol-to-Jet route, values here have been assumed to be similar to the Fischer-Tropsch (FT) routes.

^g Average of the following process pathways (RES1 + WWSD1a)/2.

^h Average of the following process pathways (WWCG2 + RECG1a)/2 and (WWLG2 + RELG1a)/2 for compressed and liquid respectively.

ⁱ Average of the following process pathways (OWLG1 + RECG1a)/2 and (OWLG1 + RELG1b)/2 for compressed and liquid respectively. There are many different substrates for anaerobic digestion, here organic municipal solid waste is assumed as it is a substrate that has an emission profile in between the extremes of manure (negative impact due to reduced emissions of CH₄) and maize Prussi *et al* [40].

^j REME1a.

^k REDE1a.

^l RES1.

^m RELG1a.

ⁿ Ammonia is not included in Prussi *et al* [40], and [42] has therefore been used instead assuming renewable electricity.

^o A methane slip of 0.79 gCH₄/MJ has been added for the methane based pathways in ICE for shipping based on Brynolf *et al* [43] and multiplied with 25 to get the CO₂-eq.

^p Values used for fuel cell pathways.

^q For gasoline and diesel respectively.

^r Based on EU Fuel Maritime proposal Annex II [44].

Table 9. Publications (scientific articles and reports) from 2016–2020 in which e-fuels are considered for one or more specific transportation modes (A = scientific article; R = report; C = conference paper; LS = literature search; SB = snowballing).

Reference	Type of publication (how it was found)	Transportation modes considered			
		Road, light-duty	Road, heavy-duty	Ocean	Air
Ajanovic and Haas [47]	A (LS)	x			
Albrecht and Nguyen [48]	A (LS)		x	x	x
Al-Zakwani <i>et al</i> [49]	A (LS)	x			
Artz <i>et al</i> [50]	A (SB)	x			x
Ash <i>et al</i> [51]	R (SB)			x	
Bellocchi <i>et al</i> [52]	A (LS)		x		x
Benajes <i>et al</i> [53]	A (LS)	x	x		
Berger <i>et al</i> [54]	A (LS)	x	x		
Blanco <i>et al</i> [45]	A (LS)	x	x	x	x
Blanco <i>et al</i> [55]	A (LS)	x	x	x	x
Blanco <i>et al</i> [56]	A (LS)	x	x		
Bongartz <i>et al</i> [18]	A (LS)	x			
Cantarero [57]	A (LS)		x		x
Child <i>et al</i> [58]	A (LS)	x	x		
Child <i>et al</i> [59]	A (LS)		x		
Comidy <i>et al</i> [60]	A (LS)				x
Colbertaldo <i>et al</i> [61]	A (LS)	x			
Connolly <i>et al</i> [62]	A (LS)	x	x	x	x
Cuellar-Franca <i>et al</i> [63]	A (LS)	x	x		
Daggash <i>et al</i> [64]	A (LS)	x			
Decker <i>et al</i> [65]	A (LS)		x	x	x
Deutz <i>et al</i> [16]	A (SB)	x			
Dietrich <i>et al</i> [108]	A (LS)				x
Dominković <i>et al</i> [66]	A (LS)	x	x	x	x
Drünert <i>et al</i> [67]	A (LS)				x
Falter and Pitz-Paál [68]	A (LS)				x
Faridpak <i>et al</i> [69]	A (LS)	x	x		
Fasihi <i>et al</i> [70]	A (LS)		x		x
Gnann <i>et al</i> [71]	C (LS)	x	x		
Goldmann <i>et al</i> [72]	A (LS)				x
Guilarte and Azzaro-Pantel [73]	A (LS)	x	x		
Hank <i>et al</i> [74]	A (LS)		x	x	x
Hannula [75]	A (SB)	x	x		
Hannula and Reiner [76]	A (LS)	x			
Hansson <i>et al</i> [77]	A (LS)	x	x	x	
Heesterman [78]	A (SB)	x	x	x	x
Helgeson and Peter [79]	A (LS)	x	x		
Hombach <i>et al</i> [80]	A (LS)	x			
Isermann [81]	A (LS)	x	x		
Jürgens <i>et al</i> [82]	A (LS)				x
Khalili <i>et al</i> [83]	A (LS)	x	x	x	x
Kieckhäfer <i>et al</i> [84]	A (LS)				x
Kirsch <i>et al</i> [85]	A (LS)		x		x
Knight [86]	A (LS)			x	
Koj <i>et al</i> [19]	A (LS)	x			
Koj <i>et al</i> [87]	A (LS)	x	x	x	x
Korberg <i>et al</i> [88]	A (LS)		x		
Kramer <i>et al</i> [35]	R (SB)	x	x		
Kramer <i>et al</i> [89]	A (LS)	x			
Köhler [90]	A (LS)			x	
Lehtveer <i>et al</i> [9]	A (LS)	x	x	x	
Lester <i>et al</i> [91]	A (LS)	x	x	x	x
Liu <i>et al</i> [20]	A (LS)	x	x		
Llera <i>et al</i> [92]	A (LS)		x		
Malins [93]	R (SB)	x	x	x	x
Matzen and Demirel [24]	A (SB)	x			

(Continued.)

Table 9. (Continued.)

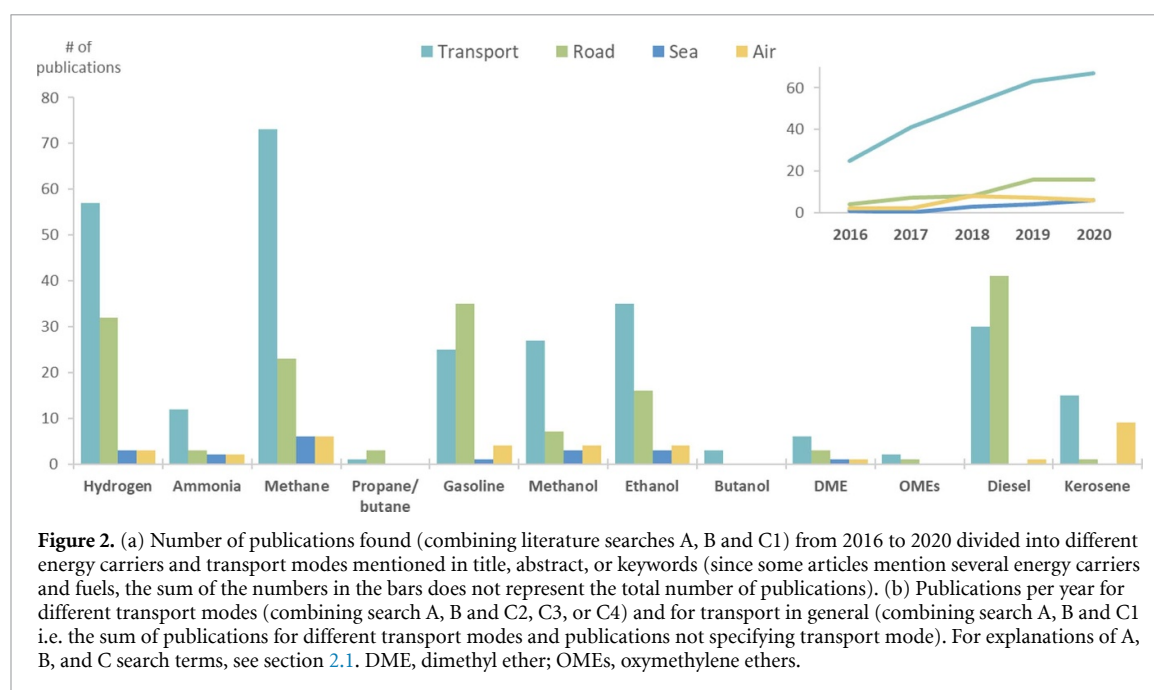
Reference	Type of publication (how it was found)	Transportation modes considered			
		Road, light-duty	Road, heavy-duty	Ocean	Air
McDonagh <i>et al</i> [94]	A (LS)		x		
McDonagh <i>et al</i> [95]	A (LS)		x		
McKenna <i>et al</i> [96]	A (LS)	x	x		
Saccullo <i>et al</i> [97]	A (LS)		x		
Monaco <i>et al</i> [98]	A (SB)	x	x		
Mortensen [99]	R (SB)				x
Müller <i>et al</i> [100]	A (LS)				x
Müller-Langer <i>et al</i> [101]	A (LS)				x
Panzone <i>et al</i> [102]	A (LS)		x	x	x
Pérez-Fortes <i>et al</i> [103]	A (SB)	x			
Plötz <i>et al</i> [104]	R (SB)		x		
Prabhakaran <i>et al</i> [105]	A (LS)	x	x	x	
Pregger <i>et al</i> [106]	A (LS)	x	x		x
Pursiheimo <i>et al</i> [107]	A (LS)	x	x	x	x
Ramirez <i>et al</i> [109]	A (LS)	x	x		
Rosenfeld <i>et al</i> [110]	A (LS)	x			
Rothbart [111]	A (LS)	x	x		
Runge <i>et al</i> [112]	A (LS)	x			
Scheelhaase <i>et al</i> [113]	A (LS)				x
Schemme <i>et al</i> [114]	A (LS)	x	x		
Schemme <i>et al</i> [115]	A (LS)	x	x		
Schmidt <i>et al</i> [116]	R (SB)				x
Schmidt <i>et al</i> [117]	A (LS)				x
Shih <i>et al</i> [118]	A (SB)				x
Tremel [119]	A (LS)		x	x	x
Trieb <i>et al</i> [120]	A (LS)		x	x	x
Trost <i>et al</i> [121]	A (LS)	x			
Uusitalo <i>et al</i> [22]	A (LS)	x			
Wanitschke and Hoffmann [122]	A (LS)	x	x		
Wevers <i>et al</i> [123]	A (LS)			x	
Wormslev [124]	R (SB)				x
Yang <i>et al</i> [125]	A (LS)		x		
Yugo [126]	R (SB)				x
Zhang <i>et al</i>	A (LS)	x			
Zhao <i>et al</i> [127]	A (SB)	x			
Total number of publications per transport mode		52	52	22	37

4. E-fuels for future road transport

Road transport can be decarbonized using options other than e-fuels. BEVs and hydrogen fuel cell electric vehicles (FCEVs) have received considerable research and development effort over the last decade. While FCEVs have struggled to emerge at scale, BEVs have seen a steady increase in production and sales [2] and most major manufacturers have announced aggressive plans for increased BEV sales over the next decade [128]. Most high-volume BEV applications have been passenger cars, with light trucks and heavy-duty applications being a greater challenge due to greater payload, charging infrastructure and/or range requirements. An industry-wide transition to BEVs or hydrogen based FCEVs will require considerable investment in charging points for BEVs and a H₂ distribution system and stations for FCEVs [35]. Hydrogen use in ICEVs is also a possibility, but not considered to the same extent as FCEVs. Renewable fuels containing carbon such as biofuels and e-fuels (used in ICEVs or FCEVs, as well as PHEVs) are also a possibility and these options are associated with lower fuel distribution investments.

4.1. Publications involving road transport

A total of 70 publications (80 including conference proceedings) of the identified publications addressed e-fuels in road transport with at least a basic level of specificity (i.e. mentioned the use of e-fuels for light-duty and/or heavy-duty road transport, in total 52 publications addressed each area, see table 9). Brynolf *et al* [5] reviewed the literature through 2015–2016 and showed that Fischer–Tropsch (FT) liquid



hydrocarbons in the form of diesel and gasoline were the most commonly discussed e-fuels for transport, with methane and methanol also mentioned frequently. In papers published since 2016, similar fuels are discussed but occasionally other fuels, such as, DME and oxymethylene ethers (OMEs), as seen in figure 2. Propane, butane, butanol isomers, ethanol, and ammonia were also noted in the literature since 2016. E-fuels under consideration for road transportation can be divided into those for spark ignition (SI) engines or compression ignition (CI) engines. E-fuels most often identified for SI engine applications include methane, methanol, and gasoline-range hydrocarbons (from methanol to gasoline, MTG, or FT processes). E-fuels for CI engines include diesel-range hydrocarbons (typically from FT), DME, and OMEs. Several papers described the use of e-fuels generically (e.g. ‘synthetic fuels’) and were not classified further. Likewise, some papers also discussed bio-e-fuels [76, 91], but these were not always described in further detail. Hydrogen, included in figure 2 for comparison, is typically envisioned for FCEVs, but can also be used in SI engines [129, 130].

Many papers involving road transportation considered a few specific e-fuels and assessed their widescale production potential as part of the overall transport system. A few studies compared several possible e-fuels in terms of economic and environmental aspects related to production [91, 98, 115, 131–133], but did not address functional attributes and infrastructure differences in any detail.

Very few publications specifically assessed and compared implementation aspects for different e-fuels in road transport. The most comprehensive study found in this respect was conducted by a FVV working group (the Research Association for Combustion Engines of the German auto industry) [35]. Kramer *et al* [35] gave a detailed assessment of costs associated with numerous e-fuel production pathways, vehicle technologies and infrastructure requirements for a 100% defossilized transport sector. The study included BEVs, H₂ FCEVs, and ICEVs operating on e-methane, e-methanol, e-gasoline, e-diesel, e-propane, e-DME, and e-OME. Gnann *et al* [71] compared the cost and environmental performance of heavy-duty conventional diesel, e-methane, e-methanol, H₂ FCEVs, and BEVs. Neither study finds a clear winner for every road transport vehicle application. Different renewable e-fuel options involve significant differences/tradeoffs in powertrain and fuel cost, performance attributes, technical readiness, as well as renewable energy and infrastructure needs. Holmgren *et al* [34] estimated the cost of heavy-duty powertrains (two truck types) using e-DME, e-methanol, e-ethanol, e-FT-diesel, e-liquefied biogas, e-compressed biogas, biofuels (liquid and gaseous), H₂ FCEVs, BEVs, and electric road systems. The cost was expressed as the relative mobility cost including vehicle investment costs, vehicle service and repairs, and fuel costs (including FDC) and the e-fuels end up in the higher relative mobility cost range compared to the other options [34].

A discussion of studies indicating the specific prospects for e-fuels for road transport in terms of estimated introduction rate follows. Lehtveer *et al* [9] assessed the cost-effectiveness of e-fuels for GHG reduction from an energy system perspective using cost optimized modelling and reported that in the scenario most favorable to e-fuels, they provide in 2070 approximately 15% of the global energy demand for

transport. In other scenarios not favorable to e-fuels, e.g. with large-scale introduction of CCS, e-fuels are not a cost-effective solution, since climate targets can be met at lower total energy systems cost if captured CO₂ is stored instead of reused [9]. Malins [93] reported the status and prospects of e-fuels for transport in the European Union (EU) and outlined four scenarios for the introduction of e-fuels to 2050. These scenarios included 10% and 50% of total transport energy demand (assuming drop-in e-fuels), 50% of total truck energy demand (assuming e-diesel) and one scenario for the aviation sector. Connolly *et al* [62] presented a scenario for a 100% renewable energy system in Europe by the year 2050 where one assumption is the introduction of e-fuels (in the form of DME and methanol) for heavy-duty road vehicles, shipping and aviation corresponding to half of their total fuel demand.

In scenarios for the EU in 2050, Blanco *et al* [45] found that e-fuels (mainly e-diesel) provide up to 50%–60% of total diesel demand for road transport and shipping when CCS is limited, and to some extent for cars when direct electrification with BEVs is limited. Blanco *et al* [55] assessed the costs, drivers and barriers, and the potential for e-methane in the EU through 2050. They found that the demand for e-methane for transport varies considerable in the assessed scenarios, with liquefied methane a possibility for heavy-duty transport and ocean transport.

Lester *et al* [91] analyzed the potential introduction of e-fuels in the Danish energy system in 2050 and find that the majority of the produced e-fuels are used in the road sector except for the case when no biomass import is allowed when e-fuels dominate for both road, ocean, and air transport and then primarily produced in connection with biomass production, i.e. as bio-e-fuels.

4.2. Cost estimates

The costs for producing different e-fuel options, in the near and more long term, are widely discussed in the literature and recently reviewed by Grahn *et al* [6]. However, assessment of the total costs of using e-fuels, including also fuel distribution and vehicle costs, is more challenging [35]. A new fuel, not currently produced or distributed at scale, would require a new production and fuel distribution system (e.g. pipelines, fuel terminals, tanker trucks, and filling stations). The exceptions are e-fuels that are compositionally equivalent to existing fuels (e.g. e-gasoline, e-diesel, e-jet, e-methane). Gaseous fuels add cost due to the equipment and energy needed to compress and/or liquify the fuel for transport and refueling, and additional vehicle hardware for fuel handling and storage [71]. Kramer *et al* [35] concluded that the total cost for light-duty ICEVs using e-fuels were not necessarily higher than using H₂ in FCEVs or electricity in BEVs given the uncertainty in the underlying costs.

Figure 3 shows the estimated near-term (i.e. ~2030) mobility cost (in € vehicle km⁻¹) for BEVs, various e-fuels, bio-e-fuels and fossil fuels for LDVs (figure 3(a)) and HDVs (figure 3(b)), when combining near-term FPC estimates from Grahn *et al* [6] with vehicle cost estimates [33–35, 39]. The lowest-cost options for both LDVs and HDVs are fossil fuels when excluding subsidies and taxes. Thus, a transition to alternatives by 2030 would require policy measures (e.g. taxes on fossil fuels and/or subsidies of alternatives).

The differences in cost per vehicle km between LDV options is smaller than for HDVs. This can be explained by differences in annual distance travelled, with LDVs travelling less distance which leads to vehicle investment costs being relatively more important than fuel costs [34]. As a result, the vehicle costs comprise the majority of the total costs for LDVs. The differences between the e-fuel alternatives are relatively small with bio-e-fuels (green bars in figure 3) having the lowest cost. Biofuels are not included, but for comparison, most forest-based biofuels pathways would have lower costs than all bio-e-fuels and e-fuels [32, 34].

However, e-fuels have the advantage of theoretically unlimited scale, unlike biofuels which are constrained by biomass availability. Figure 3 also shows, in contrast to studies such as Kramer *et al* [35] and Gnann *et al* [71], that for HGV40 HDVs, BEVs are estimated to be lower cost than any e-fuels, bio-e-fuels or hydrogen in the base case (figure 3(b)). It is however important to keep in mind that the conclusion depends greatly on the type of heavy vehicle and its operating pattern. Also note that potential costs for reduced payload and/or additional driver costs for BEVs and downtime due to more stops for charging is not included in figure 3. The least-cost alternative for HDVs among the e-fuels are bio-e-methanol and bio-e-DME.

The carbon abatement costs for e-fuels in road transport in this study are estimated to be 150–1140 € tonne⁻¹ CO₂ depending on e-fuel pathway and road application (see figure 4). The broad span of estimated carbon abatement cost for e-fuels is mainly related to the uncertainty in e-FPC (spanning from optimistic fuel cost to high fuel cost in table 2). Light-duty road transport is in the lower part of the range and heavy-duty in the upper part. For comparison the estimated carbon abatement cost for BEV in road transport is in the range –120–110 € tonne⁻¹ CO₂. However, the abatement cost is sensitive to the underlying assumptions (particularly the vehicle costs for LDV but also the potential GHG impact of the bio-e-fuels which depend on the assumed raw materials and production pathways) and therefore uncertain, which is reflected in the broad ranges. The FDC is for example handled differently in different studies. For

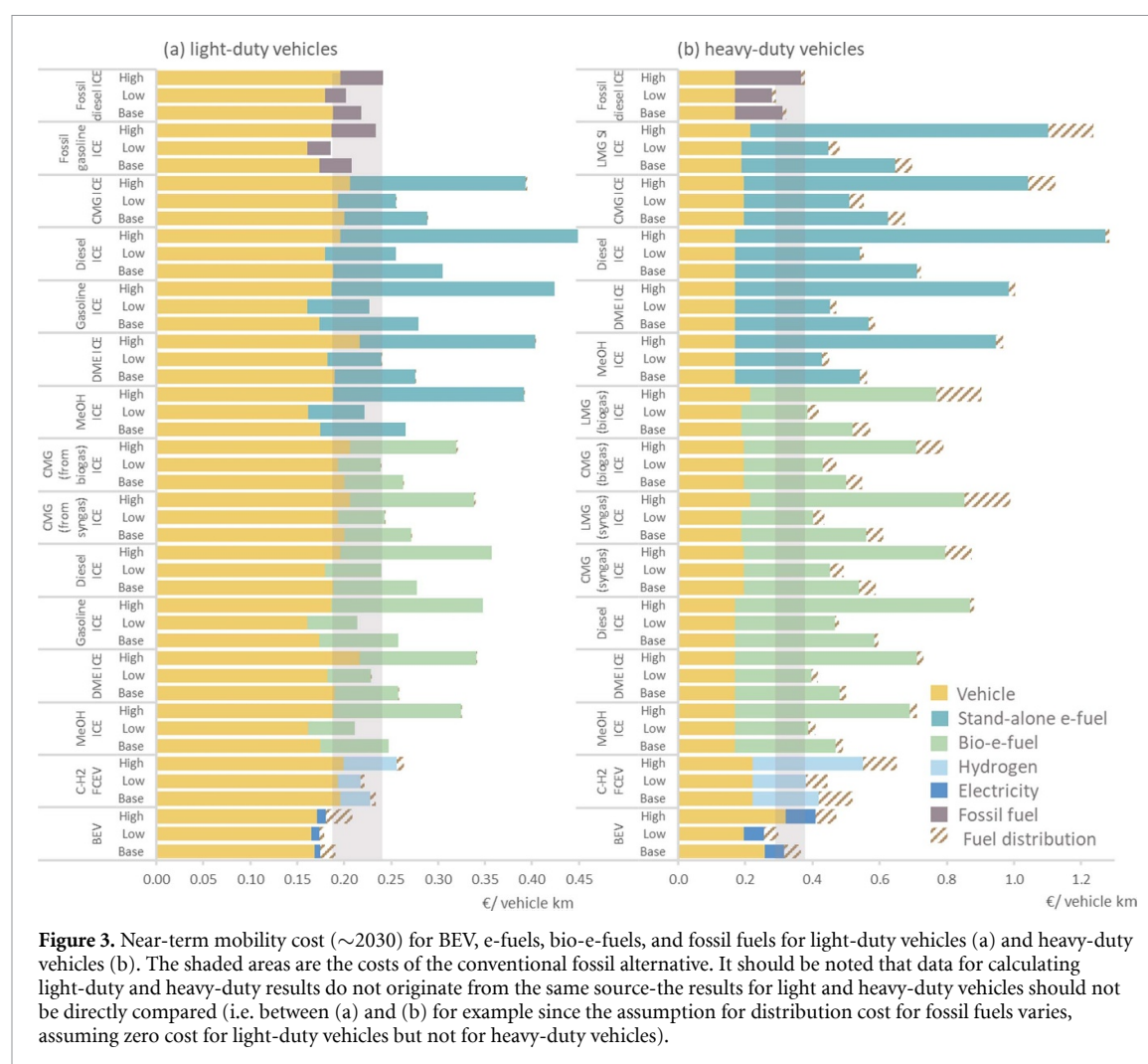


Figure 3. Near-term mobility cost (~2030) for BEV, e-fuels, bio-e-fuels, and fossil fuels for light-duty vehicles (a) and heavy-duty vehicles (b). The shaded areas are the costs of the conventional fossil alternative. It should be noted that data for calculating light-duty and heavy-duty results do not originate from the same source—the results for light and heavy-duty vehicles should not be directly compared (i.e. between (a) and (b) for example since the assumption for distribution cost for fossil fuels varies, assuming zero cost for light-duty vehicles but not for heavy-duty vehicles).

LDVs using non-conventional fuel the abatement cost is determined mainly by the vehicle cost assumptions rather than fuel cost as the vehicle costs dominate the total cost. In the long-term e-fuels could be produced with lower costs [6] but will still be more expensive than the conventional fuel options.

5. E-fuels for ocean transport

The International Maritime Organization (IMO) has a goal of cutting the carbon intensity of all ships (new build and existing) by at least 40% by 2030 compared to a 2008 baseline. To reach zero- or low-carbon shipping, the main options are: (a) renewable electricity with fully battery-electric propulsion, (b) renewable hydrogen or ammonia in fuel cells or ICEs, (c) renewable e-fuels or biofuels in FCs or ICEs, (d) sails and wind, and (e) continued use of fossil fuels combined with carbon capture on-board ships. However, there is a lack of guidance on what fuels are suitable for different shipping segments. Hydrogen, ammonia, or battery electric-propulsion are discussed as main options to reach a shipping sector with low or zero GHG emissions [134, 135]. The potential of biofuels to reduce GHG emissions is also discussed in several articles and reports [136–142]. E-fuels for shipping are also mentioned in several studies (see table 9). The possibility of applying carbon capture onboard ships and the possibility using sails and wind as the main source of energy are also discussed [3, 136, 143].

Ships have traditionally used relatively low-cost fuels in the form of heavy fuel oils and diesel fuels with high sulfur content which makes the step to zero carbon fuels larger from a cost perspective. There are several different categories of ships with different operational profiles (e.g. coastal, inland, and ocean-going ships) which affect what decarbonization options are preferable. So far, the main fuel shift in shipping is the introduction of liquefied natural gas (LNG) [134]. However, this introduction is driven foremost by stricter sulfur regulations, not by decarbonization. There are several initiatives for introducing renewable marine fuels, such as hydrogen, methane, and methanol [136, 144, 145]. Within the two categories coastal and

inland shipping, there are already several battery-electric ships in operation while for ocean going ships that are travelling long distances between bunkering, batteries are not a plausible option [146, 147].

5.1. Publications involving ocean transport

Twenty-two publications (26 including conference proceedings) that addressed e-fuels for the shipping sector, at least at a basic level of specificity, have been identified (table 9). In 2012, Vergara *et al* [148] suggested the use of e-fuels in ocean transport and then specifically dedicated land-based synfuel refineries using CO₂ from coal power plants and hydrogen produced from sustainable sources to mitigate carbon emissions in the maritime sector. In 2021, Korberg *et al* [27] published the most extensive study on e-fuels in shipping so far. They estimated the total cost of ownership for four ship types (large ferry, general cargo, bulk carrier and container ship) and three operational profiles for biofuels, bio-e-fuels, and e-fuels for seven possible energy carriers (electricity, methanol, DME, diesel, liquefied methane, biodiesel, liquefied hydrogen, and ammonia). Korberg *et al* [27] found that e-fuel options were more expensive than their corresponding biofuels. Compared to Korberg *et al*, this study is based on a more updated review of e-FPCs.

Methanol and ammonia are the most discussed e-fuels for shipping (see figure 2). Liquefied e-methane is also discussed in some studies [149]. The increased use of LNG in shipping could make e-methane more viable. Hydrogen is also discussed in several studies but is not considered an e-fuel in this article.

The IMO has published studies assessing current GHG emissions from shipping and projections of future emissions. In the latest study [134] the term e-fuels was not mentioned but use of hydrogen, ammonia, synthetic methane, synthetic methanol and synthetic ethanol were considered with estimated costs between 3 and 11 times higher than for heavy fuel oil (9 USD/GJ).

A future European energy system including the maritime sector (and deep sea shipping) is analyzed in Blanco *et al* [45] and Blanco *et al* [55]. They found that liquid fuels, such as biofuel and e-fuels, are used in greater amounts when more biomass is available. In terms of e-methane, Blanco *et al* [55] noted that fuel choice for marine transport is highly influenced by fuel price and efficiency and the industry may find liquefied e-methane attractive. Connolly *et al* [62] presented a scenario for a fully renewable energy system in Europe by the year 2050 where half of the fuel demand in the shipping sector is assumed to be met with e-fuels in the form of DME and methanol (also for heavy-duty road vehicles and aviation).

Lester *et al* [91] analyzed the introduction of e-fuels to the Danish energy system and in their base case suggested that the maritime sector would prefer biofuels or ammonia if import of biomass is restricted. E-fuels are primarily produced in connection with biomass production and mostly used in the road sector. In contrast, Connolly *et al* [62] analyzed a scenario where e-fuels are the main choice for decarbonizing the transport sector and concluded that replacing conventional fossil fuels in trucks, ships, and aircraft increases the total cost of the energy system by around 3%. Lehtveer *et al* [9] found that e-fuels are cost-effective for reducing GHG emissions in transport when CCS is not a large-scale technology, but to what extent e-fuels are introduced in the shipping sector is not mentioned.

5.2. Cost estimates

All e-fuel options are considerably more expensive than the existing fuels used in shipping [27, 134], see also figure 4. This may be a reason why they have not been extensively discussed yet. The e-fuel options are also indicated by Korberg *et al* [27] to be more expensive than their corresponding biofuels.

Figure 5 shows the estimated near-term mobility cost (representing annual operation cost) for two ship types, a large ferry and a container ship, using propulsion system cost, fuel consumption data, and FDC from Korberg *et al* [27] and near term FPC data from Grahn *et al* [6]. Fuel production is the largest contributor to the annual mobility cost for both ship types. Bio-e-fuels have lower mobility cost than stand-alone e-fuels. The least cost options are, bio-e-methanol ICE, bio-e-DME ICE, bio-e-LMG ICE and battery electric propulsion (BE) for the large ferry category, and bio-e-methanol ICE, bio-e-methanol FC, bio-e-DME ICE, and bio-e-LMG (biogas) ICE for the container ship category (for which battery-electric solutions is not an option). Compared to road-transport even larger incentives are needed for the shipping sector to make e-fuels cost-competitive compared to conventional marine fuels.

The carbon abatement costs estimated for the different included e-fuels for shipping are 150–1250 € tonne⁻¹ CO₂ (see figure 4), slightly higher than for road transport. For comparison the estimated carbon abatement cost for liquefied hydrogen in shipping is 220–850 € tonne⁻¹ CO₂. For large ferries, e-bio-methanol has the lowest carbon abatement cost (150–810 € tonne⁻¹ CO₂). The carbon abatement cost for the battery-electric large ferry is 410–890 € tonne⁻¹ CO₂. The large spread of carbon abatement cost for the methane-based fuels are to some extent caused by the methane slip from marine ICE engines, but also by larger fuel distribution and onboard storage costs. The carbon abatement cost for the bio-e-fuels could increase if biomass associated with higher life cycle GHG emissions due to for example direct and indirect land-use change are considered.

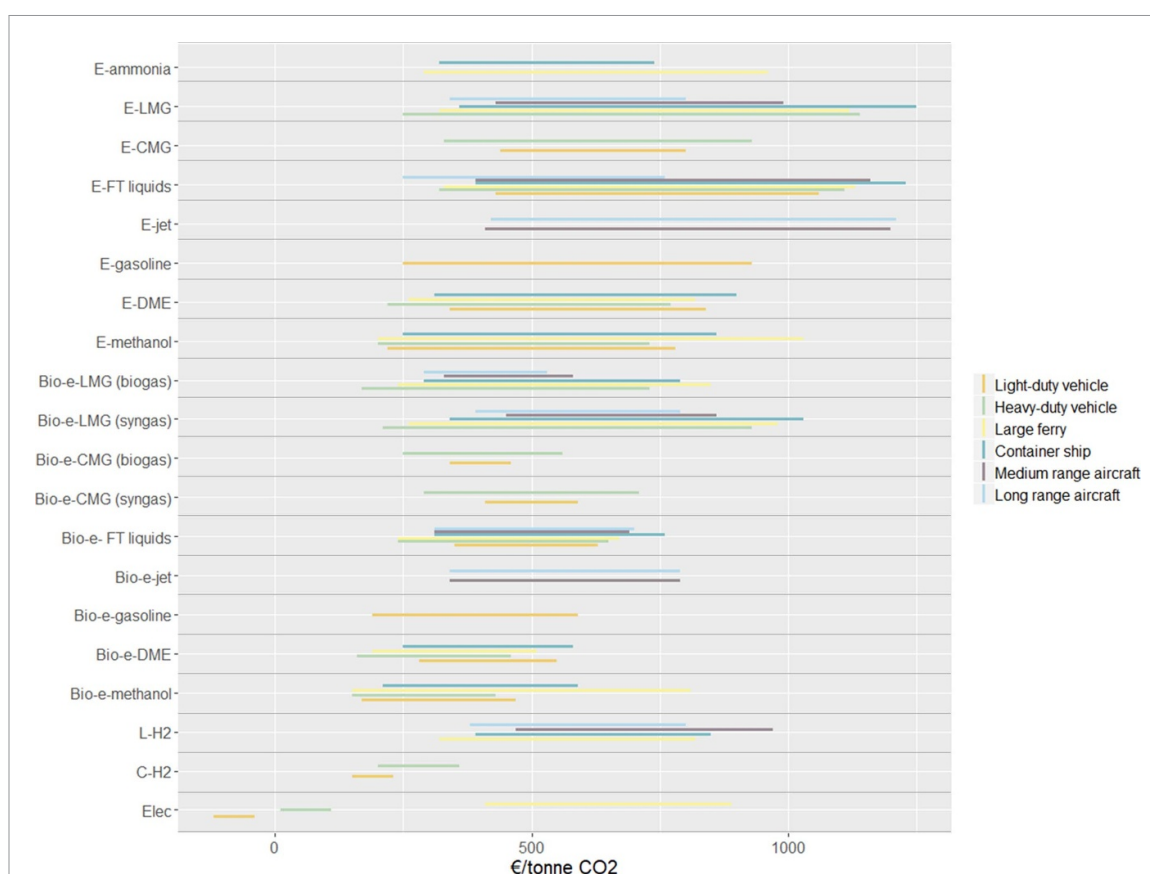


Figure 4. Ranges of estimated carbon abatement cost (€ tonne⁻¹ CO₂) for e-fuels, bio-e-fuels, compressed and liquid hydrogen, compressed methane, and battery electric for road (light-duty and heavy-duty), ocean (large ferry and containership) and air transport (medium-range and long-range aircraft) given the assumptions made.

6. E-fuels for air transport

The aviation sector has recently shown a considerable interest in low GHG fuel solutions [150]. The International Air Transport Association has committed to reduce 50% CO₂ emissions from aviation by 2050 and achieve carbon-neutral growth from 2019 [151, 152]. To achieve these goals, low or zero emitting alternative aviation fuels, such as hydrogen, e-fuels, or biofuels are required [67, 93]. The main options for low GHG fuels in aviation include bio-jet fuels, hydrogen in jet engines (or possibly fuel cells), battery-electric propulsion, and e-fuels. Fully battery-electric propulsion is considered for short range aircraft, while hybrid propulsion is discussed for all ranges [26].

6.1. Publications involving air transport

A total of 37 studies (42 including conference proceedings) addressing e-fuels for the aviation sector at least at a basic level of specificity were identified (table 9). Some studies [67, 72, 117, 126, 153] focused mainly on the techno-economic perspective, resource assessment, and combustion properties of e-fuels for aviation, while the other studies focused either on scenarios and the demand of e-fuels for aviation in the future transportation system or represent feasibility studies. One study [72] reported physical and combustion properties of e-fuels in aircraft engines and a few studies also included discussion of the environmental aspects related to production of e-bio-fuels for aviation [93, 116, 117].

E-fuels for aviation can be used in two ways; either in modified jet engines (e.g. e-jet fuels) or in fuel cells [72, 154]. Depending on the types of e-fuels, different modifications of conventional jet engines may be needed. The most commonly considered e-fuels for aviation in the literature is e-jet fuel produced from FT synthesis [67, 155]. Other e-fuels discussed for use in aircraft include methanol-to-jet (MTJ), liquefied methane, and n-octane produced via all-electrochemical synthesis processes (also liquefied hydrogen produced via water electrolysis is discussed but not considered an e-fuels in this paper) [72, 117, 153]. Goldmann *et al* [72] also mention ammonia as a possible e-fuel option for aviation but it can only be used in combination with a fuel that facilitates the ignition in aircraft engines, e.g. hydrogen.

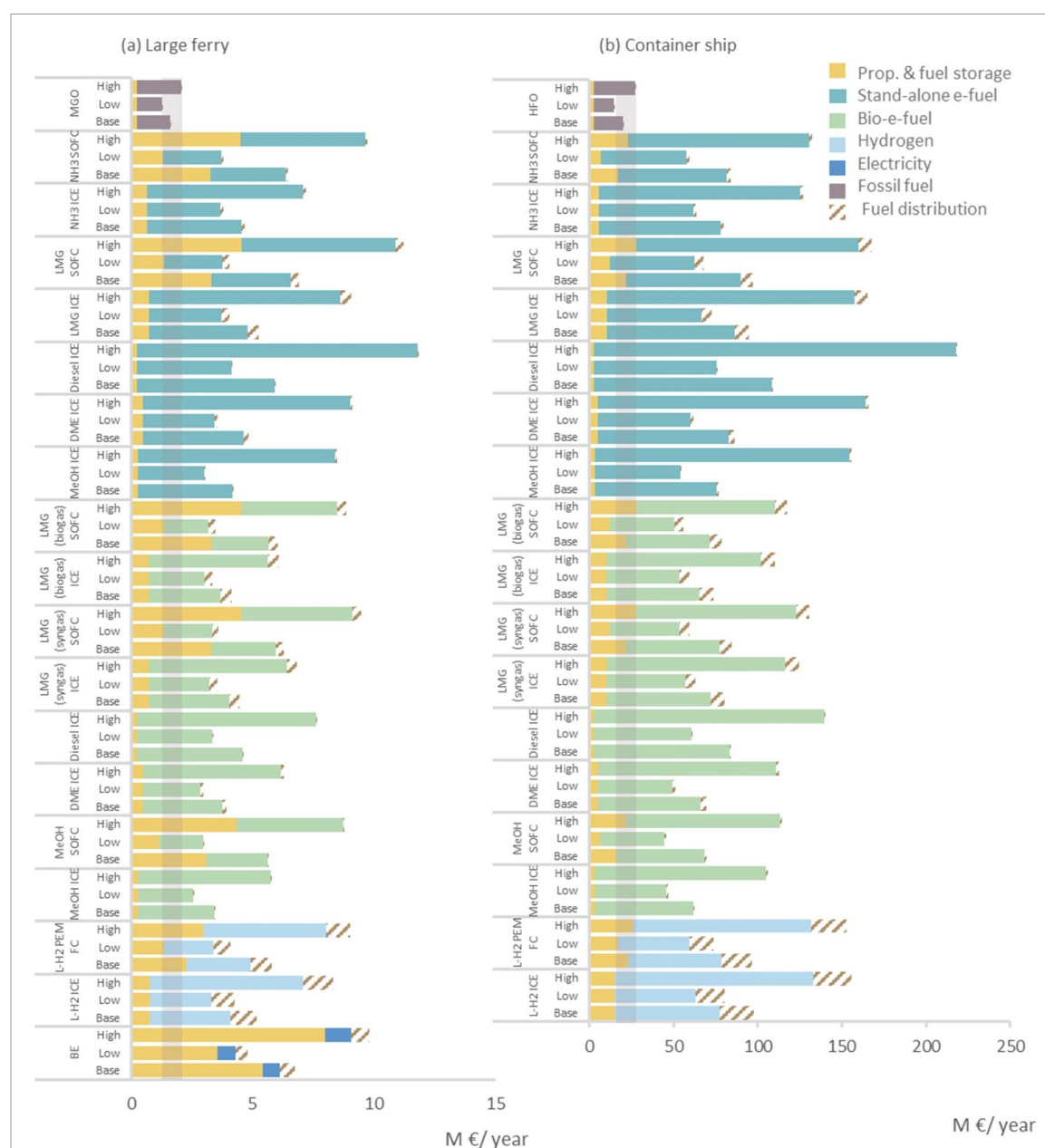
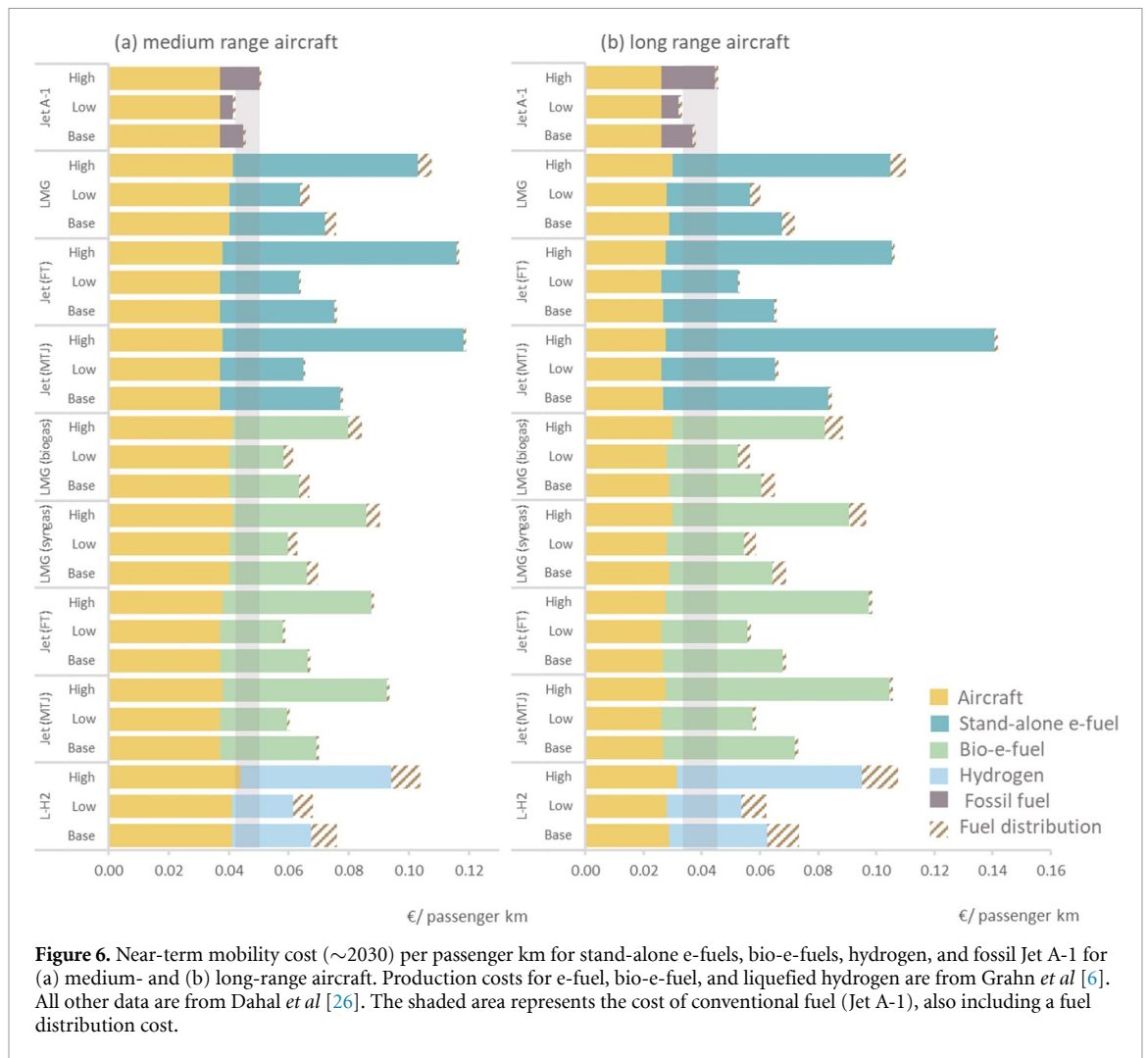


Figure 5. Near-term mobility cost (~ 2030) for different stand-alone e-fuels, bio-e-fuels, hydrogen, battery-electric (BE) and marine gas oil (MGO) for (a) large ferry with 1260 h of annual operation and 6 h between bunkering and (b) container ship with 5280 h of annual operation and 480 h between bunkering. Production costs for e-fuel and bio-e-fuel were taken from Grahn *et al* [6] all other data were taken from Korberg *et al* [27] considering a 3% discount and technical lifetimes for the components. The shaded area represents the cost of the conventional fossil alternative (MGO ICE, HFO ICE), also including a fuel distribution cost.

Malins [93] estimated that meeting 50% of aviation energy demand in the EU in 2050 by e-fuels in the form of e-kerosene would require a 25% increase in EU electricity generation. Also Connolly *et al* [62] present a scenario for the energy system in Europe by the year 2050 where half of the fuel demand in the aviation sector is assumed to be met with e-fuels in the form of DME and methanol (which is also the case for heavy-duty road vehicles and shipping). In the scenarios for the EU in 2050 in Blanco *et al* [45] e-jet fuels are introduced only in the case when CCS is limited and in some cases supports 60%–90% of total jet fuel demand. Mortensen *et al* [99] performed a feasibility study on sustainable aviation fuels for 2030 including an estimation of the supply potential for 2025 and a scenario for e-fuels introduction supplying 2%–3% of the Nordic aviation demand in 2050.

Drünert *et al* [67] assessed e-jet FPCs, the CO₂ resources needed, and the electricity demand for a range of cases for e-jet fuels to be introduced in the German aviation sector in 2030 and 2050. They found that local CO₂ point sources may be insufficient to produce the large-scale e-kerosene usage in aviation in 2050. Lester *et al* [91] considered e-fuels in the 2050 Danish energy system which outlines that e-jet fuels, including bio-e-jet fuels will be needed for fulfilling the aviation demand, in Denmark 2050. Cantarero [57] presents



scenarios for the future transport sector in Nicaragua including one where aviation (and HDVs) is expected to use e-fuels at large-scale.

E-jet fuel derived through the methanol pathway consists of more than 90% iso-paraffins which have good cold flow properties for aircraft engines [153]. The authors in [72] reported that except for electro-n-octane (e-n-octane), other e-jet fuels are not compatible in existing jet engines due to the differences in combustion properties compared to Jet A-1 [72]. The main drawback of e-hydrogen and other e-fuels, such as e-methane, and e-ammonia, is their low volumetric energy densities, which require larger, and high pressure or cryogenic, tank systems and modifications to fuselage, engines as well as the fuel supply system of the aircraft [72].

It can be interpreted that e-jet fuel via the FT pathway would not need to be newly approved by American Society for Testing and Materials (ASTM) since the FT pathway has been certified for blend-in of 50% FT-based fuels and given that the e-jet fuel meets the chemical and physical specifications for blending with conventional jet fuels [156]. Nevertheless, the e-jet fuel produced via methanol pathway, needs prior approval according to ASTM D7566 for use in commercial aviation according to ASTM D7566 [153]. A few studies have discussed the CO₂ impacts of e-jet fuels [67, 153, 157].

6.2. Cost estimates

Six studies covered e-jet FPCs via techno-economic analysis [26, 67, 99, 117, 153, 155]. Schmidt *et al* [117] showed that the production cost of e-jet fuel produced via the FT pathway is higher than the methanol pathway. Dahal *et al* [26] estimated the direct operating cost of eight aircraft concept designs with seven fuels (including e-jet, liquefied e-methane, and liquified hydrogen among the options). Figure 6 shows the estimated near term mobility cost (operating cost per passenger kilometer) for medium range and long range concept aircraft using FPC from Grahn *et al* [6] while all other data for calculating the direct operating costs are from Dahal *et al* [26]. For the two aircraft types studied, the least cost fuel options are bio-e-LMG (biogas) and bio-e-jet fuel (both via FT and MTJ). For medium range aircraft all e-fuels and bio-e-fuels are

less costly than the hydrogen option while for long range aircraft the hydrogen option is less costly than some of the e-fuels (FT and MTJ e-jet fuel pathways).

The carbon abatement costs for the different included e-fuels for aviation are in this study estimated to be 250–1210 € tonne⁻¹ CO₂ (see figure 4). For all e-fuels and bio-e-fuels, except the LMG options, the carbon abatement cost is lower for the medium range aircraft than LR.

7. Prospects and challenges for different e-fuels

What are the prospects for different e-fuels and do the feasibility of different e-fuels vary between transport modes? From an overall perspective, factors to consider when assessing e-fuels and other transport fuels for different transport modes include GHG emissions and costs as well as other factors such as availability of a distribution infrastructure, impacts on vehicle/vessel/aircraft capability, and other emissions. Costs included in this study cover vehicle on-cost (i.e. additional cost above vehicles using conventional fuels), FPC (which includes costs for electricity, carbon source if applicable, operation and maintenance costs, annuitized capital costs for the production plant), and costs associated with distribution and refueling infrastructure.

From the literature review it is not possible to more specifically conclude which e-fuels are most attractive for each transport mode. However, in terms of the most promising e-fuels for each transport mode, a recent overview of challenges and possibilities for decarbonization of heavy-duty road transport, shipping and aviation by Gray *et al* [8] identified methanol and e-methane as the most promising options in shipping in the near term while hydrogen and ammonia may contribute in the long term. This is similar to the findings in the present study which from a cost perspective find e-methanol and liquid e-methane most cost-effective for short-range sea shipping and these fuels and ammonia for deep-sea shipping (see table 10). Liquid e-methane could potentially continue from the current use of LNG in shipping. For light-duty road transport, the cost comparisons in this study find different liquid e-fuels including liquefied methane to be lowest cost (for the given assumptions) and for heavy-duty road transport liquid e-fuels and e-DME. Some more details about the prospects for different e-fuels are presented below.

7.1. Liquid e-fuels

Liquid e-fuels are in general hindered most by higher FPCs and criteria emissions (e.g. PM, NO_x, CO, unburned hydrocarbons) compared to gaseous fuels (such as e-methane, and e-DME but also H₂) and direct use of electricity. E-gasoline, e-diesel, and e-jet fuel have an advantage over other e-fuels because they are fungible with existing fuel and hence compatible with existing vehicles and fuel distribution systems. Their high energy density means fewer impacts on vehicle capability (long range, rapid refueling) and the least impact on vehicle volume and mass as compared to BEVs and gaseous fuels [158]. These aspects are not fully covered in the cost comparison in this study. However, e-gasoline and e-diesel are the most complex and costly e-fuels to synthesize and their production has the highest demand for renewable electricity (on a per km traveled basis) [5, 159]. Due to this and the low cost of fuel distribution relative to fuel production (Holmgren *et al* [34]; Lönnqvist *et al* [160]), these fuel options, as indicated in figures 3–5, end up in the higher mobility cost range of all the e-fuels in this study. In addition, gasoline-range and diesel-range hydrocarbons, regardless of origin, produce criteria emissions during combustion. Despite advances in engine and aftertreatment technology and large reductions in criteria emissions, the stringency of future emission regulations and zero-emission vehicle (ZEV) mandates pose challenges for ICE vehicles using e-fuels [161, 162].

E-methanol (mainly discussed for ocean transport) and other liquid e-fuels containing oxygen share many of the advantages and disadvantages of e-diesel and e-gasoline but would require a new (or at least modified) distribution and refueling system. While they are relatively simple to distribute, dispense, and use in vehicles, there is no established distribution system or fleet of methanol-capable vehicles in use today.

7.2. Gaseous e-fuels

Gaseous e-fuels such as e-methane, e-DME, and e-propane each have unique considerations as they must be compressed or liquefied for efficient storage on the vehicle. DME and propane are liquefied through mild compression [163], whereas methane can be stored as high pressure gas or liquified (e.g. for heavy-duty road, ocean and aviation transport to increase energy density). Fuel distribution is complicated by the additional equipment needed to distribute, compress, and dispense these fuels. Likewise, fuel handling and storage on the vehicle are complicated by the higher pressure and greater fuel storage system volume and mass. While compressed methane has high energy density relative to battery electricity storage [48, 92, 164–166], it has lower energy density than liquid and liquefiable e-fuels [18, 167].

Methane, however, is already a well-established alternative fuel for road transport, mainly for heavy-duty applications [168]. One advantage of e-methane, at some locations, is that the current natural gas

distribution networks, seasonal storage caverns, and vehicles could be used. Regardless of the methane source, its high global warming potential (about 30 times that of CO₂ for a 100 year timeframe) means that leakage must be tightly controlled in all phases of production, distribution, and use to achieve a substantial GHG emissions benefit [169–171]. This is valid regardless of transport mode.

By comparison, compressed hydrogen requires fewer steps to produce than different e-fuels but is not yet well established as a transportation fuel. H₂ in ICEVs, relying on well-established IC engine technology, could potentially serve as a nearer-term bridge technology to FCEVs [159]. In the long term, FCEVs have advantages in terms of higher efficiency and by avoiding the NO_x emissions of H₂ ICEVs [172]. For aviation, jet engines that can run on hydrogen are under development [26].

7.3. Criteria emissions

E-fuels do not directly address desires for continued reduction in criteria emissions from their combustion in ICEs [46]. Despite advances in engine and aftertreatment technology and large reductions in criteria emissions, the stringency of future emission regulations and ZEV mandates pose challenges for ICE vehicles using e-fuels [161, 162]. While e-gasoline and e-diesel might have a minor criteria emissions benefit by reducing the content of aromatic hydrocarbons and olefins, the non-conventional e-fuels may offer various degrees of opportunity for criteria emissions reduction albeit with uncertainties. Methanol, methane, DME, and H₂ are attractive in that they tend to form very little particulate matter (PM) but particle number could still be a constraint [114, 172]. The primary criteria emission for H₂ combustion is NO_x. E-fuels also may have lower sulfur content than conventional fossil fuels, reducing SO_x emissions and catalyst poisoning in aftertreatment systems. This may be particularly beneficial for ocean transport which currently uses bunker fuels with high sulfur content [24]. By limiting the number of pollutants that need to be controlled, aftertreatment may potentially be simplified, made more effective and/or reduced in cost.

Given that vehicles powered by e-fuels in IC engines would have some criteria emissions in their exhaust, these vehicles would not meet most current definitions of a ZEV. For example, the California Air Resources Board defines a ZEV as a one that ‘produces no emissions from its on-board source of power’ [173]. There is discussion that e-fuel vehicle emissions might be sufficiently low as to have no adverse environmental or human health impact and could, therefore, be labeled a ‘zero-impact emission vehicle’ and hence be considered as acceptable as a ZEV [161, 174]. For example, H₂ ICEVs receive a partial ZEV credit in California [175].

Marine (IMO) regulations for criteria pollutant emissions are less strict than for road transport and it should be possible to comply with the stricter NO_x regulations with most e-fuels at least in combination with exhaust abatement technologies in marine applications [156].

8. Policy and regulations

Policies are crucial for the introduction of e-fuels, regardless of transport mode. What is the status of policy instruments linked to e-fuels and does the support differ between transport modes? Policy and regulations linked to e-fuels are described in this section from an EU perspective. Until the Renewable Energy Directive (RED II Directive), published at the end of 2018 and implemented into the national law of the EU Member States in mid-2021 [176], e-fuels were not promoted as such within the EU alternative fuel policies. The RED I Directive [177] mostly involves direct use of hydrogen and implementation of biofuels for reaching the European 2020 targets, likely because this pre-dates the demonstration of e-fuel technologies.

The European strategy on clean and energy-efficient vehicles, published in 2010, recognized only liquid biofuels and gaseous fuels (LPG, CNG and biogas), hydrogen fuel cell vehicles and electric vehicles [178]. E-fuels are not recognized as a means of CO₂ reduction, nor recognized by monitoring or reporting regulations of the Emission Trading Scheme [179]. CO₂ based renewable fuels are incentivized in Germany by the Indirect Land Use Change Directive as a part of their national targets [180].

In principle, the still acting Fuel Quality Directive from 2009 [181] allows for CO₂ based fuels to contribute to the emission reduction targets. However, in the case of fuel blends and petrol vehicles the directive puts restrictions on some liquid e-fuels, such as methanol and ethers (containing five or more carbon atoms), as oxygenates for petrol, and can only be blended to a maximum of 3% and 22% respectively (not requiring vehicle alteration). According to the European Green Deal [182] a set of new policies for sustainable alternative fuels for the different transport modes would be published between 2020 and 2021 [183] that will follow up on the RED II.

According to the RED II directive, ‘Renewable fuels of non-biological origin’ are inclusive of e-fuels originating from carbon emissions with the likely exception of biogenic CO₂. E-fuels of non-renewable origin, from waste processing gas or exhaust gas, named ‘recycled carbon fuels’ (Article 2.35), are not defined as renewable fuels but may be included for fulfilling the renewable energy targets in the transport sector

(Article 25). To define e-fuels of non-biological origin as renewable, the energy content derived must come from renewable sources other than biomass (Article 2.36), and it is unclear in what category the recycled carbon fuels from biomass fired power plants belong. As an interpretation of the RED II Directive, e-fuels with biological origin can be recognized as advanced biofuels, which could be debated and possibly confusing in the implementation phase. This confusion could delay industrial investments regardless of transport mode as it is up to Member States to decide their positions.

In terms of the origin of electricity, Article 27 states that to be defined as renewable liquid and gaseous transport fuels of non-biological origin, the electricity needs to be defined as fully renewable. For e-fuels this means that the electricity used needs to be counted as fully renewable, and if from the electricity grid it may be claimed once and only in one end-use sector. It is, however, left unclear what is the case of the advanced biofuels with hydrogen addition, which according to the definition used in [184] also are e-fuels from biological origin.

RED II further requires that e-fuel production units are connected directly to renewable electricity generation units (wind turbines, solar etc) and not to the grid (Article 27). This restricts the opportunities of e-fuels as a storage agent or as a means to manage intermittency. Furthermore, it also restricts the e-fuel production units from being connected to already existing renewable energy installations. Finally, RED II indicates that e-fuel producers are requested to add to the renewable deployment or finance renewable energy production.

In the recent revision of the RED II directive, published in July 2021, few additions on e-fuels were added. The electricity used to produce renewable fuels of non-biological origin should not be counted in the share of the renewables, to avoid double counting. The target of 2.6% share of renewable fuels of non-biological origin in 2030 was introduced and multiplier factors are proposed to promote the use of these fuels for marine and aviation modes (1.2 times their energy content). Thus, the use of e-fuels for air and sea transport is proposed to be specifically promoted.

Overall, it is unclear how e-fuels would count towards the renewable EU target in transport, on the basis of the final energy or on the basis of the renewable electricity input, which results in quite different contributions. The recent proposal is that it is on the basis of final energy. The more specific methodology for assessing GHG emissions savings for recycled carbon fuels proposed by the EU Commission does not differ between transport modes.

The Energy System integration strategy and Hydrogen strategy for a climate-neutral Europe, both published in July 2020, propose a comprehensive terminology for all renewable and low-carbon fuels and a European system of certification. This initiative is highly needed to bring more clarity into the policy framework of e-fuels. Moreover, the promotion of the use of renewable fuel of non-biological origin is fully in line with these strategies.

In terms of shipping, e-fuels are like other marine fuels considered in the proposed Fuel EU Maritime which if implemented may promote the introduction of alternative marine fuels [44, 185].

9. Discussion

There are several e-fuel reviews (e.g. Brynolf *et al* [5], Grahn *et al* [6], Ababneh and Hameed [28], Ince *et al* [29]), but this is the first study (to our knowledge) which analyses the different situational applications within transport and connects the analysis to policy implications.

In recent years, there are more studies investigating the potential use of e-fuels for road-based transport compared to aviation followed by ocean shipping. However, due to the efficiency relationship to other options, e-fuels would be expected to first target sectors that are difficult to electrify such as long-distance ocean and air transport [7]. On the other hand, the cost and carbon abatement cost for e-fuels are lowest for light duty vehicles, since the vehicle cost represents a larger fraction of that cost (which is due to generally lower utilization of light duty vehicles). The upper span for the carbon abatement cost is rather similar for all transport options investigated in this study and are driven by the high e-FPC assumed in the high cost scenario. The somewhat larger research interest in e-fuels for aviation than for ocean transport is likely because there are few other low-carbon options for aviation. Though, the need to decarbonize the entire transport sector in general, not only long-distance transport, is used in many studies to motivate the investigation of e-fuels as a potential option. In some studies, the need for e-fuels is taken for granted and the focus is on possible production pathways and associated costs rather than exploring the potential for e-fuels for a specific application. This article tries to make an overall review of the studies that specifically investigate the potential role of e-fuels in the transport sector.

The literature contains a wide range of scenarios suggesting different future roles of e-fuels for different transport modes, from no use to scenarios where e-fuels supply the majority of future demand in several transport modes. In reality, the cost development for e-fuels and competing fuel options as well as several

Table 10. Selected key aspects for the prospects of e-fuels for different transport modes.

	Road transport		Ocean transport		Air transport	
	Light-duty	Medium and heavy-duty	Costal, inland waterway and short sea	Deep sea	Short-range	Medium- to long-range
Main alternative propulsion options considered	BEV, H ₂ FCEV, biofuels and e-fuels ICEV	BEV, H ₂ FCEV, biofuels and e-fuels ICEV	BE, LNG ICE, biofuels ICE, H ₂ ICE/FC, e-fuels ICE/FC	Biofuels, LNG ICE, H ₂ ICE/FC, ammonia ICE/FC, e-fuels ICE/FC	BE, bio-jet, e-jet, H ₂ -jet/FC	Bio-jet, e-jet, (H ₂ -jet for Medium-range)
Most promising type of e-fuels from the cost-perspective in this study (e-fuels including bio-e-fuels)	Liquid e-fuels and CMG	Liquid e-fuels and e-DME	E-methanol, liquid e-methane (to replace LNG), e-DME	E-methanol, e-ammonia, e-DME	<i>Not assessed</i>	E-jet, liquefied e-methane
Potential role of e-fuels	Niche segments	All segments (especially long-range)	Niche segments	All segments	All segments ^a	All segments

^a The development of electric aircraft might challenge this.

other factors will influence the prospects for e-fuels. Table 10 summarizes some key aspects for the prospects of e-fuels for different transport modes, including e.g. the main competing options, most promising e-fuel types for different transport modes, and suitable segments for each transport mode.

For an e-fuel solution to be adopted, it needs to be sufficiently attractive compared to the other available options for the specific transport mode when considering all relevant factors. E-fuels may be of interest for all segments for aviation, for deep sea shipping and for heavy-duty road transport while for light-duty road transport and short and regional shipping where electrification is being implemented, e-fuels may be more relevant for niche segments. For road transport, and despite continuing reductions in road vehicle emissions and requirements, criteria emissions may still be an important obstacle for e-fuels.

For road transport, the disadvantage for e-fuels which cannot take advantage of the existing fuel infrastructure might be exacerbated by the current and planned rise of electric vehicles [186] as the use of such an e-fuel would require the development and deployment of an additional fueling infrastructure for this sector. Compared to retail customers in road transport, infrastructure challenges are lower for commercial users using dedicated fleets with home bases and/or dedicated routes. Uptake by commercial users may offer a mechanism enabling use of e-fuels which are incompatible with the existing infrastructure, but such e-fuels might struggle to attain economies of scale. In general, the cost assessment in this study does not fully capture the advantage for e-fuels that use existing infrastructure (diesel, gasoline, and jet type e-fuels) as it does not capture the chicken and egg problem linked to investment in new infrastructure but mainly focuses on the future mature case where there is large-scale use of e-fuels and needed infrastructure.

Ueckerdt *et al* [7] suggest a merit order should prioritize the use of hydrogen and e-fuels in sectors that are hard to abate and/or impossible to electrify such as chemical feedstock, primary steel production and long-distance aviation and shipping. From a general perspective it is possible that the viability of e-fuels in one sector may lead to greater viability in other sectors due to lower FPCs, acceptance, etc. Given the long lifetimes of the existing road vehicle, ship, and aircraft fleets and the urgency of addressing climate change, the use of drop-in e-fuels (such as e-diesel, e-gasoline, and e-jet fuel) might be a required element in a portfolio of actions to reduce transportation GHG emissions.

E-fuels, H₂, and battery-electric solutions will all require substantial increases in renewable power generation, with e-fuels followed by H₂ requiring the most power for an equivalent amount of propulsion (e.g. e-fuel ICEVs use about 3–5 times more electricity than BEVs). Renewable electricity may become a constrained resource if needed in every sector. With carbon pricing, e-fuels may be outpriced by more economically efficient uses of renewable electricity such as H₂ FCEVs, BEVs and electrified short-range aircraft and shipping or by fossil fuels with CCS [9, 46]. Applications demanding high energy density fuels,

whether to minimize the impact on vehicle range, payload, or refueling time, are intangibles that increase the attractiveness of e-fuels for certain applications.

Another potential challenge for e-fuels for transport is the renewable CO₂ needed. Hansson *et al* [77] estimated the amount of CO₂ needed to produce e-fuels for Swedish national shipping as well as for other transport modes and concluded that availability of renewable CO₂ was not a limiting factor in Sweden. However, this might not be the case in all countries. Over a longer-time perspective DAC of carbon may be an interesting option.

Combined biofuels and e-fuels are limited by the amount of sustainable produced bioenergy, where biomass waste flows as assumed in this study are even more limited (for example estimated to 10–66 EJ agricultural residues, 3–35 EJ forestry residues and 12–120 EJ waste in a review of 90 studies by [187]). For a specific 2050 estimate of available bioenergy see for example Staples *et al* [188].

Policy instruments will be a key factor for the prospects for e-fuels for all transport modes. Additional regulatory approaches and in some cases changes to current ones seem needed before e-fuels will be used at scale in any transport mode. E-fuels should be allowed to compete with other mitigation options for different transport modes on a level playing field. Thus, transport CO₂ policies would need to be technology-neutral; for example, realization of potential bans for IC engines in the future might not allow for many of the solutions using e-fuels. Vehicle CO₂ regulations would need to change to a more holistic well-to-wheel basis, away from their current tailpipe basis [178]. With existing regulations, vehicle manufacturers see no regulatory benefit if their vehicles use e-fuels instead of fossil fuels, unlike the zero tailpipe CO₂ emissions assumed for BEVs or FCEVs [189]. While fuels in some regions are regulated for carbon intensity or renewable content (RED II, U.S. Renewable Fuels Standard, California Low Carbon Fuel Standard), success for e-fuels may require regulations with a well-to-wheel or cradle-to-grave basis (involving both vehicles and fuels). The higher cost of e-fuels will likely be an incentive to improve fuel efficiency and to use more efficient powertrains, e.g. PHEV [158].

This study assesses costs in 2030, but lower production costs of e-fuels are expected in the more long-term (around 2040–2050) assuming increased technical maturity and more large-scale implementation [6]. However, it is uncertain when e-fuels will reach maturity in the market.

How e-fuels should be handled within RED II also needs to be clarified [93, 189]. Other necessary changes may include allowances for new fuel compounds or properties associated with non-conventional fuels, e.g. higher oxygen content [132]. Finally, ZEV mandates may need to be modified to allow for ICE vehicles running on e-fuels with ‘zero-impact’ tailpipe emissions [161, 162]. Also, the outcome of the ongoing discussion about if a well-to-wake or tank-to-propeller perspective should be used when regulating GHG emissions from shipping within the IMO will be important for the prospects of e-fuels in ocean shipping.

Finally, future e-fuel studies should focus on the transport modes that are more difficult to abate and assess which e-fuels are best suited for aviation, long-distance shipping and long-distance heavy-duty road transport from a sustainability perspective covering costs, environmental performance (not only GHG emissions) etc.

10. Conclusions

The potential of e-fuels as a means to decarbonize the transport sector is being increasingly discussed in the literature, for long-distance road, ocean, and air transport. More studies have addressed e-fuels for the road transport sector (often considering both light-duty and HDVs) than aviation and shipping (the latter being least explored). There are some recent studies comparing e-fuels with other options for some transport modes [26, 27] however, there is still a need for more detailed studies for all transport modes as some of the options are under development.

This study highlights that different e-fuels are discussed and to some extent more promising for different parts of the transport sector, that the carbon abatement cost for e-fuels is sensitive to assumption about e-FPC as well as vehicle cost, and that e-gasoline and e-diesel end up in the higher mobility cost range of all the e-fuels for both road and ocean transport when infrastructure cost is considered. It also shows that bio-e-fuels (i.e. combined biofuel and e-fuels production) produced from biomass waste flows and renewable electrolytic hydrogen (assumed to have no or low impact on direct and indirect land use change) are more cost-competitive than stand-alone e-fuels production.

The literature contains a wide range of scenarios suggesting different future roles of e-fuels for different transport modes, from no use to scenarios where e-fuels supply most of the future demand in several transport modes. There are many uncertainties in terms of production costs and environmental performance, making it too early to rule out, or strongly promote, particular e-fuels for different transport modes.

For e-fuels to play a significant role in transportation, their relative attractiveness compared to other transport options needs to be improved which will involve multiple stakeholders and regulatory considerations. Policy instruments will be critical. Incentives will be needed for e-fuels to be cost-effective in the near- to mid-term in most cases, as for most other low-carbon transportation options (as long as there are not sufficient carbon policies for fossil fuels). Linked to this, increased clarity on how e-fuels are linked to existing and suggested policies such as the RED II is called for. In practice, the feasibility of e-fuels for different transport modes will depend on, e.g. the development of competing fuel options, renewable electricity production, implementation of CCS, biomass availability, and policies.

Author contributions

S B, conceptualization, writing—original draft, review & editing, visualization; J H, J E A, I R S, T J W: conceptualization, writing—original draft, review & editing; M G, A D K, E M, M T: writing—review & editing.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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