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Original research article

Renewable hydrogen and synthetic fuels versus fossil fuels for trucking, shipping and aviation: A holistic cost model

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ABSTRACT

Potential carbon neutrality of the global trucking, shipping and aviation sectors by 2050 could be achieved by substituting fossil fuels with renewable hydrogen and synthetic fuels. To investigate the economic impact of fuel substitution over time, a holistic cost model is developed and applied to three case studies in Norway, an early adopter of carbon-neutral freight transport. The model covers the value chains from local electricity and fuel production (hydrogen, ammonia, Fischer–Tropsch e-fuel) to fuel consumption for long-haul trucking, short-sea shipping and mid-haul aviation. The estimates are internally consistent and allow cross-mode and cross-fuel comparisons that set this work apart from previous studies more narrowly focused on a given transport mode or fuel. The model contains 150 techno-economic parameters to identify which components along the value chains drive levelized costs. This paper finds a cost reduction potential for renewable fuels of 41% to 68% until 2050, but carbon-neutral transport will suffer asymmetric cost disadvantages. Fuel substitution is most expensive in short-sea shipping, followed by mid-haul aviation and long-haul trucking. Cost developments of electricity, direct air capture of carbon, vehicle expenses, and fuel-related payload losses are significant drivers.

1. Introduction

Achieving carbon-neutrality by 2050 represents a significant challenge for global trucking [4], shipping [5] and aviation [6] sectors. Unlike the continuous improvements in battery storage technology for passenger and light-duty vehicles [7], only fossil fuels (fF) meet the considerable technical and economic requirements of most truck, ship and plane traffic [1]. Hence, with the regulatory banishment of greenhouse gas emissions (GHG) [8], there is widespread interest in using renewable hydrogen and synthetic fuels (hereafter summarized as renewable fuels or RF) [1,9]. The scope of this study excludes battery-electric propulsion and bio-fuels[1], focusing instead on the cornerstones of global hydrogen strategies [10]. Produced from renewable energy sources, water, and optionally carbon dioxide or nitrogen captured from the atmosphere, the respective fuels are hydrogen (eH) [11], Fischer–Tropsch e-fuels (eF) [12] and ammonia (eA) [13]; the e stands for renewable, electricity-based fuels. E-fuel as a synthetic copy of today's mode-specific fossil fuels can be used in existing combustion engines, whereas hydrogen and ammonia depend on electrochemical conversion in fuel cells or adjustments in combustion engines and fuel tanks [1]. Considering trans-European freight transport, the most promising technical fuel pathways are eH and eF for long-haul trucking [1], eH, eA and eF for short-sea shipping [5,14] and eH and eF for mid-haul aviation [6,15,16]. The use of renewable fuels, however, is cost-intensive [9]. Climate targets propose to gradually increase the use of renewable fuels in truck, ship and plane transport [17], but uncertainty regarding future costs and competitiveness poses significant pressure on real-world decisions. Thus, this research focuses on the following critical questions: (i) What are the current and future costs of renewable fuels, considering the cost reduction potential along the value chains?, (ii) How does the cost structure of trucking, shipping, and aviation change with the integration of renewable fuels?, and (iii) How does the cost-competitiveness within and across transport modes change due to renewable fuel use? To analyze this, the paper proposes a techno-economic analysis using a holistic approach. The model estimates future costs of electricity, renewable fuels, and their use in selected transport applications while considering mode-specific cost data (Fig. 1). The analysis encompasses the cost reduction potential along the value chains and investigates the sensitivity to uncertain costs of electricity, carbon, vehicle technologies, and fuel-dependent payload losses. The competitiveness of renewable fuel use to varying cost levels

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[1] For the techno-economic potential of battery-electric trucking see [1,2], for bio-fuels in aviation see [3].

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List of abbreviations

€	Euro
η	Process efficiency
a	Years
AM	Annual vehicle mileage
Bh	Block hours
Capex	Capital expenditures
CC	Maximum cargo capacity
CO_2	Carbon dioxide
ct	Eurocent
eA	Electricity-based renewable ammonia
eF, e-fuel	Renewable Fischer–Tropsch electro-fuel
eH	Electricity-based renewable hydrogen
eEl	Renewable electricity
fF, f-fuel	Fossil-based fuel
Fix	Fixed
Flh	Full load hours
GHG	Greenhouse gas emissions
GWh	Gigawatt-hours
h	Hours
H_2	Hydrogen
HFO	Heavy fuel oil
kg	Kilogram
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hours
l	Liter
LCOD	Levelized cost of fuel delivery
LCODi	Levelized cost of fuel distribution
LCOE	Levelized cost of electricity
LCOEy	Levelized cost of electrolysis
LCOF	Levelized cost of fuel
LCOH	Levelized cost of raw hydrogen
LCOP	Levelized cost of fuel production
LCOR	Levelized cost of refueling
LCORe	Levelized cost of reactant
LCOS	Levelized cost of fuel buffer storage
LCOT	Levelized cost of transport
LCOTr	Levelized cost of fuel transformation
LCOV	Levelized cost of vehicle
$LCOX^i$	Levelized cost of an arbitrary process i
LH_2	Liquid hydrogen
LHV	Low heating value
m	Meters
M	Million
m^3	Cubic meter
MTOW	Maximum take of weight
N	Lifetime
N_2	Nitrogen
Opex	Operational expenditures
PEM	Proton exchange membrane
Q	Annual outcome quantity
R&M	Repair and maintenance
RF	Renewable fuels
t	Tonnes
TEU	Twenty-foot equivalent unit
UCRF	Universal capital recovery factor
ULRC	Underground lined rock cavern
UR	Utilization rate per vehicle
var	Variable
WACC	Weighted average cost of capital

of fossil fuels is also investigated. The model is adaptable to real-world scenarios, location-specific fuel production, and transport applications. The paper presents three real-world case studies for trans-European transport: long-haul trucking, short-sea shipping, and mid-haul aviation. Norway is chosen as a framework, with three selected locations for electricity production: onshore wind, offshore wind, and hydropower.

2. State-of-the-art and progress beyond

This section summarizes the scope of this work, giving an overview of relevant literature. It is divided into three sections: Section 2.1 focuses on models for future costs of renewable fuels, Section 2.2 on models for future transport costs, and Section 2.3 on the use of metrics for techno-economic assessment. Section 2.4 highlights this study's progress beyond the state-of-the-art.

2.1. Models to estimate future costs of renewable fuels

Existing research on estimating the costs of hydrogen and synthetic fuels, driven by renewable energy systems, varies in spatial resolution and considered time frames [18]. Studies range from analyzing individual plant operations [19,20] to supply chains on country-level [21] or global level [13]. They also consider different electricity sources and fuel types, including hydrogen [11], ammonia [13], e-fuels [12], or fuel portfolios [22]. Some studies focus on fuel production [11], while others also examine fuel conditioning [22], storage systems [23], and fuel distribution at domestic [21] or global [22] scales. Some studies analyze process costs independently [24] or optimize the interaction of components along the value chain [11,22]. However, cross-study comparisons of different fuel types and process resolutions are challenging due to divergent assumptions and model setups [18]. Extending the existing literature on costs of electricity generation, hydrogen, ammonia, and e-fuel production, conditioning, and distribution, the present study also covers the fuel supply in trucking, shipping, and aviation using a holistic approach. Following the methodical approach of [24], the study compares today's and future costs along the fuel value chains without optimizing the interaction of components. This choice is made as a compromise between the model's richness of process detail and its holistic nature.

2.2. Models to estimate future costs of carbon-neutral transport

Motivated by the need for comparing carbon-neutral transport costs with conventional transport costs and deriving policy implications for a successful energy transition, numerous studies explore this topic [9]. However, these studies vary in their system perspectives, considered time frames, and scopes. Some focus on international [25] or national [26] transport systems, while others examine costs on vehicle level [4]. Additionally, they analyze costs from present-day [4] to future projections [2]. Many studies concentrate on a single transport application such as trucking [4], shipping [5,26] or aviation [6,15,27] and evaluate the use of one [28] or several [29] fuel options. While certain studies focus solely on comparing cost differences in new tank and propulsion systems to the conventional benchmark [14], others take into account the vehicle's total cost of ownership [4], and some even consider the associated costs of refueling infrastructure [30]. However, to ensure reliable cost comparability across fuels and transport modes,

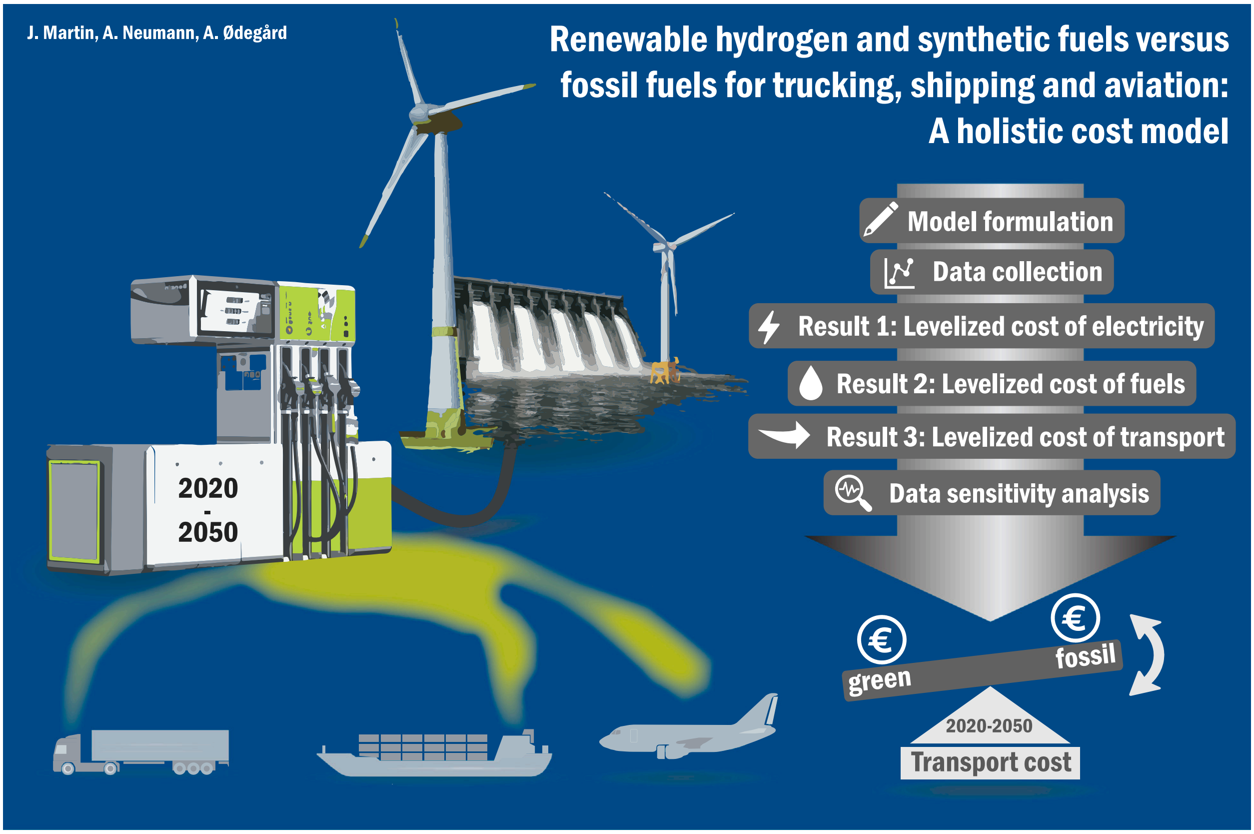

Fig. 1. Graphical abstract.

it is crucial to have uniform assumptions throughout the fuel value chain and its application to different transport modes [9]. This study takes a holistic approach, linking selected fuel and transport value chains, and investigates the impact of renewable fuel use on the cost-competitiveness of carbon-neutral transport in trucking, shipping, and aviation. Thus, it differs from previous literature in its comprehensive modeling approach and comparability.

2.3. Levelized cost metric and total cost of ownership

This study's methodological approach aligns with the existing literature on techno-economic analysis, specifically in the comparison of levelized cost of energy and total cost of ownership for various fuel and transport technologies.

Levelized cost metric: The levelized cost metric determines average electricity generation costs over a power plant's lifetime, considering all relevant life-cycle costs [31]. It is applied to various renewable energy technologies, including electricity generation [32,33], and extended to hydrogen [34], ammonia [13], and e-fuel production [12]. The metric is also used to assess individual process steps, such as vehicle charging [4] and direct air capture [35]. Horvath et al. [14] employ the metric to compare the levelized transport costs of different ship technologies.

Total cost of ownership: While the passenger car sector prioritizes capital expenditures (Capex) during the purchase process [36], the commercial sector focuses more on operational expenditures (Opex) due to high annual mileage and longer lifetimes [4]. The total cost of ownership analysis evaluates cost-competitiveness by considering the initial purchase cost and annual operating expenses throughout the vehicle's lifespan. Noll et al. [4] compare today's fossil-based total cost of ownership with carbon-neutral trucking for three truck types in selected European countries. Additionally, other studies explore potential cost changes over time to project future cost trends [2]. This study extends and applies these approaches to trucking, shipping, and aviation.

The cited references are not exhaustive in terms of work carried out in the field, but highlight the relevance of assessments in the context of this work's scope. They underscore the lack of holistic studies that estimate future costs of renewable fuels for transport in general and cross-mode comparisons for trucking, shipping, and aviation in particular.

2.4. Progress beyond state-of-the-art

The progress beyond the state of the art and thus the novelty of this work contributes in the following dimensions:

- Compiling 150 techno-economic parameters in a database for renewable electricity generation, fuel production and distribution, and for the total cost of ownership in long-haul trucking, short-sea shipping and mid-haul aviation.
- Development of a holistic cost model to compare levelized costs across fuels (hydrogen, ammonia and e-fuel), modes (trucking, shipping and aviation), and time (2020 to 2050).
- Evaluating the cost-competitiveness of carbon-neutral transport until 2050. The cost estimates are internally consistent and allow cross-mode and cross-fuel comparisons that set this work apart from previous studies on carbon-neutral transport more narrowly focused on a given transport mode or fuel.
- Investigating the sensitivity of transport costs to the main cost drivers along the value chain in a unique level of detail.

3. Methods and data

This section presents the methods applied in the present study, followed by the techno-economic data used. A graphical overview of

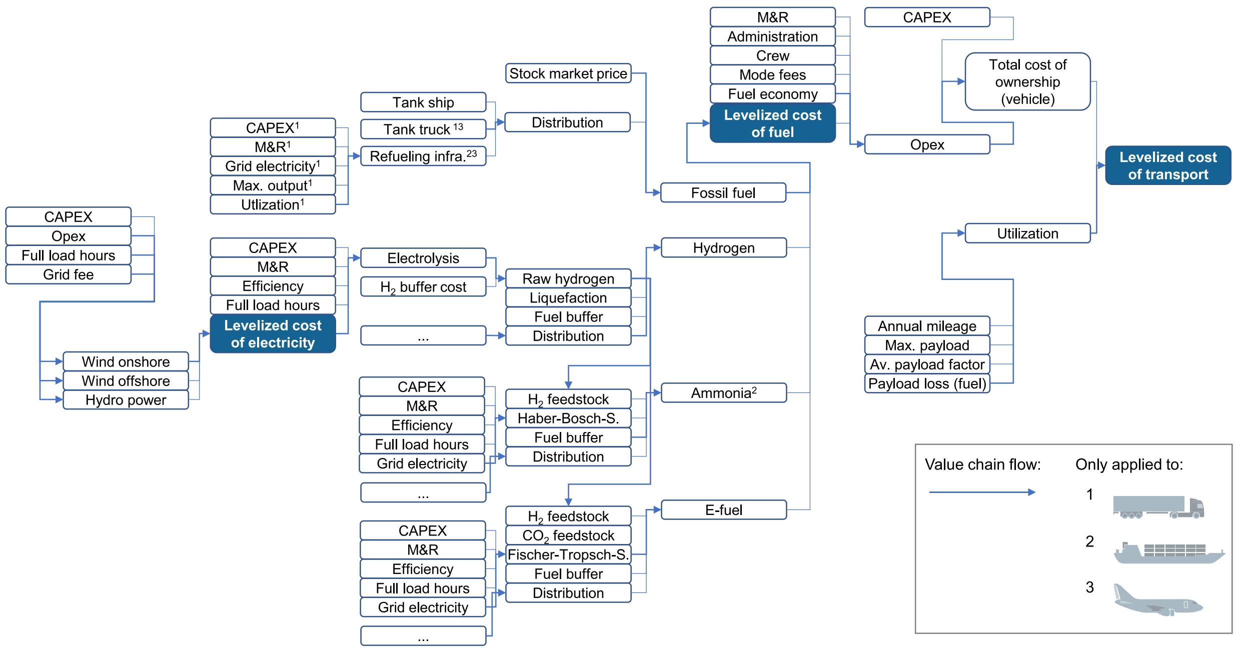

Fig. 2. Structure of the holistic cost model: local sources of renewable electricity generation, fuel production and distribution obtains the levelized cost of fuel, resulting in the levelized cost of transport.

the model's structure is given in Fig. 2, in which the three methodical cornerstones are highlighted: levelized costs of electricity, fuel, and transport.

3.1. Levelized cost metric

To compare fuel and transport alternatives, the concept of levelized cost is applied, which conventionally assigns a power plant's total lifecycle cost to one unit of energy output. Short et al. [31] describe the methodology background in detail. Based on Eqs. (1)–(3), the levelized costs of electricity for offshore wind, onshore wind and hydropower (step 1), fuel options (step 2) and cross-mode transport (step 3) are calculated. The latter is the sum total of the levelized costs of individual processes along the value chain, taking into account efficiency losses as shown in Eqs. (4)–(14).

$LCOX^i$ is the levelized cost of an arbitrary process i (e.g. wind power, electrolysis, truck transport), $Capex^i$ capital expenditures of i, $Opex^{i,fix}$ fixed operational expenditures of i per year, Q^i annual outcome quantity of i and $Opex^{i,var}$ variable operational expenditures of i per outcome unit. $UCRF$ represents the universal capital recovery factor, which is calculated in the standard way [31]. The weighted average cost of capital ($WACC$) is set to 6% over N as the specific lifetime of i.

$$LCOX^i = \frac{Capex^i * UCRF + Opex^{i,fix}}{Q^i} + Opex^{i,var} \tag{1}$$

$$UCRF = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1} \tag{2}$$

$$LCOT = \sum_i LCOX^i \tag{3}$$

Our holistic cost model obtains the levelized costs of electricity ($LCOE$, Eq. (11)), fuel production with distribution ($LCOF$, Eqs. (4)–(10)) and transport ($LCOT$, Eqs. Eq. (3); (12)–(14)). For the latter, total lifecycle costs are extended to the total costs of ownership.

3.2. Levelized cost of fuel

First, $LCOX^i$ are applied to the levelized cost of fuel ($LCOF$) to compare the cost-competitiveness of fF, eH, eA and eF. $LCOF$ are disentangled in the levelized cost of fuel delivery ($LCOD$) and the levelized cost of fuel production ($LCOP$):

$$LCOF = LCOD + LCOP, \tag{4}$$

with

$$LCOD = LCOR + LCODi + LCOS^{fuel}, \tag{5}$$

to obtain $LCOD$ by adding the levelized cost of refueling ($LCOR$) plus levelized cost of fuel distribution ($LCODi$) and levelized cost of fuel buffer storage ($LCOS^{fuel}$).

$LCOR$ are calculated by applying the $LCOX$ metric to fuel station R, with $Q^{R,max}$ as the maximal fuel output at the fuel station per year and UR^R as the station's average utilization rate:

$$LCOR = \frac{Capex^R * UCRF + Opex^{R,fix}}{Q^{R,max} * UR^R} + Opex^{R,var} \tag{6}$$

$LCODi$ are calculated for fuel trucks following Eqs. (12)–(14), and values for $LCODi$ and $LCOS^{fuel}$ of fuel ships are used from the literature. Eqs. ((7)–(8)) are used to obtain $LCOP$ by adding the levelized cost of fuel transformation ($LCOTr$), levelized cost of reactants ($LCORe^P$), and levelized cost of raw hydrogen ($LCOH^P$) for the production process P:

$$LCOP = LCOTr + LCORe^P + LCOH^P \tag{7}$$

$$LCOP = \frac{Capex^{Tr} * UCRF + Opex^{Tr,fix}}{Q^{Tr,Flh}} + Opex^{Tr,var} + \frac{LCORe}{\eta^{P,Re}} + \frac{LCOH}{\eta^{P,H}} \tag{8}$$

Eq. (8) is used to obtain $LCOP$ by applying the $LCOX$ metric to a transformation process (including fuel synthesis and liquefaction) with $Q^{Tr,Flh}$ as the average output per year in full load hours, plus levelized cost of reactant (nitrogen or carbon), plus levelized cost of raw hydrogen ($LCOH$), with $\eta^{P,Re}$ and $\eta^{P,H}$ as efficiency in the production process. For the fuel path eH, no synthesis process and reactant are required, but here $LCOTr$ describes the levelized cost of hydrogen liquefaction.

Eq. (9) is used to obtain $LCOH$ determined by the levelized cost of electrolysis ($LCOEy$) plus $LCOS^{cav}$ as the hydrogen storage cost in caverns, the latter based on literature values:

$$LCOH = LCOEy + LCOS^{cav}, \tag{9}$$

and Eq. (10) is used to obtain $LCOEy$ by applying the $LCOX$ metric to an electrolysis process with $Q^{Ey,Flh}$ as the average output per year in full load hours. Renewable electricity is used as the feedstock, factored as the levelized cost of electricity ($LCOE$) with $\eta^{Ey,El}$ as efficiency in the electrolysis process. The cost of water is neglected, which is the second feedstock with comparably marginal cost impact [12]:

$$LCOEy = \frac{Capex^{Ey} * UCRF + Opex^{Ey,fix}}{Q^{Ey,Flh}} + Opex^{Ey,var} + \frac{LCOE}{\eta^{Ey,El}} \tag{10}$$

Eq. (11) is used to obtain $LCOE$ by applying the $LCOX$ metric to a generator of renewable electricity (hydro, offshore wind or onshore wind) with $Q^{El,Flh}$ as the average output per year in full load hours. For offshore wind, $Opex^{El,var}$ includes the grid connection cost to the mainland:

$$LCOE = \frac{Capex^{El} * UCRF + Opex^{El,fix}}{Q^{El,Flh}} + Opex^{El,var} \tag{11}$$

3.3. Levelized cost of transport

Eq. (12) is used to obtain the levelized cost of transport ($LCOT$) as the levelized cost of vehicle ($LCOV$) plus $Opex^{add,var}$ as the additional cost per unit. The additional costs per unit include for example administrative, infrastructure fees or cargo handling costs which supplement the total cost of ownership. Eq. (13) is used to obtain $LCOV$ by applying the $LCOX$ metric to a truck, ship or plane with $Q^{V,tkm}$ as the average mileage per year in tonne-kilometer. Eq. (14) is used to obtain $Q^{V,tkm}$, by AM^V as the annual vehicle mileage, $CC^{V,max}$ as the maximum cargo capacity per vehicle and UR^V as the utilization rate per vehicle. Besides an average load factor driven by market failure, UR^V also covers payload losses due to higher tank volumes or mass restrictions for some fuel alternatives. The analyzed fuels (fF, eH, eA, eF) are used, factored as the levelized cost of fuel ($LCOF$), with $\eta^{V,F}$ as a vehicle's fuel efficiency:

$$LCOT = LCOV + Opex^{add,var} \tag{12}$$

$$LCOV = \frac{Capex^{V} * UCRF + Opex^{V,fix}}{Q^{V,tkm}} + Opex^{V,var} + \frac{LCOF}{\eta^{V,F}} \tag{13}$$

$$Q^{V,tkm} = AM^{V} + CC^{V,max} * UR^{V} \tag{14}$$

3.4. Techno-economic data

Global data for 150 techno-economic parameters throughout the value chains are collected for 2020 (meant to represent present-day values), 2030 (2035) and 2050 from at least one peer-reviewed literature source (including review papers) or industry report, supplemented and validated through company interviews. These representative data points are used to define the order of magnitude for each parameter. If more than one or no literature source is available, a weighted average based on interviews with experts and own expertise is applied. For a five-year resolution, missing data is interpolated between the years. For the 23 most uncertain parameters in the investigated literature, best- and worst-case scenarios are used as shown in parentheses in Table 1 and illustrated with error bars in Figs. 4–7. Key cost drivers are investigated in a separate sensitivity analysis. Following the literature, the parameters for new technologies are assumed at industrial scale and increasing market diffusion, and considered from a price-taker perspective. Hence, strong scaling and learning effects for all components shape the cost curves. eH and eA are used in fuel cells, and fossil fuel (fF) and eF are used in mode-specific internal combustion engines. Costs of necessary replacements of components, such as fuel cells, over the vehicle's lifetime is considered by assuming proportionally higher Capex. The final results are compared in €cent per kWh for fuels and in € per tonne-kilometer for transport in 2020 values. Data on energy content always refer to the low heating value (LHV). Taxes and subsidies for fossil-based and carbon-neutral technologies and fuels are excluded. By using location-specific renewable capacity factors and mode-fees, the model is applied to Norway as illustrated in Fig. 3. The option of fuel import from other countries [12,22] is beyond this study's scope, focusing on the domestic energy production in three locations which are either attractive for offshore wind, onshore wind, or hydropower generation. The solar power potential of Norway lies below 1.2 MWh/kWp [37], and is thus neglected, not playing a significant role in Norway's energy strategy for 2050 [38].[2] Table 1 is a data extract for 2020, 2035 and 2050.

Electricity generation:

For onshore and offshore wind installation along Norway's coastline, a moderate complexity is assumed on the mid-bound of existing cost estimations including uncertainty as the cost range [24,32,40,41]. The Capex degradation is in line with [39]. For hydropower, a constant Capex over the time period is applied without further reduction potential [24,45]. Full load hours for Norwegian offshore wind are represented by the Norwegian "Sørlige NordsjøII" wind farm [43], for onshore wind by the Stavanger region [42], and for hydropower by "Aura" in Mid-Norway, which generates electricity for continuous industrial alumina production [46]. For offshore wind, additional costs for the undersea connection to the mainland are included [24].

Electrolysis:

Renewable hydrogen is produced in electrolysers using renewable electricity to split water into hydrogen and oxygen. For a large electrolysis installation in Norway, the latest cost review of [12] is used, including uncertainty as the cost range [11,51]. An increase in electrolyser efficiency [12], common Opex and lifetime is assumed following the literature [24,34,47]. The electrolyser only works when electricity is being produced and thus it has the same full load hours as the chosen electricity source. Water costs are neglected due to insignificance in overall costs (see [12,85]).

H_2 buffer storage:

All further process steps such as hydrogen liquefaction and fuel synthesis require a constant mass flow of hydrogen [22]. Ensuring a sufficient hydrogen supply from fluctuating renewable sources necessitates an overproduction. Hence, H_2 underground lined rock caverns (ULRC) are assumed as buffer storage for compressed hydrogen [48,86]. Buffering the mis-match between electricity generation and further processing, lower full load hours of the electricity source result in proportionally higher storage costs. Levelized storage costs of 0.98 ct/kWh_{LHV}, 0.62 ct/kWh_{LHV}, and 0.45 ct/kWh_{LHV} are assumed for hydrogen from onshore wind, offshore wind, and hydropower respectively [24,48]. Since the potential of ULRC in specific regions has not yet been investigated, Fig. A.9 (Appendix) demonstrates the sensitivity to varying storage costs. This also provides context on salt caverns and underground pipe storage as alternative technologies.

H_2 liquefaction:

For the distribution of eH, the gas is liquefied (−252.8 °C) using a cryopump system [49]. The energy-intensive process requires stable, renewable electricity supplied by the Norwegian grid[3] with respective costs [81]. The electricity demand follows [22] as a starting value

[2] As solar power comes with relatively low energy cost and has synergies with wind power generation [34] future work should investigate the cost reduction potential also for countries with limited solar potential.

[3] In 2020, Norwegian hydropower resources covered 92% of electricity generation supplemented by wind power and biomass, a rarity among countries worldwide [25].

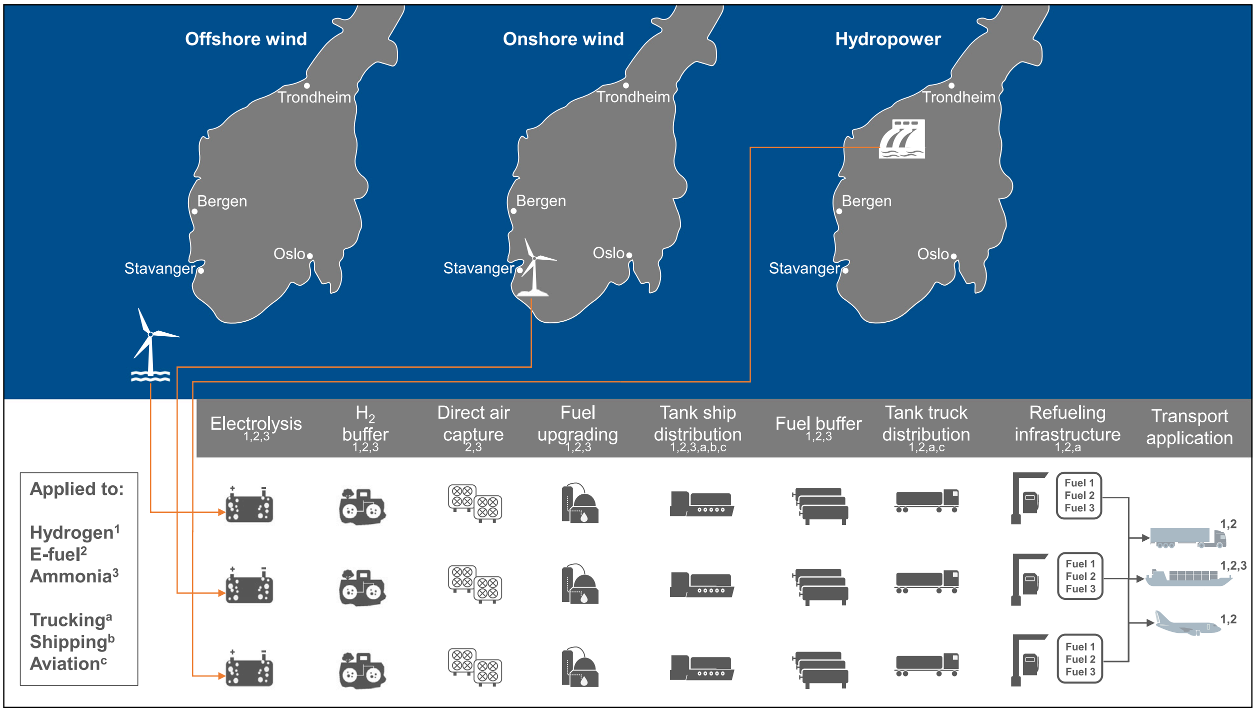

Fig. 3. Selected sites of the case study for Norway: Each value chain from electricity generation, fuel production, and distribution to fuel consumption is investigated individually.

in 2020, combined with [87] for 2040. For Capex, the cost estimates from [49] (originally based on the year 2009) are harmonized to 2300 €/kW$_{el}$ [22]. For 2040, the long-term cost target by [49] is considered, which is also in line with the reduction potential of 2/3 calculated by [87]. For both electricity demand and Capex, the target values are assumed to be reached in 2040 and stable thereafter. A hydrogen evaporation rate of 5% is applied[4] [50].

Ammonia synthesis:

The feedstock hydrogen is stored in underground lined rock caverns (see H_2 buffer storage). To produce ammonia, a second reactant nitrogen is captured from the atmosphere. The Haber–Bosch process transforms hydrogen and nitrogen to ammonia with subsequent liquefaction. Capex values are assumed following [13], offsetting the investment cost for ammonia liquefaction in the plant Capex. The Haber–Bosch process is a sophisticated technology, so further cost reduction is neglected [13]. Ammonia synthesis requires high full load hours of stable, renewable electricity supplied by the Norwegian grid with respective costs [81].

E-fuel synthesis:

Liquid hydrocarbons from Fischer–Tropsch synthesis are near-identical copies of today's fossil fuels for use as blending or substitution in modern internal combustion engines [1,12]. The synthesis requires high full load hours of stable, renewable electricity supplied by the Norwegian grid with respective costs [81]. For simplicity, cost differences between liquid hydrocarbon end products (synthetic diesel, heavy fuel oil, jet fuel) are neglected and an average energy density 11.5 kWh$_{LHV}$/kg and 10 kWh$_{LHV}$/l is applied which is in line with the literature [12,24,51]. Capex values are assumed following the literature review of [51], and include uncertainty as the cost range [12,22,24]. The feedstock hydrogen is stored in underground lined rock caverns (see H_2 buffer storage). To produce e-fuel, a second reactant carbon is captured from the atmosphere [12,35]. The hydrocarbon synthesis transforms carbon and hydrogen into synthetic crude oil, followed by upgrading to the desired end product [12,22,24]. The exact share of hydrogen, carbon and electricity as feedstocks depends on the end-product. Hence, e-fuel is calculated based on the average values from the literature [24,50].

CO_2 direct air capture:

Direct air capture based on solid sorbent technology is still a prototype [52], cost data are limited and estimates are widely spread [12,24,35,89]. For 2020, 600 €/t CO_2 are assumed which is slightly lower than the costs of market-leader Climeworks in 2017 [52]. For 2035, 190 €/t CO_2 and for 2050, 90 €/t CO_2 are assumed, which are averages in the literature [12,18,35].

Fuel shipping:

Large-scale prototypes for LH_2-tank ships exist only as concepts [22]. Compared to tank ships for ammonia and crude oil, the limited amount per shipment and insulation requirements for liquid hydrogen significantly add to the distribution costs [12,22]. Existing cost data for shipping over 4000 km distance is used, and translated with a linear relation into specific costs in €/100*km [12]. For all modes, tank ships transport the first part of the fuel distribution to ports and seaside airports along the Norwegian coast.

Fuel buffer (liquid):

After shipping fuel to the nearest port of consumption, a buffer storage is assumed to balance mismatched tank truck refilling. In case of direct bunkering between tank ships and end-use ships, the storage is considered as a buffer between production and tank ship refilling. For eH existing data for liquid hydrogen storage is used following [23,53] (6,6 M USD for 3500 m^3 tank). NASA's long-term cost reduction target of 50% [53] is assumed for 2045. For eA and eF buffers, no further cost reduction is considered over time due to mature technology following [22].

Tank semi-trailer and truck unit:

Semi-trucks with tank trailer supply inland fuel stations, which is a cost-efficient solution for countries where pipeline distribution

[4] Releasing hydrogen into the atmosphere can have a negative climate impact [88]. Thus, sustainability assessments should compare the actual amounts of hydrogen release with avoidance measures such as boil-off reliquefaction.

Table 1
Extract of data for 2020, 2035 and 2050. The upper and lower bounds in parentheses represent the uncertainties used in Figs. 4–7. Data on energy content always refer to the low heating value (LHV). Data placed solely in the central column is relevant for all years.

	2020^x	2035^y	2050^z	Source
Offshore wind				
Capex [€/kW$_{el}$]	3,200 (+/−500)	2,000 (+495/−505)	1,650 (+/−500)	[24,39–41]^{xyz} [32]^x
Opex [% of Capex]		3		[24,32]^{xyz}
Lifetime [a]		25		[24,32]^{xyz}
Full load hours [h/a]		4,400 (+/−100)		[32,42,43]^{xyz}
Sea cable [ct/kWh$_{el}$]	1.50	1.04	0.70	[24]^{xyz}
Onshore wind				
Capex [€/kW$_{el}$]	1,500 (+/−150)	1,030 (+305/−295)	950 (+/−250)	[13,24,40]^{xyz} [32,44]^x [39]^{yz}
Opex [% of Capex]		2.5		[13,24,32,40]^{xyz}
Lifetime [a]		20		[13,24,32,40]^{xyz}
Full load hours [h/a]		3.200 (+/−200)		[24,32,42]^{xyz}
Large hydro				
Capex [€/kW$_{el}$]		2,350		[24,45]^{xyz}
Opex [% of Capex]		2.5		[24,45]^{xyz}
Lifetime [a]		50		[24,45]^{xyz}
Full load hours [h/a]		7,000 (+/−1,000)		[24,45,46]^{xyz}
Electrolyser (PEM)				
Capex [€/kW$_{el}$]	1,100 (+/−390)	525 (+235/−230)	330 (+/−190)	[11,12,24,47]^{xyz}
Opex [% of Capex]		3		[24,34]^{xyz}
Lifetime [a]		25		[24,35,47]^{xyz}
Full load hours [h/a]		Equal to electricity source		
Efficiency [%]	64.2 (+/−5.7)	67 (+/−7.0)	72.2 (+/−6.9)	[12]^{xyz}
Water cost		neglected		
H_2 buffer storage				
Onshore wind system [ct/kWh$_{H2}$]		0.98		[24,48]^{xyz}
Offshore wind system [ct/kWh$_{H2}$]		0.62		[24,48]^{xyz}
Hydro system [ct/kWh$_{H2}$]		0.45		[24,48]^{xyz}
H_2 liquefaction				
Capex [€/kW$_{H2}$]	2,300	1,255 (+0/−255)	700 (+300/−0)	[49]^{xyz} [22]^y
Opex [% of Capex]		2		[50]^{xyz}
Lifetime [a]		30		[49]^{xyz}
Full load hours [h/a]		8,000		[49]^{xyz}
Feedstock electricity [kWh$_{el}$/kWh$_{H2}$]	0.360	0.222	0.210	[22,49]^{xyz}
H_2 evaporation [%]		5		[50]^{xyz}
Ammonia synthesis				
Capex [€/kW$_{fuel}$]		995 (+/−50)		[13]^{xyz}
Opex [% of Capex]		5		[13]^{xyz}
Lifetime [a]		30		[13]^{xyz}
Full load hours [h/a]		8,000		[13]^{xyz}
Efficiency [%]		99		[13]^{xyz}
Feedstock electricity [kWh$_{el}$/t$_{fuel}$]		738		[13]^{xyz}
Feedstock H_2 [kg$_{H2}$/t$_{fuel}$]		177		[22]^{xyz}
Feedstock N_2 [kg$_{N2}$/t$_{fuel}$]		823		[22]^{xyz}
E-fuel synthesis				
Capex [€/kW$_{fuel}$]	800 (+/−150)	525 (+260/−125)	400 (+300/−100)	[12,24,51]^{xyz}
Opex [% of Capex]		3.5		[24,51]^{xyz}
Lifetime [a]		25		[24,51]^{xyz}
Full load hours [h/a]		8,000		[24]^{xyz}
Feedstock H_2 [kWh$_{H2}$/kWh$_{fuel}$]		1.25		[24]^{xyz}
Feedstock CO_2 [kg$_{CO2}$/kWh$_{fuel}$]		0.341		[24,50]^{xyz}
Feedstock electricity [kWh$_{el}$/kWh$_{fuel}$]		0.045		[50]^{xyz}
CO_2 direct air capture				
CO_2 [€/t]	600 (+100/−150)	190 (+95/−80)	90 (+/−50)	[12,18,24,35]^{xyz} [52]^x
Fuel shipping				
LH_2 tank ship [ct/kWh*100km]	0.045	0.039	0.038	[12]^{xyz}
E-fuel tank ship [ct/kWh*100km]	0.0075	0.0043	0.0025	[12]^{xyz}
Ammonia tank ship [ct/kWh*100km]	0.0125	0.0093	0.0075	[12]^{xyz}
Distance shipped (one way) [km]		500		

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Table 1 (*continued*).

	2020^{x}	2035^{y}	2050^{z}	Source
Fuel buffer				
eH [ct/kWh]	3	1.67	1	[23]^{x}[22,53]^{z}
eF [ct/kWh]		0.04		[22]^{xyz}
eA [ct/kWh]		0.325		[22]^{xyz}
Tank semi-trailer				
LH_2 - Capex [€/trailer]	750,000	380,000	250,000	[23,50]^{xyz} [53]^{yz}
LH_2 - Net capacity [kg]		4,300		[23,54]^{xyz}
LH_2 - Payload [kg]		4,500		[23]^{xyz}
fF/eF - Capex [€/trailer]		60,000		[55]^{xyz}
fF/eF - Net capacity [m^3]		50		
Fuel type independent				
Opex fix [% of Capex]		2		[23]^{xyz}
Mileage [km/a]		65,000		[23,50]^{xyz}
Lifetime [a]		12		[23]^{xyz}
Trip length (one way) [km]		150		
Return trip		empty		
Tank truck unit				
Capex [€/truck unit]		90,000		[23,50,55]^{xyz}
Opex fix [% of Capex]		10		[23,55]^{xyz}
Opex var incl. trailer [€/km]		0.125		[50,55]^{xyz}
Mileage [km/a]		65,000		[23,50]^{xyz}
Lifetime [a]		9		[23,50]^{xyz}
Fuel demand [kWh/km]		3.2 (32 l/100km)		[1,23]^{xyz}
Average speed [km/h]		50		
Driver salary incl. social security [€/h]		25		
Working days; hours [days/a; h/day]		230; 8		
Diesel price net at fuel station [€/l]		1		[55]^{xyz}
Fuel station (truck)				
fF/eF - Capex [M€/station]		2		
eH - Capex [M€/station]	6	4	3	[2,50]^{xy}[56]^{x}
eH - Fuel station utilization rate [%]	70	85	100	
Fuel type independent				
Opex [% of Capex]		1.5		[2,50]^{xyz}
Fuel output max [GWh/a]		43		[56]^{xyz}
Lifetime [a]		15		[2]^{xyz}
Long-haul trucking				
Cargo trailer				
Capex trailer [€]		40,000		[55]^{xyz}
Lifetime [a]		12		[23]^{xyz}
Max. payload [t]		25		[1]^{xyz}
Average load factor [% of max. payload]		60		[4,57]^{xyz}
Truck (fuel type independent)				
Mileage [km/a]		120,000		[1,50,55]^{xyz}
Lifetime [a]		10		[23,50]^{xyz}
R&M, tyres incl. trailer [€/a]		15,000		[2,23,50,55]^{xyz}
Insurance, fees incl. trailer [% of Capex]		2		[4,55]^{xyz}
General expenses (office) [€/a]		3,000		[55]^{xyz}
Driver salary incl. social security [€/a]		60,000		
Working days; hours [days/a; h/day]		245; 8		[55]^{xyz}
Travel expenses [€/a]		7,000		
Road tolls Norway [€/km]		0.11		[58]^{xyz}
Truck (fuel type dependent)				
Fossil fuel/e-fuel (internal combustion engine)				
Capex [€/truck unit]		110,000		[2,23,55]^{xyz}
Fuel demand [kWh/km]		3.2 (32l/100km)		[2,23,55]^{xyz}
Hydrogen (fuel cell)				
Capex [€/truck unit]	350,000 (+/−50,000)	150,000 (+50,000/−20,000)	140,000 (+20,000/−40,000)	[1,55,59]^{x} [2]^{xyz}[60]^{yz}
Fuel demand [kWh/km]	2.98 (+/−0.161)	2.75 (+/−0.161)	2.69 (+/−0.161)	[2,12,61,62]^{xyz}
Short-sea shipping				
Ship (fuel type independent)				
Mileage [km/a]		152,011		[63,64]^{xyz}
Average days at sea [days/a]		190		[64]^{xyz}
Working days [days/a]		340		

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Table 1 (*continued*).

	2020^x	2035^y	2050^z	Source
Loading and unloading days [days/a]		100		
Ship length [m]		135		[63]^{xyz}
Installed power [kW]		7,200		[63]^{xyz}
Service speed [knots]		18		[63]^{xyz}
Lifetime [a]		25		[5]^{xyz}
Insurance [% of Capex]		0.66		[65]^{xyz}
Repairs & Maintenance [€/a]		215,294		[65]^{xyz}
Drydocking [€/a]		285,882		[65]^{xyz}
Crew salary incl. social security [€/a]		1,399,412		[65]^{xyz}
Travel expense [€/a]		25,000		
Administration [€/a]		225,882		[65]^{xyz}
Max. payload (dead-weight) [t]		9,450		[63]^{xyz}
Average load factor [% of max. payload]		65		[57]^{xyz}
Max. container [TEU]		750		[63]^{xyz}
Port fee [€/container]		10		[66]^{xyz}
Shipping (fuel type dependent)				
Fossil fuel/e-fuel (internal combustion engine)				
Capex ship [M€/ship]		28.2		[5,65,67]^{xyz}
Tank capacity HFO [GWh]		9		[63]^{xyz}
Fuel demand [kWh/km]		647 (28t/24h)		[63,65,68]^{xyz}
Spares & Lubricating oils [€/a]		517,059		[63,65,67]^{xyz}
Hydrogen (fuel cell)				
Capex ship [M€/ship]	–	56.4 (+11.3/–9.8)	36.66 (+2.8/–5.6)	[5,14,65]^{yz}
Fuel demand [kWh/km]	–	534 (+/–32.4)	519.20 (+/–32.4)	[61]^{yz}
Spares & Lubricating oils [€/a]	–	292,941	292,941	[65]^{xyz}
Payload loss (fuel) [% of max. payload]		10		[1]^{xyz}
Ammonia (fuel cell)				
Capex ship [M€/ship]	–	56.4 (+11.3/–9.8)	33.84 (+5.6/–2.8)	[5]^y [28]^z[65]^{yz}
Fuel demand [kWh/km]	–	534 (+/–32.4)	519.20 (+/–32.4)	[61,65,68]^{yz}
Spares & Lubricating oils [€/a]	–	292,941	292,941	[65]^{xyz}
Payload loss (fuel) [% of max. payload]		12		[1]^{xyz}
Mid-haul aviation				
Aviation (fuel type independent)				
Maximum take of weight MTOW [t]		73.5		[69]^{xyz}
Max. payload [t]		20		[70]^{xyz}
Average load factor [% of max. payload]		75		[57,71]^{xyz}
Flight control rate [€/Bh]		444		[72]^{xyz}
Fuel handling cost airport [ct/kWh]		0.15		
Crew [€/Bh]		500		[73,74]^{xyz}
Maintenance variable [€/Bh]		501		[72]^{xyz}
Maintenance fixed [€/Bh]		401		[74]^{xyz}
Insurance plane [% of Capex]		0.3		[71,74]^{xyz}
Cargo handling [€/flight]		150		[72]^{xyz}
Ground handling [€/flight]		1,379		[72]^{xyz}
Airport fee [€/flight]		649		[72]^{xyz}
Block hours per year [Bh/a]		1,500		[71,72]^{xyz}
Lifetime [a]		25		
Aviation (fuel type dependent)				
Fossil fuel/e-fuel (jet engine)				
Capex plane [M€]		40		[71,75]^{xyz}
Fuel demand [kWh/km]		38.8 (4 l/km)		[1,69]^{xyz}
Hydrogen (jet engine)				
Capex plane [M€]	–	100 (+/–20)	52 (+28/–8)	[27,71,75]^{yz}[76]^y
Fuel demand [kWh/km]	–	38.8	38.8	[27]^{yz}
Payload loss (fuel) [% of max. payload]		18		[1,27]^{xyz}
Auxiliary data				
WACC		6%		[31]^{xyz}
Energy density (LHV)				
Diesel		11.89 kWh/kg, 10 kWh/l, 0.841 kg/l		[77]^{xyz}
HFO		11.39 kWh/kg, 11.28 kWh/l, 0.99 kg/l		[1,77]^{xyz}
Jet fuel A-1		11.99 kWh/kg, 9.8 kWh/l, 0.809 kg/l		[1,77]^{xyz}
Hydrogen		2.359 kWh/l_{liquid}, 3.00 kWh/Nm^3, 33.33 kWh/kg		[78,79]^{xyz}
Ammonia		5.28 kWh/kg, 3.19 kWh/l_{liquid}, 0.604 kg/l		[1,79]^{xyz}
E-fuel (simplification)		11.50 kWh/kg, 10.00 kWh/l, 0.87 kg/l		[1,77]^{xyz}
External energy purchase (average prices 2015–2021, excl. taxes)				

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Table 1 (*continued*).

	2020[x]	2035[y]	2050[z]	Source
Grid electricity prices, contract for services excl. taxes [€/kWh$_{el}$]		0.031 (+/−0.014)		[80][xyz]
Grid electricity prices, contract for energy-intensive manufacturing excl. taxes [€/kWh$_{el}$]		0.0275 (+/−0.0045)		[81][xyz]
Diesel prices (stock exchange), excl. taxes [€/l]		0.70 (+/−30%)		[82][xyz]
Jet fuel A-1 prices (stock exchange), excl. taxes [€/l]		0.40 (+/−30%)		[83][xyz]
HFO (IFO380) prices (stock exchange), excl. taxes [€/t]		0.36 (+/−30%)		[84][xyz]
NOK/€$_{2020}$		10		
USD/€$_{2020}$		0.85		

has techno-economic limits[5] [21]. Capex for LH_2 trailers are higher than for common fuel trailers [23], but a 33% cost reduction for the needed cryogenic tanks is assumed until 2050 [53]. For eF and fF, a common diesel trailer with 50 m^3 net-capacity is assumed [21]. For the truck unit, common market values of diesel-powered trucks are applied and constant from 2020 to 2050 [50]. A net diesel price of 1€ per liter for distribution trucks is assumed. An average distance of 150 km distribution is assumed between the nearest port and inland fuel stations. Trailers are empty on return trips.

Fuel station (truck):

Fuel stations operate on renewable electricity supplied by the Norwegian grid with respective costs [80]. For simplicity, one fuel station per fuel type exemplifies levelized costs with a maximal fuel output of 43 GWh$_{LHV}$/a [56]. For a fossil fuel station serving long-haul transport, a constant Capex of 2 M€ from 2020 to 2050 is assumed, which also applies to the e-fuel case. For a 700 bar hydrogen fuel station, factor 3 in 2020 [2,50,56], 2 in 2035 [2,50] and 1.5 in 2050, is applied proportionally. For hydrogen, a utilization rate of 70%, 85% and 100% in 2020, 2035 and 2050, is included respectively, considering early weaker fuel demand due to a shortage of fuel cell trucks.

Long-haul trucking:

For long-haul trucking, a 40-tonne semi-truck with truck unit and separate cargo semi-trailer is assumed [55], investigated for compressed eH and eF and compared to the fF, truck diesel. For all fuels, costs characterizing the truck body and trailer are identical, the average load factor is 60% [4,57], and potential loss of payload caused by lower fuel energy densities is neglected [1] (see Fig. 6 for payload loss variation). For fF and eF, an identical vehicle with a common internal combustion engine is assumed. For eH, the truck unit has a fuel cell driven electric motor and hydrogen tanks for compressed hydrogen (700 bar). For its Capex, a factor of 3.2 in 2020 [1,2,55,59], 1.4 in 2035 [2,60] and 1.3 in 2050 [2,60], is applied proportionally to the Capex of a fossil-fuel–powered truck [23,55]. See Table 1 for the cost range of Capex and Fig. 6 for Capex variation. All vehicles are depreciated over their lifetime to circumvent the uncertainty of residual values for new technologies. Combustion engine research is assumed to eventually cease and further efficiency gains are neglected. A cost compensation of low-maintenance electric drive trains and less optimized services is assumed which results in the same maintenance cost for all fuel types. To determine the total cost of ownership, market data from expert interviews and other sources is used. Road tolls vary throughout Norway. Hence, an average value for the transport triangle Oslo–Bergen–Trondheim (with AutoPass, diesel truck, >3.5 tonnes, Euro VI) is calculated, to represent the costs of the road infrastructure used [58]. Although Norway's toll system excludes carbon-neutral freight transport, government intervention is neglected.

Short-sea shipping:

Short-sea shipping denotes maritime freight transport along coastlines between countries on the same continent. The publicly available data on "Enforcer" is used [63], a typical mid-sized container feeder with 9450 dead-weight tonnes [64]. For all fuel types, the average load factor is 65% [57]. The use of eH, eA (for both market launch 2030 [28]) and eF is investigated and compared to fF, heavy fuel oil (HFO).[6] For a vessel using fF or eF, Capex of 28.2 M€ are used [5,63]. For the internal combustion engine (7.200 kW) with HFO tank (9 GWh$_{LHV}$), 2.5 M€ are assumed [14,28]. For the hydrogen-powered ship (fuel cells and cryotanks), the long-term values of [5,14] are used, assuming a factor of 2 in 2035 and 1.3 in 2050, proportionally to the Capex of the fF ship. For an ammonia-powered ship (fuel cells and cooling tanks), simpler on-board fuel storage [14,92] and initially higher fuel cell costs [14,79] are assumed, with a factor of 2 in 2035 [5] and 1.2 in 2050 [28]. See Table 1 for the cost range of Capex and Fig. 6 for Capex variation. A payload loss of 10% for hydrogen storage systems and 12% for ammonia storage systems is assumed due to their lower energy density [1] (see Fig. 6 for payload loss variation). Combustion engine research is assumed to eventually cease neglecting further efficiency gains. The analyzed fuels are all directly bunkered (tank ship to end-use ship) to avoid additional refueling infrastructure. Lower repair and maintenance costs (R&M) are assumed for electric-drive trains compared to internal combustion engines. To determine the total cost of ownership, market data from expert interviews and other sources is used. There are regional variations of port fees. Hence, the potential costs of "Enforcer" are calculated at Bergen port with a fairway fee, quay fee, cargo fee, loading/unloading fee and administrative fee [66]. Although Norway excludes carbon-neutral freight transport from public fees, government intervention is neglected.

Mid-haul aviation:

For mid-haul aviation a plane with 73.5 tonnes maximum take-off weight and 20 tonnes maximum payload is assumed, comparable to a narrow-body freighter A320 [1,70]. The use of eH and eF is investigated and compared to fF, jet A-1. The Airbus A320 list price of 110 M USD in 2018 is publicly available [75], but airlines take advantage of high discounts for bulk orders (more than −50%) [71,74]. For eH, a plane with modified jet engines and liquid hydrogen tanks is assumed to be available by 2035 [93]. The same fuel consumption for hydrogen engines is considered [27] but the average payload factor of 75% [57] is further reduced by 18% due to the volume and mass of cryotanks [1,15,27] (see Fig. 6 for payload loss variation). For Capex, a factor of 2.5 in 2035 is chosen, expecting significantly higher costs in the year of market launch compared to conventional planes [1]. For 2050 a massive cost decrease to a factor of 1.3 is assumed that still meets the challenges of complex fuel storage technology [1,27]. See

[5] Norway lacks domestic pipeline infrastructure due to the absence of natural gas in its energy mix and the challenges of connecting small centers across rough terrain. Future hydrogen pipelines are considered only for exporting large volumes to Europe [90].

[6] Since 2020, pure HFO use is globally banned by regulating a fuel's sulfur content to maximum 0.5% [91]. This regulation eliminates HFO as the most widely used ship fuel oil worldwide. In Fig. 8 results for HFO are compared to the use of maritime gas oil as low sulfur alternative.

Table 1 for the cost range of Capex and Fig. 6 for Capex variation. Plane leasing is common, but this model purchases and fully depreciates planes over their lifetimes, which leads to noticeably higher Capex costs compared to leasing values [74]. By using a constant methodology however, a better comparison to other transport modes is obtained. Although the current regulations only allow a blending of 50% Fischer–Tropsch-based eF [94], a 100% fF substitution is assumed to achieve full carbon-neutrality. The same maintenance cost are assumed for all fuel types. Equal to existing refueling, direct bunkering between tank trucks and planes is assumed for all fuels [27,95]. To identify the total cost of ownership a detailed cost breakdown is used, based on operating an A320 passenger flight over 1350 km and 2.33 block hours following [72,74], adjusted and supplemented with freight-specific parameters [57,70] and data from interviews with experts.

Auxiliary data:

The weighted average cost of capital is considered with a value of 6% for all calculations [31]. An average on historic data from 2015–2021 on Norwegian grid electricity prices for energy-intensive manufacturing [81] and services [80] is built and used where mentioned. The same applies to the stock exchange prices (benchmark) for fossil diesel [82], heavy fuel oil [84], maritime gas oil [96], and jet A-1 fuel [83]. The same distribution costs of e-fuel are applied to the f-fuel case.

4. Results and discussion

4.1. Levelized cost of electricity and renewable fuels

Fig. 4A shows the levelized costs of electricity for the considered renewable energy sources in the specified locations in Norway. In 2020, offshore wind power (9.4 ct/kWh) is nearly twice as expensive as onshore wind power (5.3 ct/kWh), and hydropower (3.0 ct/kWh) nearly half as expensive as onshore wind power. Overall, the cost levels of the electricity sources converge towards 2050, but offshore wind (4.8 ct/kWh) stays comparably expensive to onshore (3.3 ct/kWh). The cost structure of all three technologies are dominated by investment cost 60%–78%. Hence, sites with high full load hours are pivotal.

Fig. 4B shows the levelized costs of hydrogen considering the different electricity sources and technology cost data by covering Capex and Opex for the electrolysis, buffer storage cost to decouple supply and demand, liquefaction cost and fuel distribution cost (only tank ship cost shown). Electricity is the main driver of hydrogen production costs (34%–57% with a growing share towards 2050, as Capex decrease). Hydrogen from hydropower costs nearly half of hydrogen from offshore wind in 2020. Decreasing costs for electricity and electrolyzer technology harmonize the hydrogen costs in regard to the energy sources towards 2050. A cost reduction potential for hydrogen from offshore and onshore wind of more than 50% is observable. The cost estimates equal 4.57, 7.00 and 8.48 €/kg hydrogen in 2020, and 2.63, 3.25 and 3.65 €/kg in 2050, for electricity from hydropower, onshore and offshore wind respectively.

Fig. 4C shows the levelized costs of ammonia considering the different electricity sources and technology cost data by covering Capex and Opex for the ammonia synthesis, electricity costs for the electrolysis and synthesis, costs for the electrolysis and hydrogen buffer, fuel storage cost, and fuel distribution cost (only tank ship cost shown). The limited cost for ammonia synthesis including the low-cost liquefaction and storage position ammonia fuel cost slightly below the level of hydrogen in 2020 (19 ct/kWh ammonia to 21 ct/kWh hydrogen from onshore wind). Due to a comparably higher cost reduction potential of the hydrogen value chain, the cost advantage disappears in 2035 (10.1 ct/kWh ammonia to 9.8 ct/kWh hydrogen). A wider spread in ammonia costs regarding high-cost (offshore) and low-cost electricity (hydro) compared to hydrogen is observable, and can be explained by its lower energy efficiency in the production process. The cost estimates equal 568, 1000, and 1266 €/t ammonia in 2020, and 430, 532, and 603 €/t in 2050, for electricity from hydro, onshore and offshore wind respectively.

Fig. 4D shows the levelized costs of e-fuel considering the different electricity sources and technology cost data covering Capex and Opex of the hydrocarbon synthesis, electricity costs for the electrolysis and synthesis, costs for the electrolysis and hydrogen buffer, CO_2 cost, fuel storage cost, and fuel distribution cost (only tank ship cost shown). The cost for CO_2 (44%–65% of total fuel cost in 2020, 22%–39% in 2050) and the low energy efficiency in the fuel production process (electricity cost electrolysis: 18%–40% of total fuel cost in 2020, 59%–49% in 2050) are important drivers making e-fuel comparably expensive. The cost estimates equal 3.14, 4.05 and 4.61 €/l e-fuel in 2020 and 1.04, 1.27 and 1.42 €/l in 2050, for electricity from hydro, onshore and offshore wind respectively.

4.2. Levelized cost of transport powered by renewable fuels from different electricity sources

Fig. 5A shows the levelized cost of trucking considering the use of fossil fuel, and hydrogen and e-fuel based on electricity from hydro and its cost difference to onshore and offshore wind power. The result for fF-powered trucking represents the use of common truck diesel and covers today's total cost of ownership to carry out cargo freight, in which driver costs generally dominate (45%). Carbon-neutral trucking with eF in 2020 increases the fuel cost four to six times (depending on the electricity source), having a 67% fuel cost reduction potential until 2050. Today, hydrogen-powered trucking is affected by high cost for new vehicle technology (2.7 times higher) and fuel cost (2 to 3.4 times higher than today's fF, depending on the electricity source) but both indicate substantial cost reduction potential towards 2050 (55% for Capex and 59% for eH fuel cost on average). Comparing the eH and eF potential, achieving carbon neutrality of existing fleets by using cost-intensive eF seems economically unattractive as fuel costs dominate vehicle Capex in the total cost of ownership.

Fig. 5B shows the levelized cost of shipping considering the use of fossil fuel, and hydrogen, ammonia and e-fuel based on electricity from hydro and its cost difference to onshore and offshore wind power. The result for fF-powered shipping represents the use of common heavy fuel oil (use of maritime gas oil: see 4.3 Sensitivity analysis) and covers today's total cost of ownership to carry out cargo freight, in which ship Capex (28%) and fuel cost (31%) dominate. Carbon-neutral shipping with eF in 2020 increases the fuel cost 10 to 14 times (depending on the electricity source), having a 67% fuel cost reduction potential until 2050. When both eA and eH enter the maritime market around 2030, hydrogen and ammonia-powered shipping are affected by high costs for new vehicle technology (2 times higher) and fuel cost (2.3 to 3.9 times higher than today's fF, depending on the electricity source and fuel type) but both indicate substantial cost reduction potential towards 2050 (35%, 40% Capex and 26%, 19% fuel cost for eH and eA respectively). In 2035, e-fuel-powered shipping cost are at a similar cost level. Hence, e-fuel may be attractive to achieve carbon neutrality for existing ships with remaining lifetimes of more than 15 years [1,5]. The payload loss of hydrogen and ammonia-based shipping works as a multiplicator for cost increases. Ammonia-based shipping has easier fuel handling[7] and storage at −33 °C [1] but slower cost reductions for ammonia fuel cells [79], compared to hydrogen-powered shipping which has complex fuel handling and storage at −252.8 °C [1] but faster cost reductions for hydrogen fuel cells due to synergies with other markets [61]. Being at a similar cost level, the final fuel choice also depends on its availability and handling in the international port environment.

[7] For challenges in ammonia handling due to its toxicity see [92].

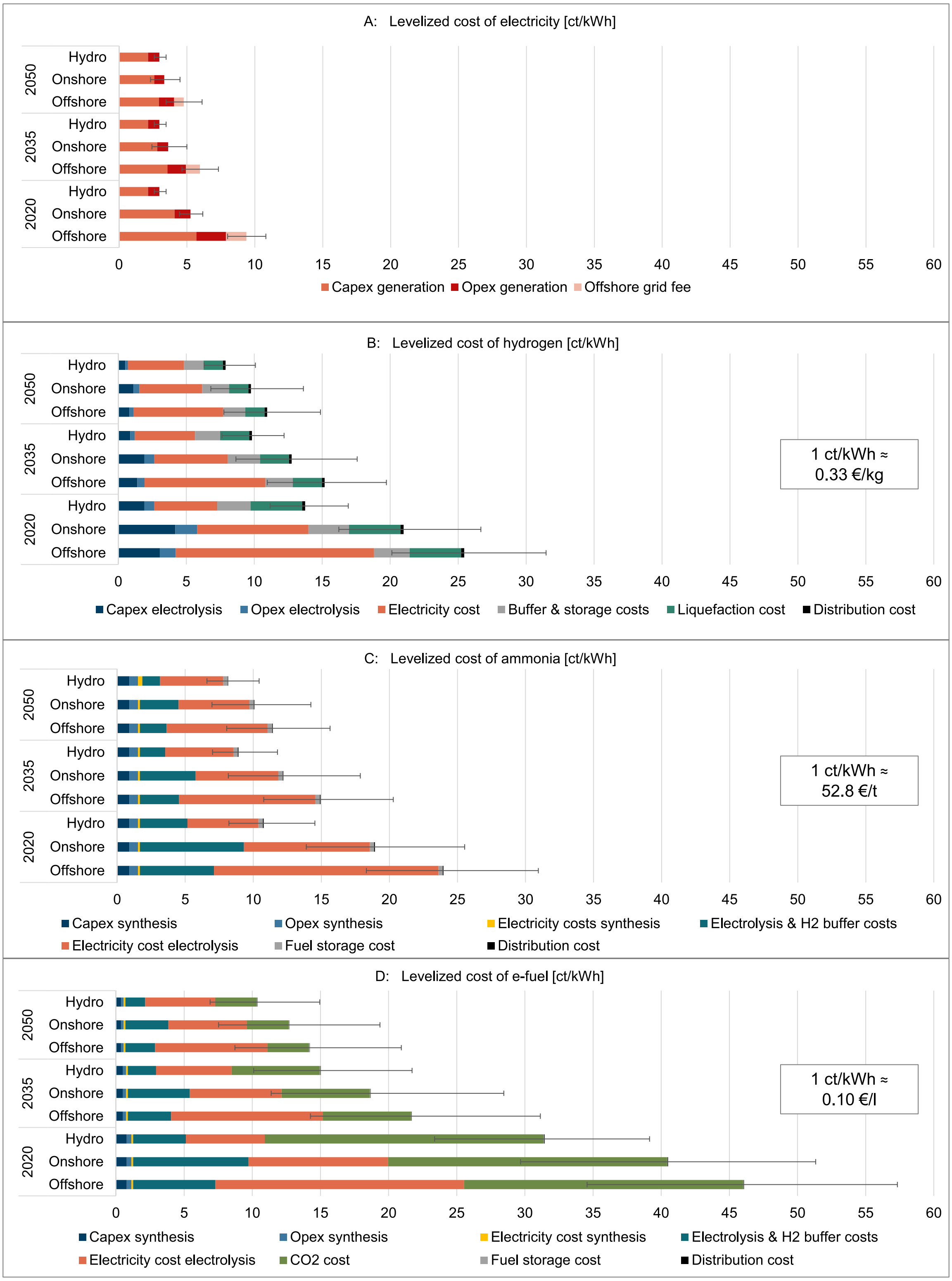

Fig. 4. Levelized costs of electricity, hydrogen, ammonia and e-fuel considering different renewable electricity sources and years (distribution costs only cover tank ships over 500 km). Error bars total the uncertainty ranges of the selected parameters.

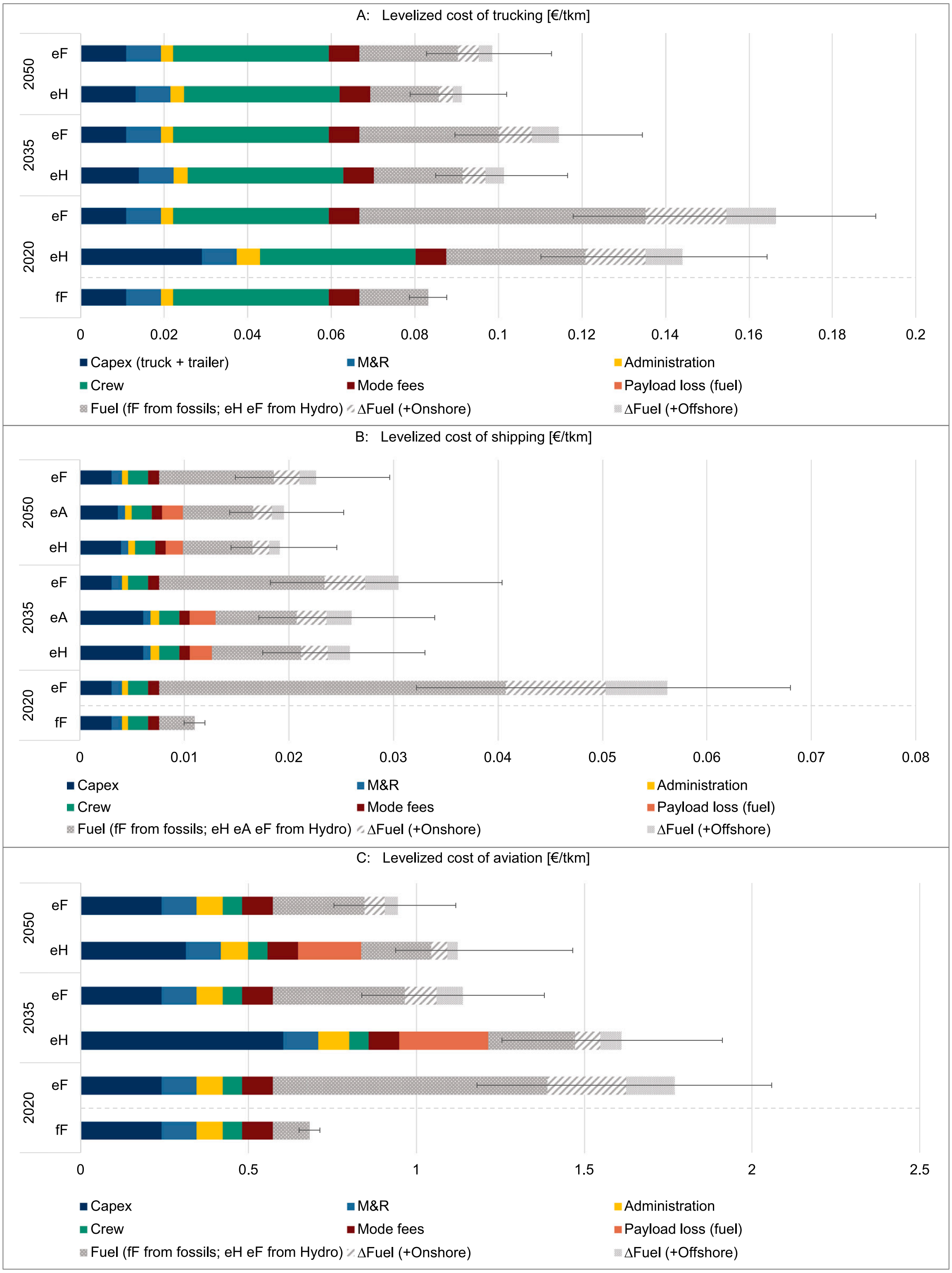

Fig. 5. Levelized cost of trucking, shipping and aviation considering fossil fuel (fF), hydrogen (eH), ammonia (eA), and e-fuel (eF) as fuel options. Error bars total the uncertainty ranges of fuel costs and vehicle technologies.

Fig. 5C shows the levelized cost of aviation considering the use of fossil fuel, and hydrogen and e-fuel based on electricity from hydro and its cost difference to onshore and offshore wind power. The result for fF-powered aviation represents the use of common Jet A-1 fuel and covers the total cost of ownership to carry out cargo freight, in which plane Capex (35%) and fuel cost (16%) dominate. Carbon-neutral aviation with eF in 2020 increases the fuel cost 7.5 to 11 times (depending on the electricity source), having a 68% fuel cost reduction potential until 2050. When eH enters the aviation market around 2035, hydrogen-powered aviation is affected by high cost for new vehicle technology (2.5 times higher) and fuel cost (2.4 to 3.6 times higher than today's fF, depending on the electricity source and fuel type) but both indicate substantial cost reduction potential towards 2050 (48% Capex and 23% eH fuel cost). The payload loss of hydrogen-based aviation works as a multiplicator for cost increases. Investments in hydrogen technology for carbon-neutral aviation will increase transport cost in the mid-term and payload limitations require new operational practices. However, hydrogen aviation may provide beneficial diversification that minimizes the risk of fossil-fuel dependency if eF falls short of expectations [12]. Specifically, the potential absence of early cost reduction of eF's carbon supply, would put the sector under unique cost pressure.

4.3. Sensitivity analysis of key cost drivers

Figs. 6A-6L display the effect of varying key cost drivers in the onshore scenario, which may be caused by cost uncertainty, conditions in other regions, or policy intervention.

Electricity cost: In trucking (Fig. 6A), e-fuel usage is more sensitive to electricity cost uncertainty (2020–2050: 0.42–0.37% slope) compared to hydrogen usage (2020–2050: 0.31–0.25% slope) due to its lower value chain efficiency. Hydrogen is the most economical option across all years, even at or below 0 ct/kWh electricity costs. In shipping (Fig. 6B), higher electricity costs influence the choice of maritime fuel towards the one with higher energy efficiency. As electricity costs rise, hydrogen becomes more cost-effective than ammonia (2035–2050: intersections at 1.9–3.9 ct/kWh). Shipping is the most sensitive mode to electricity costs due to the fuel cost difference (RF to HFO) and the fuel's share in the total cost of ownership. In aviation (Fig. 6C), eF remains the primary fuel choice throughout the investigated years, unaffected by electricity cost uncertainty.

DAC carbon cost: In trucking (Fig. 6D), e-fuel is cost-beneficial compared to hydrogen with carbon cost below 340€/t in 2020, 50€/t in 2035, and 10€/t in 2050. In shipping (Fig. 6E), e-fuel is cost-beneficial compared to ammonia with carbon cost below 100€/t in 2035 and 20€/t in 2050. In aviation (Fig. 6F), hydrogen becomes cost-beneficial compared to e-fuel with carbon cost above 720€/t in 2035 and 320€/t in 2050. Hydrogen and ammonia always remain unaffected by carbon costs.

Vehicle cost: In trucking (Fig. 6G), e-fuel becomes cost-beneficial compared to hydrogen when eH truck costs exceed 0.55M€ in 2020, 0.28M€ in 2035, and 0.21M€ in 2050. In shipping (Fig. 6H), e-fuel is cost-beneficial compared to ammonia or hydrogen when their ship costs exceed 78M€ in 2035 and 52M€ in 2050. In aviation (Fig. 6I), hydrogen is cost-beneficial compared to e-fuel when vehicle costs are below 35M€ in 2035 and 28M€ in 2050.

Payload loss: In trucking (Fig. 6J), e-fuel is cost-beneficial compared to hydrogen when payload capacity is reduced by over 11% in 2020, 8% in 2035, and 6% in 2050 due to the lower energy density of hydrogen systems. In shipping (Fig. 6K), e-fuel is cost-beneficial compared to ammonia (and hydrogen) if payload capacity is reduced by over 22% in 2035 and 2050 due to lower energy density. In aviation (Fig. 6L), hydrogen is cost-beneficial compared to e-fuel when payload loss from lower energy density can be limited to 0.5% in 2050. In 2035, hydrogen must offer better energy density than e-fuel. The values for aviation seem unattainable considering current industrial plans [27,93].

4.4. Cost-competitiveness within and across the transport modes

Fig. 7 shows the three modes' RF options investigated, and the respective transport cost increase compared to today's fossil-based transport. Compared to fF, achieving carbon-neutral long-haul trucking by using eH increases transport cost by +45% to +73% in 2020 (always depending on the electricity source), and +3% to +10% in 2050. Achieving carbon-neutral short-sea shipping by using eF early increases transport cost by +271% to +411%. When both eA and eH enter the maritime market around 2030, the increase of transport cost is +89% to +144% or +93% to +140% in 2035, and +51% to +82% or +51% to +77% in 2050, for eA and eH, respectively. Achieving carbon-neutral mid-haul aviation by using eF early increases transport cost by +104% to 159%. When eH enters the aviation market in 2035 [93], the increase in transport cost is +116% to 141%, and 53% to 67% in 2050.

While criteria such as transport time, frequency, payload capacity and flexibility also determine the choice of freight transport, asymmetric cost changes across the transport modes can substantially influence the cost-competitiveness of certain use cases and can lead to modal shift. For illustrative reasons, the transport cost of carrying one tonne of cargo over 1000 km is shown in Table 2.

Although shipping remains the cheapest and aviation the most expensive mode, the introduction of renewable fuels mostly affects shipping with the steepest cost rise toward renewable fuels. Besides fuel costs, the delayed introduction of the new propulsion (Capex) affects transport modes asymmetrically. Whereas for trucking, the cost peak of switching fuel already flattens around 2035, for shipping the eH and eA use in 2035 more than doubles the transport costs. For e-fuel-powered aviation (having no upfront investments on the consumer side), the cost burden could be mitigated by initial fuel blending, but the potential implementation of hydrogen technology to decrease e-fuel dependencies could cause additional cost peaks for operators.

4.5. Sensitivity analysis of the fossil fuel benchmark

Fossil fuel benchmark: Fossil-based transportation serves as the benchmark for comparing cost changes during the transition to carbon-neutral transport. Figs. 8A–C display the effect of varying fossil fuel costs in the onshore scenario, which may be caused by cost uncertainty, conditions in other regions, or policy intervention. The relative transport cost increase is more sensitive to lower fossil fuel costs, caused by the growing cost difference with renewable fuels. The cost order of renewable fuel options remains consistent across modes. Shipping exhibits the highest sensitivity due to the fuel costs' dominant share in overall expenses. Intersection points on the horizontal axis indicate fossil fuel costs required for the cost-competitiveness of carbon-neutral transport. The historic ranges of fossil fuel costs provide context. In trucking (Fig. 8A), even a benchmark of 2.46€/l truck diesel (Norwegian peak retail prices 2022 [97]) falls short of making renewable fuels cost-competitive today. In comparison, the retail prices in May 2022 were approximately 2.04€/l in Germany, 1.88€/l in France, and 1.83€/l in Italy [82]. Fig. 8B includes heavy fuel oil and maritime gas oil cost ranges [96] as alternatives in shipping. Ships using more expensive fossil fuels can transition more easily to renewable options. In aviation (Fig. 8C), fossil fuel costs above 1500 €/t jet fuel would be necessary for cost-competitiveness, given e-fuel's higher cost compared to hydrogen in trucking and hydrogen or ammonia in shipping.

4.6. Strengths and limitations of this work

This study is the first of its kind to comprehensively investigate both fuel and transport value chains in great detail, including individual cost components, fuel types, transport modes, and a time horizon until 2050. The model takes a holistic approach, allowing for an examination of how different costs along the value chain impact the analyzed fuels

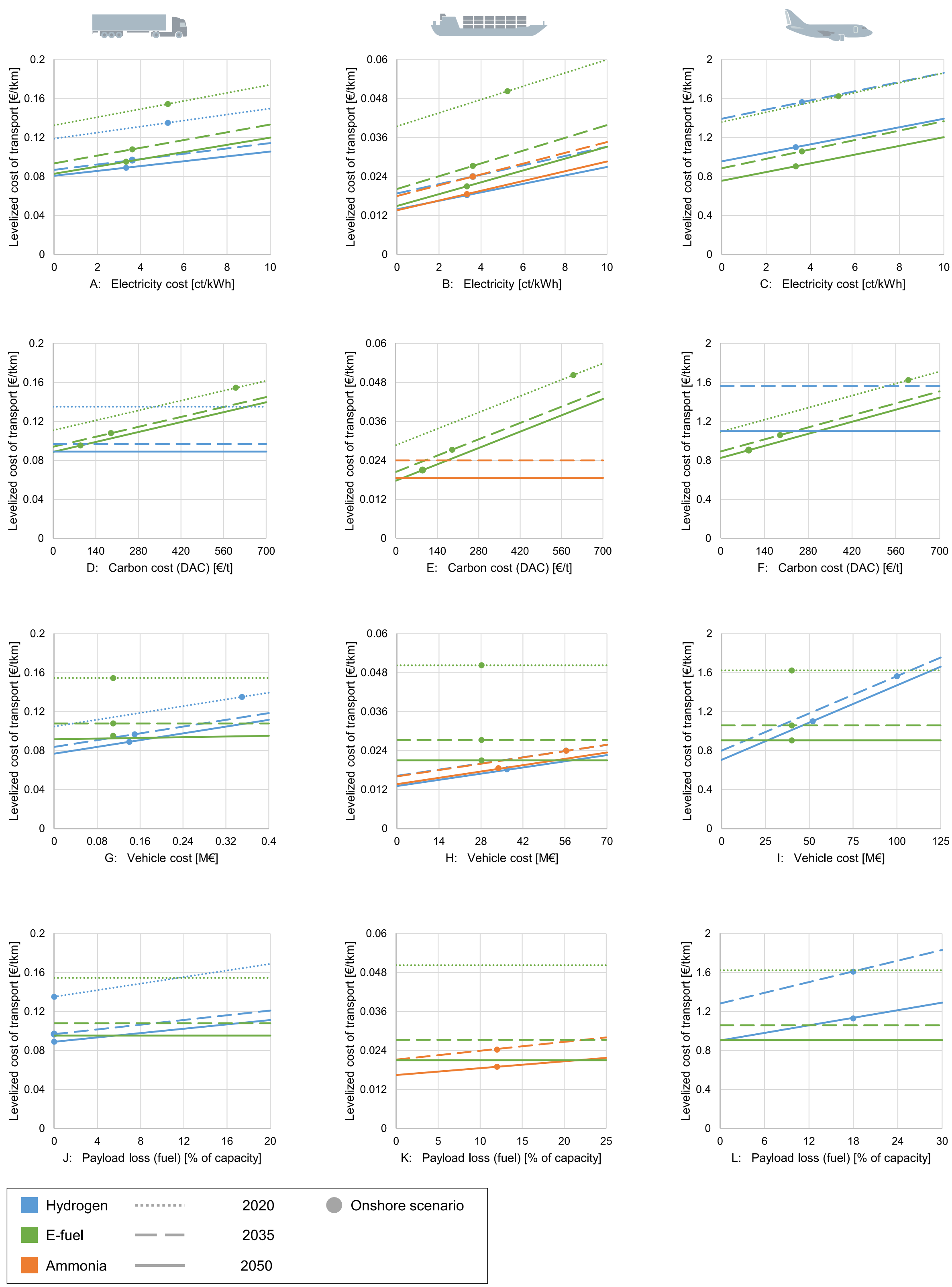

Fig. 6. Levelized cost of transport sensitivity to varying cost of electricity, carbon (DAC), vehicle technologies, and fuel-driven payload loss.

Fig. 7. Transport cost increase (percentages) in selected years driven by the fuel switch towards renewable fuels for aviation (top), trucking (center) and shipping (bottom) considering fuel options based on electricity from offshore wind (left), onshore wind (center) and hydropower (right). Shadows total the uncertainty ranges of the selected parameters.

and transport modes. The holistic data collection also considers mode-specific costs, providing context for new technologies and fuels within the total cost of transport. The model offers detailed insights into the sensitivity of key parameters without significant computational time. It is adjustable to other technologies and fuels (such as battery-electric, bio-fuel), and transport types.

Table 3 validates this study's results against literature values. The variety in model set-ups makes it hard to compare study results [9,18]. However, tendencies and deviations stand out. This study's electricity costs align with existing estimates. Its holistic fuel costs, however, are higher than in production-focused studies [11], but align with similar, holistic value chains. For 2020, [12] presents lower e-fuel costs assuming 460€/t carbon cost compared to 600€/t in this study. Overall,

Table 2
Transport costs of carrying one tonne of cargo over 1,000 kilometers (fuel from onshore wind).

	2020			2035			2050		
€	fF	eH	eF	eH	eA	eF	eH	eA	eF
Long-haul trucking	83	135	155	97		108	89		95
Short-sea shipping	11		50	24	24	27	18	18	21
Mid-haul aviation	682		1.624	1.547		1.060	1.092		906

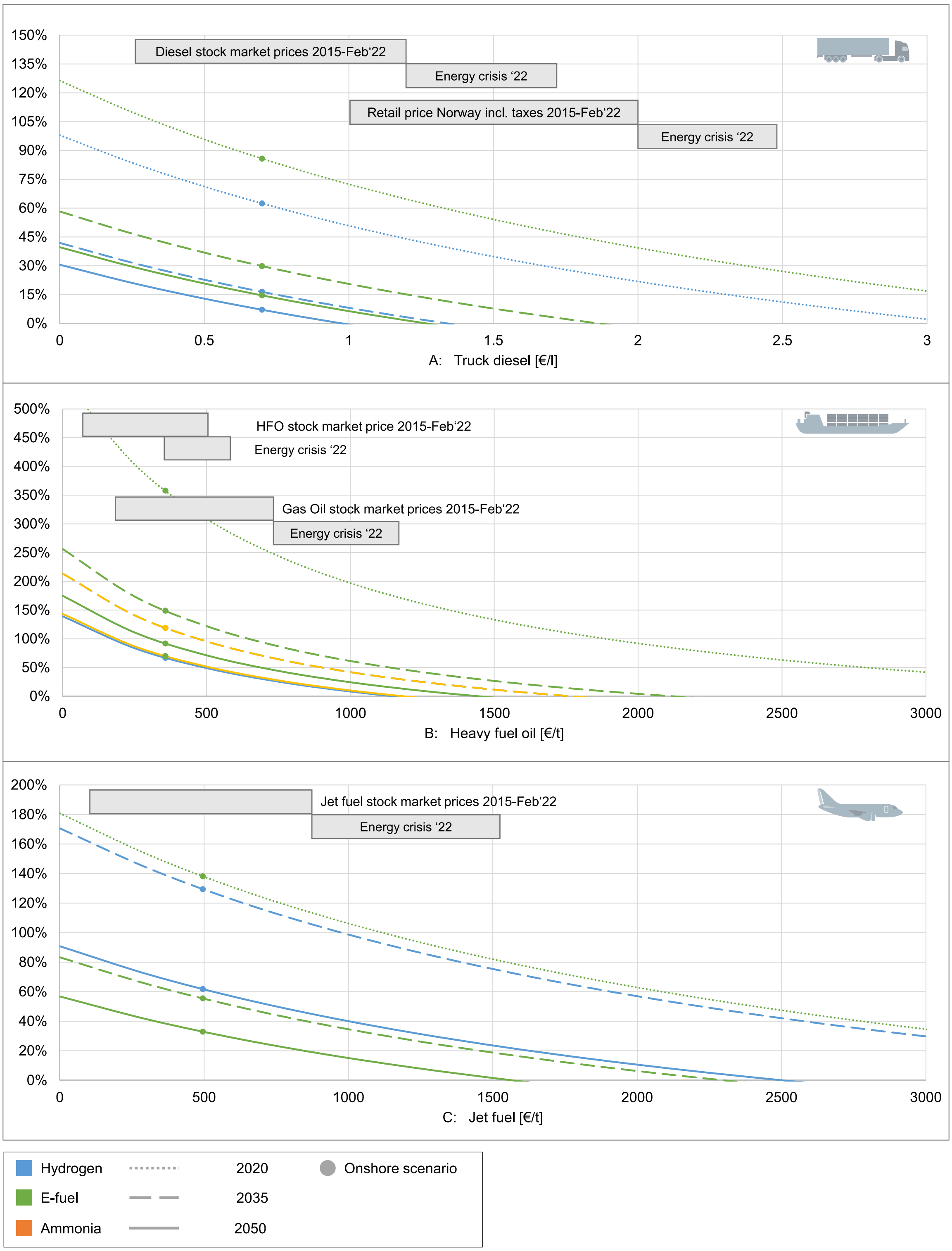

Fig. 8. Sensitivity of transport cost increase (switching from fossil to renewable fuels) to different fossil fuel benchmarks. Historic values give context [96–99].

Table 3
Comparing the results with values reported in the literature.

	This study	Literature	Unit
Hydropower 2020	3	2.8 [24]	ct/kWh
Onshore wind 2020	5.3	4–8 [32], 4.7–7.1 [39]	ct/kWh
Offshore wind 2020	9.4	7–12 [32], 9.1–14.7 [39]	ct/kWh
Hydropower 2035	3	2.8 [24]	ct/kWh
Onshore wind 2035	3.6	3.5–7.9 [32], 2.4–5.2 [39]	ct/kWh
Offshore wind 2035	6	6–11 [32], 4.7–9.3 [39]	ct/kWh
Hydropower 2050	3	2.8 [24]	ct/kWh
Onshore wind 2050	3.3	2.1–4.7 [39]	ct/kWh
Offshore wind 2050	4.8	4.1–8.8 [39]	ct/kWh
Hydrogen 2020	13.7–25.4	18 [23]	ct/kWh
Hydrogen 2035	9.8–15.2	12.1 [22], 14 [18]	ct/kWh
Hydrogen 2050	7.9–10.9	9.8 [18]	ct/kWh
Ammonia 2020	10.8–24.0	15–18 [13]	ct/kWh
Ammonia 2035	8.9–14.9	12.0 [22], 8.5–14 [13], 16 [18]	ct/kWh
Ammonia 2050	8.2–11.4	7.5–11.0 [13], 13 [18]	ct/kWh
E-fuel 2020	31.4–46.1	21 [12]	ct/kWh
E-fuel 2035	15.0–21.7	10 [12], 22 [18]	ct/kWh
E-fuel 2050	10.4–14.2	5 [12], 16 [18]	ct/kWh
fF Trucking 2020	0.083	0.115 [57]	€/tkm
fF Shipping 2020	0.011	0.013 [57]	€/tkm
fF Aviation 2020	0.68	0.18 [57]	€/tkm
eH Trucking 2020	1.5–1.7	2.7 [2]	Factor
eH Trucking 2050	1.0–1.1	1.1 [2]	Factor
eF Trucking 2020	1.6–2.0	2.5 [2]	Factor
eF Trucking 2050	1.1–1.2	1.5 [2]	Factor
eH Shipping 2030/35	1.9–2.4	5 [5]	Factor
eA Shipping 2030/35	1.9–2.4	4.3 [5]	Factor
eF Shipping 2030/35	2.1–2.8	5 [5]	Factor
eH Aviation (early)	2.2–2.4	1.9 [100]	Factor
eH Aviation 2050	1.5–1.7	1.3 [100]	Factor
eF Aviation 2020	2.0–2.6	2.5 [100]	Factor
eF Aviation 2050	1.5–1.7	1.3 [100]	Factor

fossil-powered transport costs align with a recent industry survey on total costs of ownership for freight transport [57]. Here, lower fF aviation costs are attributed to using a five times larger plane. The transport cost sensitivity when switching to renewable fuel is quantified by factors. High factors for carbon-neutral shipping in [5] validate the cost sensitivity found here. The comparably higher values might be due to the focus in [5] on costs of renewable fuel, vehicle technology, and payload loss. The holistic approach of this study, however, mitigates the dominance of these parameters, which leads to smaller cost changes.

The model's strength lies in its ability to handle the complexity of fuel and transport value chains. However, there are limitations to be investigated in future work:

- Plant sizes and operating patterns are not optimized as in other studies [11,22]. Instead suggested operating patterns (full load hours) from various literature sources are considered with respective buffer storage costs to balance potential process mismatch, following [24]. Future process optimization including the sale of by-products may yield lower fuel costs, but the overall conclusions are expected to be robust as shown in the sensitivity analysis.
- A combination of electricity sources is not investigated, which can offer the potential to further increase full load hours or production volumes while decreasing costs. The same applies to the integration of solar power in Norway.
- Vehicle operation is simplified with average parameters. Investigating real-world operating patterns can reveal additional cost details related to renewable fuel use.
- The cost reduction potentials of the used parameters are static. A dynamic feedback loop between the present model and a system model which estimates the actual market ramp-up will better represent dynamic learning and scaling effects. Investigating system costs related to infrastructure, energy demand, and potential government intervention will increase the level of detail.
- Analyzing the whole transport market was beyond scope. The presented results cover a limited selection of the market, and data specific to other use cases need to be updated for transferability. The sensitivities presented provide first insights into other regions and applications (e.g. costs of electricity, vehicles, payload losses).

5. Conclusion

This paper analyzes the levelized costs of renewable fuels and transport options for long-haul trucking, short-sea shipping and mid-haul aviation to identify the economic challenges of carbon-neutral transport by 2050. A new holistic cost model is developed and applied to Norway, which has excellent renewable energy potential and is an early adopter of carbon-neutral freight transport. The value chains for the renewable fuels hydrogen, ammonia, and e-fuel are investigated. The changes in the fuels' cost-competitiveness caused by changes in the costs of electricity generation and vehicle and fuel technology from 2020 to 2050 are benchmarked against today's freight transport's fossil-based counterparts.

Considering onshore wind, offshore wind and hydropower generation as potential energy sources, the results indicate that the three transport modes will suffer cost disadvantages when using renewable fuels compared to fossil fuels, although hydrogen, ammonia and e-fuel undergo an average cost reduction of 51%, 41% and 68% until 2050 respectively. E-fuel reacts most to lower electricity costs, due to the multiplicative effect of efficiency losses in production and consumption. The research quantifies the economic pressure of long-haul trucking, short-sea shipping and mid-haul aviation of using renewable fuels. Fuel substitution is most expensive in shipping (+271% to +411%, 2020; +51% to +106%, 2050), followed by aviation (+104% to +159%, 2020; +24% to +67%, 2050) and trucking (+45% to +100%, 2020; +3% to +18%, 2050) depending on the electricity source used for the production of renewable fuels. But the existing cost rankings are maintained over the time period: shipping remains the cheapest, whereas aviation

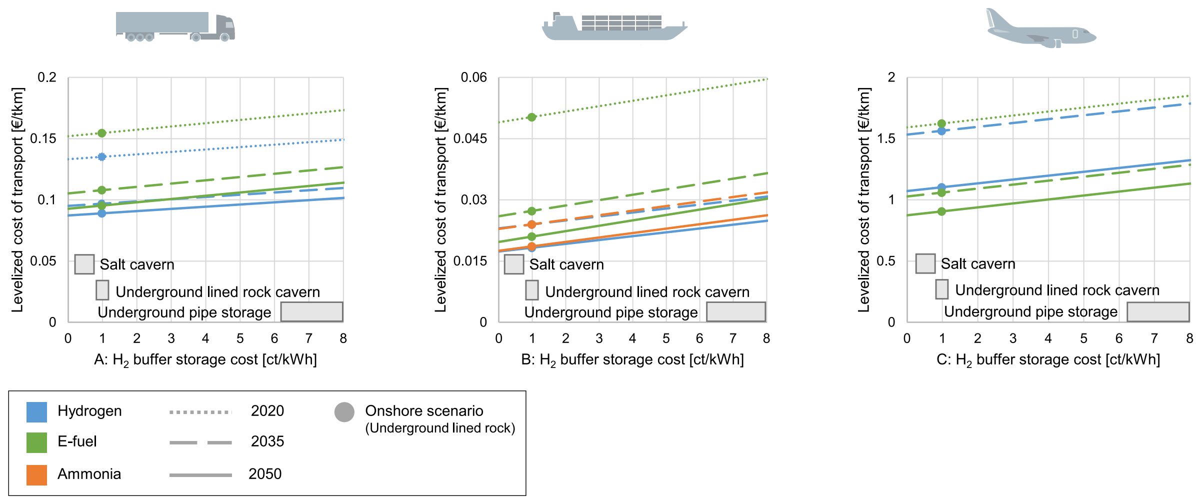

Fig. A.9. Levelized cost of transport sensitivity to varying hydrogen buffer storage costs in the onshore wind scenario. A selection of potential storage technology options give context [48]. Value chains with low process efficiencies are most affected, especially those involving e-fuel and ammonia (steeper slope).

is the most expensive. In the total cost of ownership, fuel costs will be the key cost driver for carbon-neutral transport followed by Capex of emerging vehicle technologies.

The sensitivity analyzes in this study demonstrate that future transport costs significantly rely on the cost developments of electricity, direct air capture for carbon, vehicle expenses, and payload losses, the latter resulting from lower energy densities of new fuel systems. These factors support or limit the use of different renewable fuels.

The analysis provides valuable insights for policymakers, enabling them to identify the primary factors which drive costs along the fuel and transport value chains, as well as their sensitivity to uncertainty and interventions. Understanding the timing and extent of asymmetric cost changes across transport modes can inform comprehensive transport strategies to avoid unintended mode discrimination. The holistic model used in this research is well-suited for gaining practical insights and can be customized to various fuel production setups and transport applications.

Future work may address: (i) modeling other fuels and transport types, (ii) optimizing plant size and operations, (iii) exploring public and private support for cost-competitive renewable fuels, (iv) studying the implications of asymmetric changes in transport costs on modal shift, and (v) assessing additional costs in scaling up to the energy system and transportation market level.

CRediT authorship contribution statement

Jonas Martin: Conceptualization, Methodology, Data collection, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Validation. **Anne Neumann:** Conceptualization, Writing – review & editing, Supervision. **Anders Ødegård:** Conceptualization, Data collection, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A. Sensitivity to hydrogen buffer storage costs

See Fig. A.9.

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