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Carbon abatement costs for renewable fuels in hard-to-abate transport sectors

Jonas Martin [a,*], Emil Dimanchev [b,c], Anne Neumann [a,c]

[a] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway
[b] Department of Electric Energy, Norwegian University of Science and Technology, Trondheim, Norway
[c] Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA, USA

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ABSTRACT

Renewable fuels can help to reduce carbon emissions from transportation. To inform planning decisions, this paper estimates carbon abatement costs of replacing fossil fuels with renewable hydrogen, ammonia, or Fischer–Tropsch e-fuel in Norwegian freight transport across long-haul trucking, short-sea shipping, and medium-haul aviation. We do this by applying a holistic cost model of renewable fuel value chains. We compare abatement costs across transport sectors and analyze how policy interventions along the value chains – such as carbon pricing, subsidies, and de-risking policies – impact carbon abatement costs. We estimate abatement costs of 793–1,598 €/tCO_2 in 2020 and -11–675 €/tCO_2 in 2050, depending on the electricity source, transport sector, and type of fuel. A 1 €/kg reduction in the cost of hydrogen - e.g. through a subsidy - lowers present-day carbon abatement cost by 95 €/tCO_2 for hydrogen-powered trucking, 133 €/tCO_2 for e-fuel-powered shipping, and 143 €/tCO_2 for e-fuel-powered aviation. We further show that reductions in the weighted average cost of capital materially decrease abatement cost, particularly for renewable hydrogen due to its relative capital intensity.

1. Introduction

Additional climate policy efforts are needed for "hard-to-abate" transport sectors such as long-haul trucking, shipping, and aviation, in order for governments to deliver on greenhouse gas emission targets and limit global warming to 1.5 °C [1]. Trucking, shipping, and aviation are envisioned to be one of the main sources of residual emissions toward the middle of the century, thus presenting a challenge for carbon neutrality goals [1–4]. While electrification plays a primary role as a carbon neutral option for light vehicles [5], other sectors - aviation, parts of trucking, and shipping - face significant challenges in implementing battery technology due to their substantial energy needs and operational practices adapted to use fossil fuels. For long-haul trucking, an anticipated solution involves the coexistence of battery-electric and hydrogen-powered vehicles [6–8], driven by individual use cases. However, while rapid technological innovation is expanding the application scope for batteries [9], the majority of the literature suggests that its technological potential for shipping and aviation operating across Europe could be limited [8,10,11].

European and national hydrogen plans have declared renewable fuels to be of strategic interest and an integral part of plans to achieve carbon-neutrality in hard-to-abate sectors [12–14]. For the purpose of system planning, government decision makers rely on estimates of the costs of alternative technology options. There is a large literature on the costs of renewable fuels in trucking, shipping, and aviation [15,16]. This paper investigates the cost-effectiveness of renewable fuels as climate change mitigation solutions in particular. For this purpose, we assess the carbon abatement cost of replacing fossil fuels with renewable fuels. We limit our investigation to three well-established sectors of Norwegian freight transport which are similarly important in the European context [8,16]: long-haul trucking, short-sea shipping and medium-haul aviation (hereafter, short-form mode names, such as "trucking", are used to denote the respective specific sector, while "transportation" is used to encompass all sectors). We choose Norway because it is considered a potential early adopter of renewable hydrogen and "export champion" [14], based on a relative abundance of renewable electricity [17].

We analyze a selection of renewable fuels, which has been discussed in previous literature [8,15,16] and which is of high importance to the Norwegian Government's hydrogen strategy [18]. The corresponding fuels encompass hydrogen [19], ammonia [20], and Fischer–Tropsch e-fuel (abbreviated as e-fuel) [21], with the latter two also known as

* Corresponding author.
E-mail address: jonas.martin@ntnu.no (J. Martin).

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synthetic fuels [16]. Hydrogen is produced through electrolysis, using renewable electricity to decompose water. It serves as an energy carrier, as it releases a significant amount of the electricity used in production as exergy during the reverse reaction. Given the techno-economic challenges associated with storing and handling hydrogen [8], renewable ammonia is anticipated to provide advantages as a synthesized fuel derived from renewable hydrogen and nitrogen. Ammonia can be handled in non-pressurized conditions at temperatures below −33 °C, but its high toxicity requires extensive safety concepts. E-fuels are synthesized from renewable hydrogen and carbon dioxide (CO_2). These fuels represent synthetic copies of today's hydrocarbon fuels, such as diesel or jet fuel, and can be used in existing infrastructure. For ammonia and e-fuels, we assume that the nitrogen (in the case of ammonia) and CO_2 (in the case of e-fuels) are captured from the atmosphere.[1] Thus, all fuel options are based on a closed production cycle and are therefore considered renewable[2] and carbon-neutral. We consider only scope 1 CO_2 emissions released from vehicle operation [24].

While this study focuses on a selection of renewable fuels which are part of global hydrogen strategies [25], we also explore battery-electric trucking for context (see Figs. 2–4). In addition to hydrogen and ammonia, methanol has emerged as a promising renewable fuel option to achieve carbon neutrality in shipping [11]. However, to simplify the analysis, methanol and other options are not specifically modeled here.[3] An analysis of methanol as a carbon abatement option can be found in [11] and [26], fully electric shipping in [9], and a technical comparison of fuel and battery use across transport sectors is presented in [8].

Previous literature has quantified abatement costs of carbon-neutral or low-carbon fuels [15]. In particular, [27] estimates marginal abatement costs using an energy system model, which provides an energy systems perspective but omits technological detail specific to heavy-duty trucking, shipping, or aviation. Other authors use more detailed bottom-up modeling to estimate the costs of reducing emissions within the hydrogen supply chain by replacing steam methane reforming with low-carbon alternatives [28], or by using carbon capture and storage [29]. However, these cost estimates do not quantify the abatement cost of replacing fossil transport fuels with renewable fuels (the focus of our paper). Abatement costs for different e-fuel types and hydrogen are quantified in [21], but the authors exclude end-use costs (such as vehicle costs), which are important drivers of the total cost of ownership [16]. In [30], several fuel value chains are modeled to investigate abatement costs limited to the trucking sector. Wahl and Kallo [31] and Lagouvardou et al. [26] estimate shipping costs only and use exogenous fuel costs without modeling the fuel value chain, which does not allow a distinction of how individual processes impact final costs. Brynolf et al. [15] extensively review previous cost estimates across carbon-neutral trucking, shipping, and aviation for the year 2030, and quantify abatement costs across sectors and fuels. As the authors conclude in [15], an important gap in this literature is the lack of comparability of estimates between the trucking, shipping, and aviation sectors, due to differences in the methodology of the underlying studies.

This paper's first contribution is to address this gap by applying a recently developed bottom-up techno-economic cost model [16]. The model provides comparable estimates across sectors (trucking, shipping, and aviation) as well as across fuels (hydrogen, ammonia and e-fuels) and time (2020, 2035, 2050) - based on a total cost of ownership approach. This allows us to extend previous literature that more narrowly focuses on the future cost of specific fuel types [19–21,32] or sectors [7,10,31,33] or synthesized data generated with diverse methods [15].

We also consider how abatement costs would be impacted by subsidies at different points on each fuel's value chain, which is our second contribution to the literature. Our analysis extends previous work on existing subsidies for trucking across countries [7] by investigating potential future policies at different points in time, for different processes along the value chain, and across different transport sectors. A key feature of our model is a more detailed level of disaggregation of the value chain relative to previous studies, which exclude vehicle costs [21], or use exogenous fuel costs [7,10,15,31]. In contrast, we model fuel production and transport costs endogenously. This allows us to estimate how subsidies for different processes along the value chain impact overall abatement costs across fuels and transport sectors.

This paper also investigates the impact of financial risk on transport abatement costs, which is our third contribution to the literature. Previous work emphasizes the importance of operational expenditure (OPEX) costs in the form of fuel costs from a transport system perspective and suggests that policy makers prioritize OPEX subsidies for trucking companies [7]. However, the authors' approach is not able to capture how different measures along the value chain would impact fuel costs. We leverage our models' more detailed disaggregation of cost categories to estimate how the cost of capital (i.e. WACC) influences the costs of using renewable electricity, hydrogen, ammonia and e-fuel, and, consequently, abatement costs. This allows us to indicate how policies that improve the financial risk profile for renewable fuel investments (such as Contracts for Differences) can decrease their associated abatement costs.

We quantify abatement costs as the Levelized Cost of Carbon Abatement (LCCA) [34] across sectors and fuels (this paper therefore uses the terms "abatement cost" and LCCA interchangeably). The LCCA represents societal costs from a system planner's perspective [35]. Levelized cost metrics such as the LCCA can also be interpreted as societal long-run marginal costs [36].

2. Methodology

This paper applies a holistic cost model of renewable fuel value chains in the transport sector developed in Martin, Neumann, and Ødegård [16]. Here we briefly describe the model before introducing this paper's analytical extensions. The model estimates the levelized cost (in euros per tonne-kilometer, €/tkm) of using renewable fuels in freight transport across sectors (equivalent to the total cost of ownership). It covers long-haul trucking, short-sea shipping and medium-haul aviation. We assume representative vehicle models for each transport sector which are common in European commercial transport [8,16]. For road freight, we assume a semi-truck with a maximum payload capacity of 25 tonnes and an annual mileage of 120,000 km. The assumed short-sea ship is a container feeder with a maximum payload capacity of 740 TEU (Twenty-Foot Equivalent Units, standard container) and an annual mileage of 118,231 km. The assumed narrow-body freight airplane has a maximum payload capacity of 20 t and operates 1,500 block hours[4] a year. A key feature of the model is its holistic representation of most processes along fuel value chains, which includes renewable electricity generation, fuel production, fuel distribution, and fuel use. For this work, we expand the model scope to the use of renewable electricity for battery-electric trucking. Model assumptions considering battery-electric trucking can be found in the Appendix.

[1] While CO_2 direct air capture is still in development but has the potential to supply significant volumes and to reduce reliance on fossil sources [22], utilizing biogenic or industrial carbon sources could cut e-fuel costs in the medium term. A detailed examination of the costs, scaling potential, residual emissions, and land use conflicts is done by [8] and [23].

[2] In 2020, 92% of domestic electricity generation was covered by Norwegian hydropower resources supplemented by wind power and biomass, a rarity among countries worldwide [17]. Hence, in addition to renewable electricity for electrolysis, we assume all other processes with potential grid connection to operate carbon neutral.

[3] The selection is made for tractability purposes. However, the model can be extended in future work to other technologies as shown in [16].

[4] Industry standard to measure airplane utilization, encompassing the duration from when the airplane door shuts prior to the departure until the moment it reopens after landing.

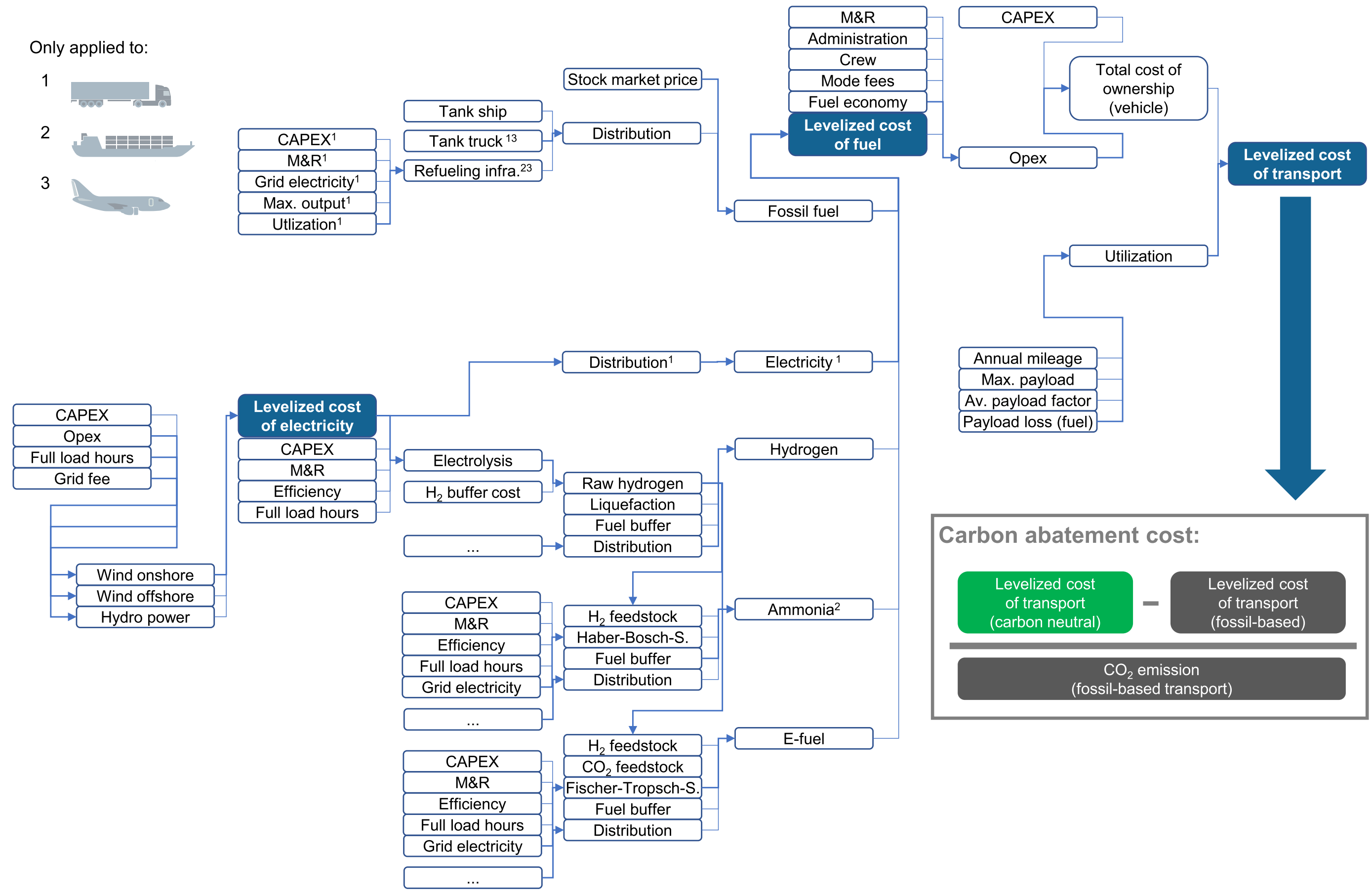

Fig. 1. Model structure based on [16].

Fig. 1 gives an overview about the structure of the underlying cost model.[5] The battery-electric value chain covers electricity generation (onshore/offshore wind, hydropower), electricity distribution,[6] mode-specific charging infrastructure, and a long-haul semi-truck (battery-electric). The hydrogen value chain covers electricity generation (onshore/offshore wind, hydropower), water electrolysis, H_2 buffer storage,[7] liquefaction, fuel buffer storage, tank ship / tank truck distribution, mode-specific refueling infrastructure, a long-haul semi-truck (700 bar tank, fuel cell), a short-sea ship (cryogenic tank, fuel cell), and a medium-haul airplane (cryogenic tank, jet engine). The ammonia value chain uses raw hydrogen[8] from H_2 buffer storage and additionally covers ammonia synthesis, fuel buffer storage, tank ship distribution, ship-to-ship direct fuel bunkering, and a short-sea ship (cooled tank, fuel cell). The e-fuel value chain uses raw hydrogen from H_2 buffer storage and additionally covers CO_2 direct air capture, e-fuel synthesis, e-fuel buffer storage, tank ship / tank truck distribution, mode-specific refueling infrastructure, a long-haul semi-truck (internal combustion), a short-sea ship (internal combustion), and a medium-haul airplane (jet engine). The fuel production is conservatively sized to cover full load hours of the connected electricity sources following [38] (thus neglecting the possibility of different optimal plant sizing) [16]. Key assumptions are shown in Table 1 and all data presented in [16]. Changes in input data relative to [16] are shown in Table 5 (Appendix).

The model allows us to explore how final transport costs depend on a large number of individual inputs (the model consists of 150 parameters). Levelized costs of transport are estimated from 2020 (meant to represent present-day values) to 2050 based on a total cost of ownership approach. Today's and future input data are compiled by [16] from global estimates in peer-reviewed literature and industry reports, validated through company interviews. To calculate values at a five-year resolution, [16] interpolate any missing data along the existing data points. Costs represent values without government intervention (taxes or subsidies). As shown in [16], the levelized costs of all carbon-neutral transport options decline over time as the compiled input data considers technological innovation and adoption-driven learning. The cost estimates of all production and vehicle components assume an industrial-scale value chain and increasing market diffusion over time. Future cost values assume that incentives have driven increasing sales volume, economies of scale, and learning effects through industrial product optimization over all technologies and sectors. Put differently, the expected cost reductions can only be achieved with political and industrial commitment starting today. We neglect competition between different fuels, which means that the shown cost reduction represents a world where a fuel value chain was built without competition from other fuels. Input parameters for the costs of individual components and processes represent central values from the literature [16]. Therefore, levelized costs estimated by the model should be seen as central estimates. We refer to the model's central estimates or assumptions as

5 Not explicitly calculated in our model are the following components: electricity distribution costs for battery-electric trucking, tank ship distribution, direct air capture, hydrogen storage, fuel buffer storage, and refueling infrastructure at ports and airports. Instead, they are considered fees based on external data inputs.

6 Mismatch between supply and demand assumed to be balanced by Norwegian hydropower [37].

7 In [16] lined rock caverns are assumed, which are also considered in this study. Given that the technical potential has not been fully explored, a sensitivity analysis of varying storage costs can be found in [16].

8 Raw hydrogen is the feedstock for hydrogen derivatives such as ammonia and e-fuel, extracted from the hydrogen value chain.

Table 1
Key assumptions used in the holistic cost model [16], extended by data for battery-electric trucking. Data on energy content always refer to the low heating value. Data placed solely in the central column is relevant for all years. All additional data used is listed in [16].

	2020	2035	2050	Unit	Source
Wind (offshore; onshore)	3,200; 1,500	2,000; 1,030	1,650;950	€/kW$_{el}$	[16]
Full load hours	4,400; 3,200	4,400; 3,200	4,400; 3,200	h/a	[16]
Hydropower		2,350		€/kW$_{el}$	[16]
Full load hours		7,000		h/a	[16]
Electrolysis	1,100	525	330	€/kW$_{el}$	[16]
Hydrogen liquefaction	2,300	1,255	700	€/kW$_{H2}$	[16]
Electricity demand	0.36	0.22	0.21	kWh$_{el}$/kWh$_{H2}$	[16]
E-fuel synthesis	800	525	400	€/kW$_{fuel}$	[16]
CO_2 cost	600	190	90	€/t$_{CO2}$	[16]
Ammonia synthesis		995		€/kW$_{fuel}$	[16]
Truck fuel station (diesel/e-fuel; hydrogen; battery)	2M; 6M; 0.47M	2M; 4M; 0.35M	2M; 3M; 0.3M	€	[16,40]
Truck tractor unit (diesel/e-fuel; hydrogen; battery)	110k; 450k; 420k	110k; 160k; 150k	110k; 155k; 150k	€	[16,40]
Fuel cost (pump, from onshore wind)	7.2/40.6; 21.6; 9.3	7.2/18.8; 13.2; 7.6	7.2/12.8; 10.2; 7.3	ct/kWh$_{fuel}$	[16]
Fuel economy	3.0; 2.53; 1.52	3.0; 1.90; 1.15	3.0; 1.79; 1.15	kWh$_{LHV}$/km	[16,40]
Maximum payload; annual mileage	25; 120,000	25; 120,000	25; 120,000	t; km	[16]
Payload factor (market + fuel density)	60; 60; 57	60; 60; 57	60; 60; 57	%	[16,8]
Ship (HFO/e-fuel; ammonia; hydrogen)	28M; -; -	28M; 56M; 56M	28M; 34M; 37M	€	[16]
Fuel cost (pump, from onshore wind)	3.2/40.5; 18.9; 21.0	3.2/18.7; 12.2; 12.8	3.2/12.7; 10.8; 9.8	ct/kWh$_{fuel}$	[16]
Fuel economy	647; -; -	647; 534; 534	647; 519; 519	kWh$_{LHV}$/km	[16]
Maximum payload; annual mileage	9,450; 118,231	9,450; 118,231	9,450; 118,231	t; km	[16]
Payload factor (market + fuel density)	65; -; -	65; 60; 59	65; 60; 59	%	[16,41]
Airplane (kerosene/e-fuel; hydrogen)	40M; -	40M; 100M	49M; 52M	€	[16]
Fuel cost (pump, from onshore wind)	4.2/40.7; 21.1	4.2/18.8; 12.9	4.2/12.9; 9.9	ct/kWh$_{fuel}$	[16]
Fuel economy	38.8; -	38.8; 38.8	38.8; 38.8	kWh$_{LHV}$/km	[16]
Maximum payload; annual mileage	20; 863,949	20; 863,949	20; 863,949	t; km	[16]
Payload factor (market + fuel density)	75; -	75; 62	75; 62	%	[16]

Table 2
CO_2 emissions per fossil fuel type applied for trucking, shipping and aviation.

Fuel type	CO_2 intensity [t$_{CO2}$/t$_{fuel}$] [44]	Fuel economy [l/km] [16]	Fuel density [kg/l] [16]	Max. payload [t] [16]	Payload factor [%] [16]	CO_2 emission [g/tkm]
Truck: Diesel	3.17	0.30	0.841	25	60	53.32
Ship: Heavy fuel oil	3.20	57.41	0.990	9,450	65	29.61
Airplane: Jet fuel	3.15	4.00	0.809	20	70	679.57

"Base Case" values to differentiate them from values derived after introducing policy interventions.

The possibility of importing fuel from other countries [21,32] is neglected, as our primary focus is on domestic energy production in three specific locations, suitable respectively for offshore wind, onshore wind, or hydropower generation [16]. Norway's solar power potential, which is below 1.2 MWh/kWp [39], is also excluded from this study, as it does not play a significant role in Norway's 2050 energy strategy [18].

In this paper, we quantify carbon abatement costs for carbon-neutral transport using the LCCA metric. Our approach is similar to levelized metrics in previous literature on abatement costs in other sectors [34,42,43]. LCCAs can equivalently be interpreted as long-run marginal abatement costs. The LCCA for a given technology is calculated using

$$LCCA = \frac{LCOT^A - LCOT^O}{E^O - E^A}. \tag{1}$$

Equation (1) calculates the levelized cost of carbon abatement in €/tCO_2 by dividing the annual costs of technology change by the carbon abatement achieved by switching fuels. $LCOT^O$ represents the levelized cost of the conventional transport[9]; $LCOT^A$ represents the levelized cost of transport for a carbon-neutral alternative. Thus, $LCOT^A$ - $LCOT^O$ is the cost associated with the technology switch. E^O represents CO_2 emissions associated with fossil fuel combustion, and E^A the emissions of the fuel alternative. CO_2 emissions are collected from Statistics Norway [44] and shown in Table 2. We only consider combustion-related CO_2 emissions (scope 1 emission [24]) during the vehicle operation and neglect up- and downstream emissions for the production and recycling process of components in the vehicle and fuel value chains. CO_2 emissions caused by e-fuel combustion are equal to the amount initially captured from the atmosphere during the fuel production process (closed carbon cycle). As a result, we assume E^A for electricity, hydrogen, ammonia and e-fuel to be net zero. We calculate the CO_2 emissions per tonne-kilometer based on representative payload capacities, which are 60% for long-haul trucking, 65% for short-sea shipping and 75% for medium-haul aviation [16]. We assume a lower payload capacity for battery-electric trucking, hydrogen and ammonia-powered shipping, and hydrogen-powered aviation, as the energy densities of the fuel systems impact either the gravimetric or volumetric requirements of the vehicle [8,16].

The levelized costs of transport ($LCOT^A$ and $LCOT^O$) are estimated for each fuel throughout its value chain in the three transport sectors. First, levelized costs are sum totals of the levelized cost of individual processes along the value chain (Equation (2)), denoted by $LCOX_i$ for process i. More precisely, the costs of upstream processes are the input costs of downstream processes, taking efficiency losses and technical dependencies into account.

$$LCOT = \sum_i LCOX_i \tag{2}$$

$$LCOX_i = \frac{Capex^i * UCRF + Opex^{i,fix}}{Q^i} + Opex^{i,var} \tag{3}$$

$LCOX_i$ is the levelized cost of an arbitrary process i (e.g. wind power generation, electrolysis, truck transport), $Capex^i$ capital expenditures of i, $Opex^{i,fix}$ fixed operational expenditures of i per year, Q^i

[9] The costs of the original, fossil-fuel-based transport include the cost of new fossil fuel infrastructure (distribution, refueling, vehicles) as we assume that existing assets have to be replaced in the time horizon of 2050.

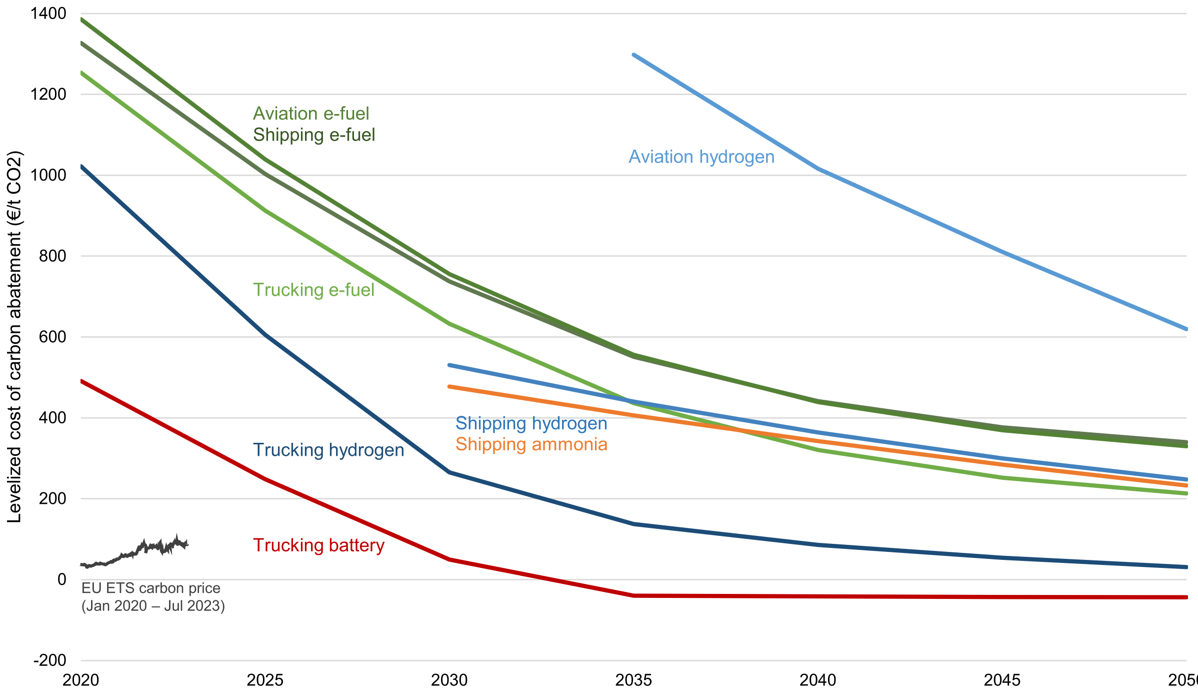

Fig. 2. Carbon abatement costs for the renewable fuels produced by onshore wind and used in three transport sectors towards 2050 (battery-electric trucking and historic EU ETS carbon prices give context [45]). For uncertainty ranges, see Fig. 4. Each line shows the costs of using a given renewable energy carrier instead of a fossil fuel benchmark.

annual outcome quantity of i, $Opex^{i,var}$ variable operational expenditures of i per outcome unit (Equation (3)). $UCRF^i$ represents the Universal Capital Recovery Factor of i, which is calculated as

$$UCRF^i = \frac{WACC * (1 + WACC)^{N^i}}{(1 + WACC)^{N^i} - 1} \tag{4}$$

where $WACC$ is the weighted average cost of capital over N^i as the specific lifetime of i. Changes in the $WACC$ impact the investment cost of capital expenditures along the value chain, allowing us to capture its impact on the cost of using renewable fuels.

We use the model to test the impact of different subsidies (equivalently, cost reductions). In section 3.2, we quantify the impact of subsidies on individual parts of the value chain and in section 3.3 we test the impacts of a portfolio of subsidies. To quantify the impact of a subsidy, we use

$$LCCA^{subsidized} = \frac{\sum_j LCOX_j^{subsidized} * s_j + \sum_k LCOX_k^{non-subsidized} - LCOT^O}{E^O - E^A} \tag{5}$$

where $LCOX_j^{subsidized}$ represents the levelized cost of a process step along the value chain j that may be subsidized; s_j is a fraction between 0 and 1 representing the impact of government intervention on the respective cost in process step j (e.g. a 10% subsidy would cause s_j to be 90%); $LCOX_k^{non-subsidized}$ denotes a process step k that is assumed to remain unsubsidized. In section 3.3, we assume a subsidy that halves the costs of the selected process step. This is chosen for illustrative purposes and our results can be extrapolated to different subsidy levels.

3. Results and discussion

3.1. Abatement costs for renewable fuels

Figs. 2 to 4 present all estimated carbon abatement costs, quantified using the LCCA metric as discussed in the previous section.

The cheapest abatement options within each sector are those that use the lowest-cost technologies in terms of €/tkm (as carbon abatement costs are calculated relative to the same fossil fuel benchmark in each sector) which is discussed in detail in [16]. As shown in Fig. 2 (based on electricity from onshore wind) in the trucking sector, the cheapest abatement is via battery-electric propulsion, which is estimated to be 491 €/tCO_2 in 2020 and −44 €/tCO_2 in 2050.[10] Hydrogen-powered trucking has twice as high abatement costs as battery-electric trucking in 2020, which can be explained by lower fuel economy (66% more energy needed) in combination with higher fuel costs of hydrogen (95% higher than electricity). Abatement costs for e-fuel in trucking are even higher than for battery-electric because the comparably low vehicle Capex of a conventional truck does not offset higher fuel costs (245% higher than electricity) combined with a lower fuel economy (97% more energy needed). However, compared to shipping and aviation, the use of e-fuel is more cost-effective in trucking, where fuel costs constitute a smaller share of the overall cost structure [16]. While shipping is more sensitive to e-fuel costs than aviation, primarily because fuel costs play a predominant role in the shipping sector and heavy fuel oil is comparably cost-efficient [16], the higher CO_2 intensity of heavy fuel oil (+7% compared to jet fuel) brings e-fuel use to similar carbon abatement costs as those observed in aviation. In shipping, ammonia and hydrogen are assumed to become available in 2030 [16]. In that year, ammonia exhibits the lowest abatement cost of 478 €/tCO_2, which decreases to 233 €/tCO_2 in 2050. In comparison to hydrogen, ammonia-powered shipping benefits from lower fuel costs and greater payload capacity due to a higher energy density of the fuel system [8]. In aviation, e-fuel use costs 1,386 €/tCO_2 in 2020. It remains the cheapest abatement option in this sector all the way to 2050, when it is estimated to cost 330 €/tCO_2. Hydrogen-powered aviation lags significantly behind due to high airplane Capex and a notable loss of payload resulting from the fuel storage system, which increases the overall transport costs [16].

[10] Negative carbon abatement costs refer to a situation where the cost of technology change not only reduces emissions but also generates economic benefits or cost savings.

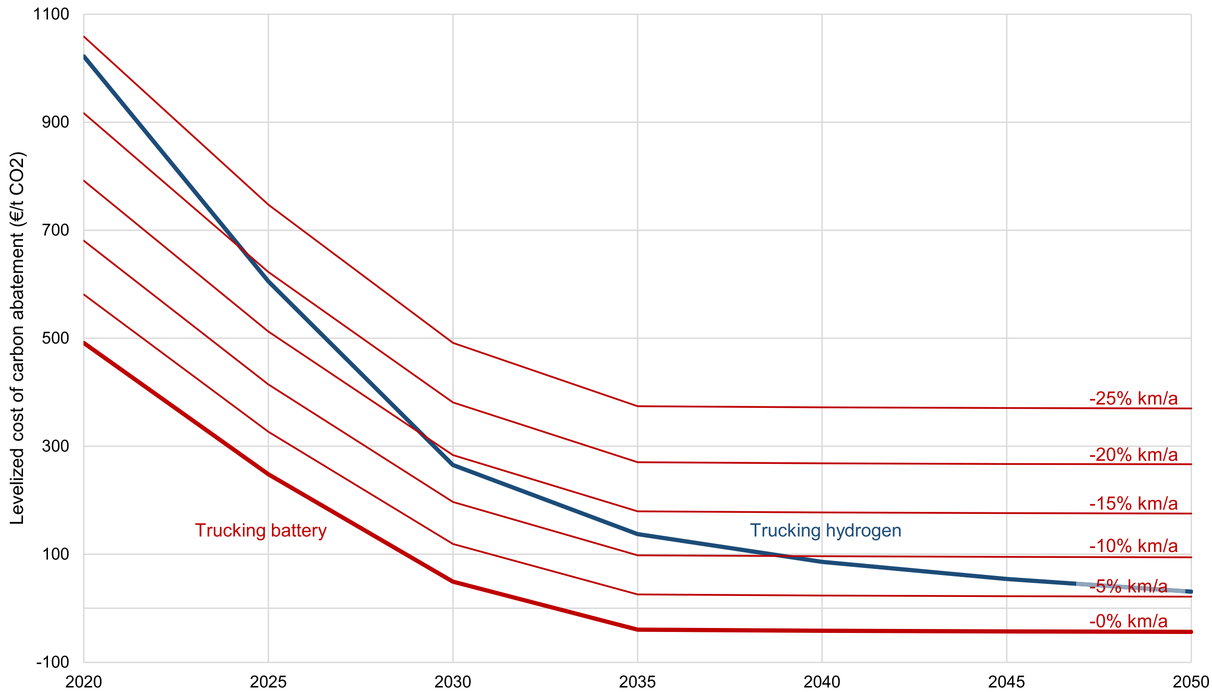

Fig. 3. Carbon abatement costs for battery-electric trucking, with different mileage limitations, are compared to hydrogen-based trucking up to 2050. Each line shows the cost of using a given renewable energy carrier instead of a fossil fuel benchmark.

The abatement costs of using e-fuels in shipping and aviation are similar. This raises questions whether the two sectors may compete for e-fuel demand. This will not necessarily be the case because shipping also has access to more cost-effective fuel alternatives.

In Fig. 3 we reduce the annual mileage of battery-electric trucking and investigate the impact on its abatement cost. Recall that the Base Case battery costs shown in Fig. 2 assume the same annual mileage for battery trucking and hydrogen. However, transport companies face high uncertainty regarding the fleet efficiency of battery-electric trucks (due to e.g. waiting times for charging, or charging power availability in dense areas) [40]. The results indicate how dependent abatement costs are on the technological capability and infrastructure availability associated with battery trucking, for which the assumed annual mileage is a proxy. To give context, a daily loss of driving time (1 hour/ 30 minutes/ 15 minutes), on 245 days per year, and an average driving speed of 50 km per hour would reduce the annual mileage (120,000 km) by 12,250 km (−10.2%), 6,125 km (−5.1%), and 3,063 km (−2.6%), respectively. Hydrogen-powered trucking could be an attractive alternative, where the potential mileage loss of battery-electric trucks becomes economically prohibitive. However, rapid improvements in battery technology, the increasing density of infrastructure, and the potential optimization in rest periods used for charging put high pressure on the competitiveness of hydrogen-powered trucking.

Fig. 4 presents the LCCA for fuel and transport options in ascending order for 2020, 2035 and 2050 respectively. The shown error bars cover the range of cost values in the literature [16]. Overall, the source of electricity (hydro low-cost, offshore high-cost), the efficiency of fuel value chains from production to consumption (battery highest, e-fuel lowest [16]), and the specific carbon intensity of the fossil fuels replaced (heavy fuel oil highest, jet fuel lowest) are the driving factors behind the cost ranking. In 2020, comparing across sectors and electricity sources, we find the lowest abatement costs in the trucking sector, equal to 446 €/tCO_2 for battery-electric trucks and 793 €/tCO_2 for hydrogen-powered trucks, both produced from hydropower and assuming the same annual mileage. Battery-electric and hydrogen-powered trucking are the lowest-cost abatement options throughout the studied time frame if electricity comes from hydro. This is due to the trucking sector exhibiting a moderate cost premium on a €/tkm basis [16] and the relative emission intensity of diesel-powered trucks (Table 2). The next-lowest abatement cost is found for e-fuel in the shipping sector based on hydropower equal to 1,005 €/tCO_2 in 2020. Its rank underlines the sensitivity to and thus the importance of cheap electricity sources in the context of renewable fuel use since this abatement option is even cheaper than early hydrogen use in trucking from more expensive onshore wind. For trucking, e-fuel from low-cost hydropower could outperform hydrogen use with its initially high Capex and fuel from high-cost offshore. However, in 2035, hydrogen-powered trucking is the second most cost-effective abatement option across all electricity sources, second only to battery-electric trucks. This shift is driven by significant Capex reductions. The potential for such a cost decline diminishes the appeal of e-fuel usage. For the shipping industry, the utilization of ammonia and hydrogen as fuels presents appealing alternatives, making e-fuel attractive only when it can exclusively leverage low-cost electricity from hydropower. Consequently, e-fuels produced from onshore or offshore wind sources consistently result in higher abatement costs compared to the use of ammonia and hydrogen in shipping. Compared to hydrogen, ammonia demonstrates a lower abatement cost when sourced from low-cost electricity, while the situation reverses with high-cost electricity sources. Moving forward to 2050, ammonia and hydrogen-powered shipping remain competitive as abatement options due to substantial reductions in Capex, despite ongoing declines in e-fuel costs. In contrast, hydrogen-powered aviation, assumed available as of 2035, remains the most expensive carbon abatement option across all electricity sources. E-fuel is a cost-competitive option in the aviation sector until 2050.

The results reveal that the availability of low-cost electricity for harder-to-abate transport sectors (and those more sensitive to electricity costs) may be important if policy makers wish to support multiple sectors at the same time. In this context, the possibility of importing low-cost renewable fuels from resource-rich global sites and their use in trucking is explored by [33].

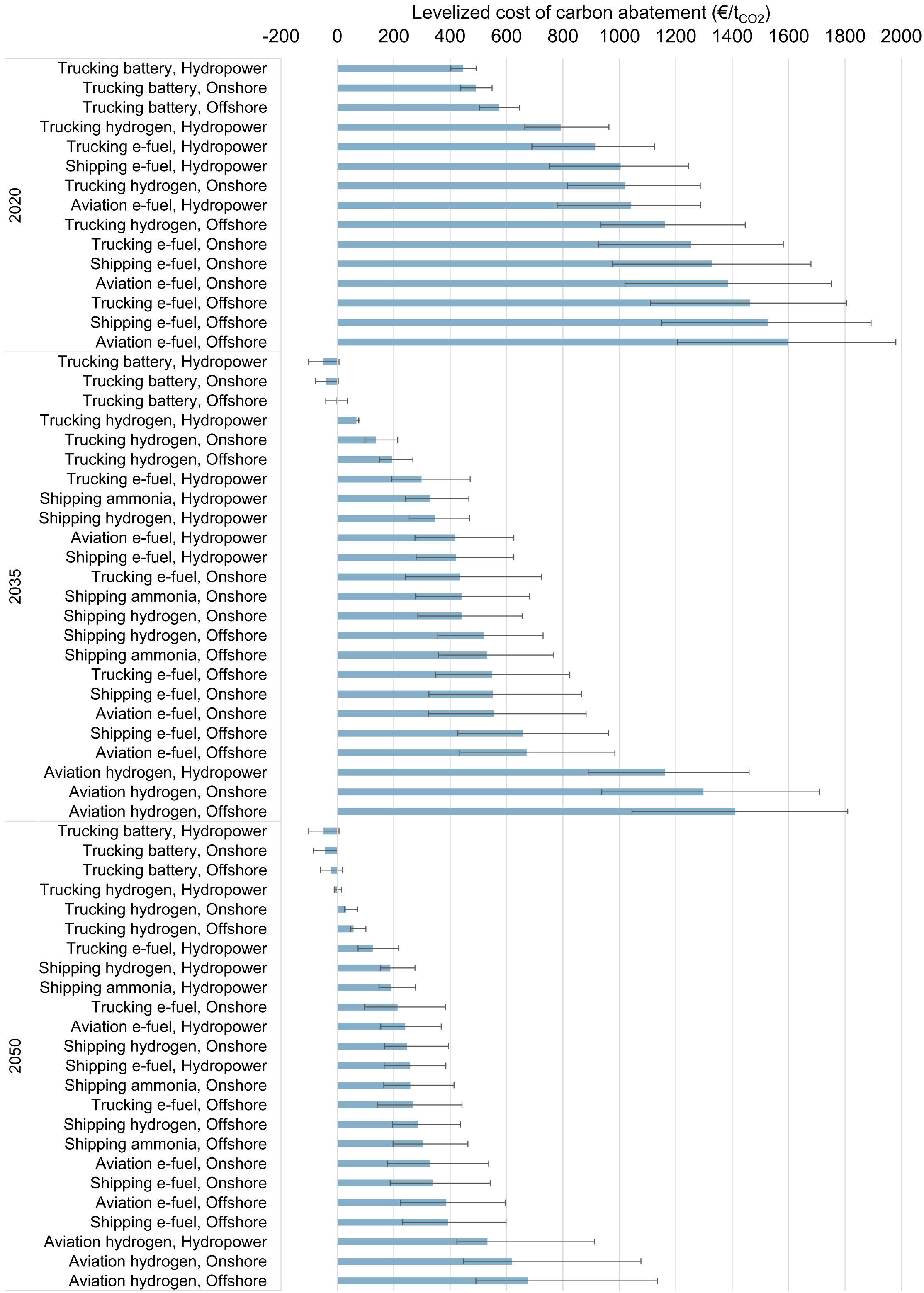

Fig. 4. Carbon abatement cost for the renewable fuels produced by hydropower, onshore wind, and offshore wind and used in three transport sectors for 2020, 2035 and 2050 (battery-electric trucking gives context).

3.2. Impact of cost reductions at different points on the value chains of renewable fuels

Fig. 5 shows how government support for individual cost inputs (on the x-axis) impacts total carbon abatement costs (on the y-axis). These costs represent fuels derived from onshore wind power, which is between the costs of hydro and offshore wind and may be considered more broadly representative. Reduction in input costs can be interpreted as representing subsidies that lower the cost incurred by producers for a given input. For example, the U.S. Inflation Reduction Act provides tax credits for clean hydrogen equivalent to a subsidy of up to 3 $/kg, or approximately 2.5 €/kg (based on the 2021 exchange rate). Such a

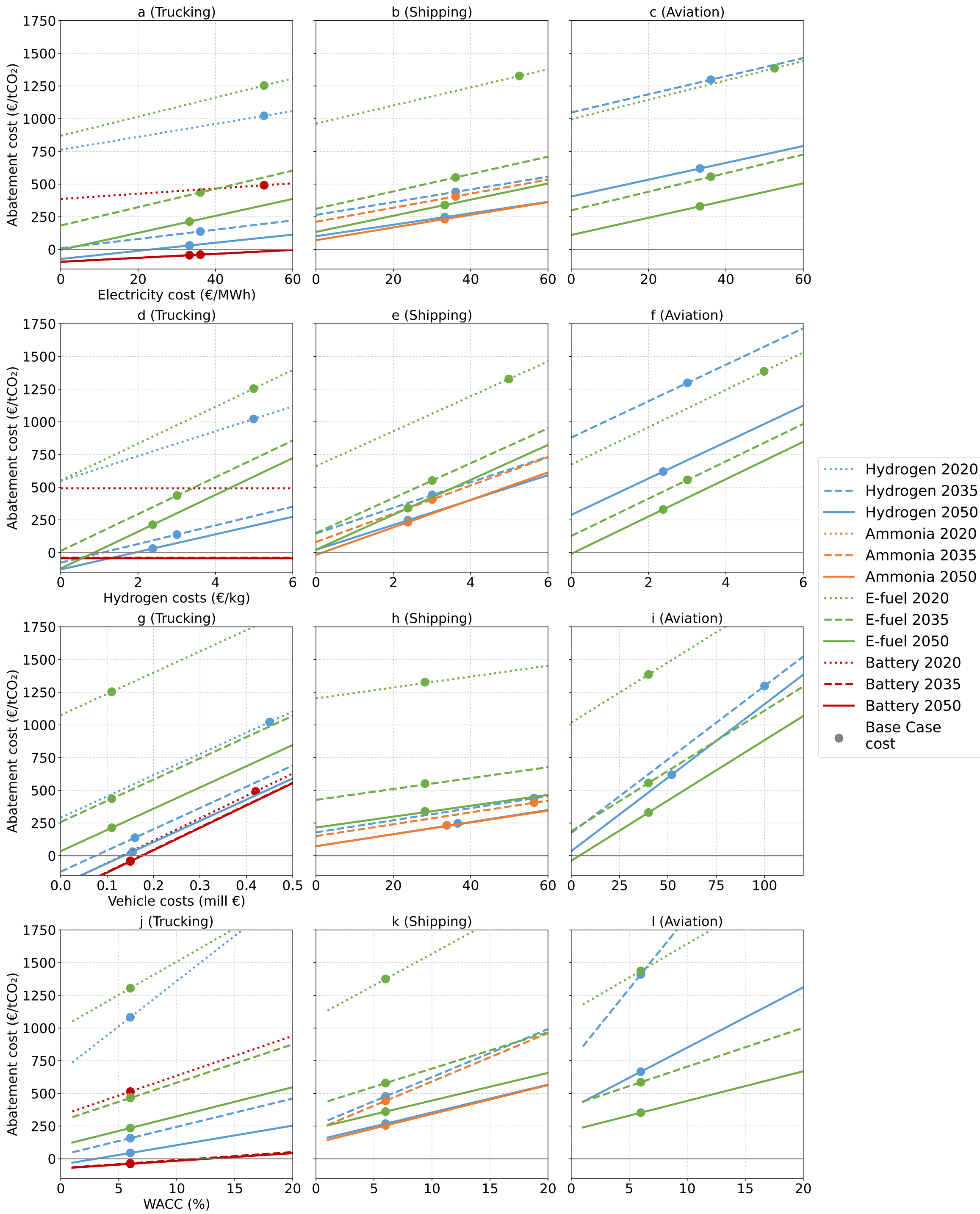

Fig. 5. Impact of cost changes on carbon abatement cost. Each line shows the abatement cost of using a given renewable fuel instead of a fossil fuel benchmark (battery-electric trucking gives context). The slope of the line indicates the impact of government intervention that changes a given input cost or parameter (x-axis) on abatement costs (y-axis).

subsidy would bring the carbon abatement cost for hydrogen-powered trucking to 786 €/tCO_2 in 2020 (as shown in panel d in Fig. 5), down from 1,022 €/tCO_2 under Base Case costs.

Within sectors, we find that subsidy impacts differ between technologies. As shown by the comparably flat slope, battery-electric trucking is the least sensitive to changing electricity costs. This is because it represents the most efficient system by far (approximately 80% for battery-electric, 30% for hydrogen-powered, and 20% for e-fuel-powered trucking; all values well to wheel energy efficiency [16]). In trucking and shipping, subsidies on the costs of hydrogen or electricity lower the cost of e-fuel-powered transport more than battery-electric and hydrogen-powered transport (as shown by the steeper slope). This can be explained by the multiplicative effect of higher efficiency losses in e-fuel production (e-fuel synthesis) and consumption (internal combustion engine), which make these fuels more dependent on the costs of electricity and hydrogen. For aviation, the differences between hydrogen and e-fuel are minor because both fuels are burned in jet engines with the same assumed efficiency. Here, the difference is due to energy losses in the e-fuel synthesis.

Over time, the impact of electricity costs on abatement costs decreases; this is due to efficiency improvements in the conversion processes (such as electrolysis). For vehicles using fuel cells, this development is strengthened by additional efficiency gains of the fuel cell systems impacting both the slopes for electricity and hydrogen cost changes. In contrast, the slopes for hydrogen cost changes in aviation are parallel over time for both fuel types (as there are expected no efficiency gains).

Comparing slopes for vehicle cost changes (panels g-i in Fig. 5), hydrogen or e-fuel-powered trucking run almost parallel, whereas battery-electric trucking, ammonia or hydrogen-powered shipping and hydrogen-powered aviation are more sensitive (steeper slopes). Differences in slopes are caused by two factors: payload limitations caused by vehicles operating below full load (market inefficiency) [7,46] and payload limitations caused by mass and volume requirements of the respective fuel system (fuel-based payload constraints) [8,16]. Within a given mode, we assume that market inefficiencies affect all vehicle types equally. The lines for hydrogen and e-fuel-powered trucking are parallel because we assume the same payload capacities for both options. In this sector, a fuel-based payload limitation is only assumed for battery-electric trucking due to the battery system's comparably high share of the vehicle's weight and volume [7,8]. In shipping and aviation, payload limitations are present due to requirements for ammonia or hydrogen storage (see Table 2) and these impact overall transport costs [16]. As a result, these technology options are relatively more sensitive to vehicle costs, which must be allocated to less cargo (steeper slopes). Overall these results also reflect the importance of improvements in the energy density of tank systems and optimizing transport patterns to achieve high load factors.

Next, we quantify the effect of policies that impact the Weighted Average Cost of Capital (WACC) across renewable fuel value chains (panels j-l in Fig. 5). Such policies may include interventions that decrease financial risk, such as long-term contracts. For example, it has been estimated that the use of Contracts for Differences in the UK has lowered renewable WACC by 3% [47]. Our model assumes a WACC of 6% across all renewable fuel value chains covered in the Base Case, but this parameter is uncertain and may be significantly higher for specific projects and geographies. Risk is considered a key barrier for the "first of a kind projects" necessary for renewable fuel development [48].

This analysis estimates that a 1% point change in the WACC changes carbon abatement costs for battery-electric trucking by 30 €/tCO_2 and hydrogen-powered trucking by 69 €/tCO_2 in 2020, and by 37 €/tCO_2 and 110 €/tCO_2 in hydrogen-powered shipping and aviation in 2035. This suggests that de-risking capital investments along the value chain may be an important part of future policy packages. This finding extends existing work which emphasizes the importance of OPEX costs and suggests that policy makers prioritize OPEX subsidies to trucking companies [7]. Our results highlight the importance of capital costs because the holistic scope of our model captures the impact of the cost of capital on the total cost of fuel production.

Varying the WACC has a greater impact on capital-intensive technologies. Generally, hydrogen and ammonia value chains are more capital-intensive than battery-electric and e-fuel value chains (as shown by the steeper slopes in Fig. 5). Besides the fuel production assets, this is mainly due to the capital cost of new vehicle technologies, particularly in the first years when new vehicles become available.

These results may underestimate the importance of the WACC, because we do not capture its impacts on the cost of electricity distribution (for battery-electric trucking), tank ship distribution, direct air capture, hydrogen storage, fuel buffer storage, and refueling infrastructure at ports and airports. This is because the costs associated with these assets enter into our model exogenously as fees. A more detailed representation is left for future work. We note however, that this omission impacts the relative impacts of the WACC on different sectors. Nevertheless, the overall conclusions should be robust, as the mentioned components (besides direct air capture[11]), primarily increase the impact of the WACC on hydrogen-powered transportation which is already the most affected.

The combination of capital costs of hydrogen-powered vehicle technology and infrastructure outweighs additional capital expenses related to the synthesis of e-fuel (and comparably low-cost vehicles) or vehicle costs in battery-electric transport (and comparably low-cost electric infrastructure). The impact of the WACC decreases over time (illustrated by the decreasing slopes). This is because most technologies become less capital intensive due to learning and scaling effects along the value chains [16].

3.3. Policy mixes for renewable fuels

The previous section examined the impacts of one type of government intervention at a time. We now explore the impact of potential policy mixes aiming at deploying renewable fuels. Fig. 6 presents hydrogen for long-haul trucking, ammonia for short-sea shipping and e-fuel for medium-haul aviation, each shown in 2035, with fuels produced from onshore wind power.

The vertical line on the right side of each figure separates the carbon-neutral transport and possible incentives (left) from the fossil fuel-powered counterpart including the impact of CO_2 pricing and fuel cost variation (right). Potential component and process subsidies along the value chain bring the carbon-neutral transport cost down (left), potential CO_2 pricing bring fossil fuel-powered transport costs up (right). All transport options are shown in terms of their total cost of ownership in cost per tonne-kilometer. We choose parts of the value chain that may receive future subsidies based on ongoing policy processes [12,48, cf.]. For illustrative purposes, we subsidize components and processes with the equivalent of 50% of its cost. Although we halve the costs of several dominant cost drivers in the value chain, additional carbon pricing remains necessary to close the gap in total cost of ownership for shipping and aviation. Importantly, Fig. 6 quantifies the absolute value of each cost parameter and thus the amount of subsidy assumed, which allows for our results to be extrapolated for alternative absolute values.

Fig. 6 also displays the impact of potential changes in the cost of fossil fuels. The bottom corner of the light gray bar (e.g. 0.7 €/l for trucking, tax-free, EU average production cost between January 2020 and March 2022 [49]) represents the Base Case fossil fuel cost [16]. Potential fuel cost changes can be interpreted either as cost volatility or as the impact of taxes or subsidies on fossil fuels. For example, the indicated carbon prices can be replaced by an increase in fuel costs equal to 0.30 €/l diesel fuel for the hydrogen trucking case in 2035 (represented by the light gray bar on the right). As an indication of the total economic impact, this fuel cost increase equates to a public cost of 292M €, 2.4B €, and 6.5B €in Norway, Germany, and the EU respectively, assuming a traffic volume of 16.6B tkm in Norway, 137.1B tkm in Germany and 367.2B tkm in the European Union in 2021 for road freight >30.5 tonnes, and a fuel economy of 30 l/100 km and 16 t average load [50]. In comparison, diesel production cost of June 2022 (peak of Energy crisis'22) excluding all taxes equaled approximately 1.30 €/l [49]. At similar production cost in 2035, renewable hydrogen would easily be cost-competitive with fossil diesel without carbon pricing. Fuel prices could also increase if policy makers remove existing fossil fuel subsidies, which could include additional pricing of environmental and social damages [51]. In [16], fossil fuel costs of 1.40 €/l, 1,800 €/t, 2,400 €/t are needed to make hydrogen-powered trucking, ammonia-powered shipping, and e-fuel-powered aviation cost-competitive in 2035 respectively, which are in line with the values shown here.

[11] Furthermore, [16] show the limited impact of DAC carbon cost variation. They find that for the shipping industry, carbon costs of 100 €/t (a 47% reduction from the Base Case) in 2035 and 20 €/t (a 78% reduction) in 2050 would make e-fuel more economically attractive than ammonia. At the same time, [22] show that Capex (affected by WACC) only accounts for 26–30% in the levelized cost of direct air capture.

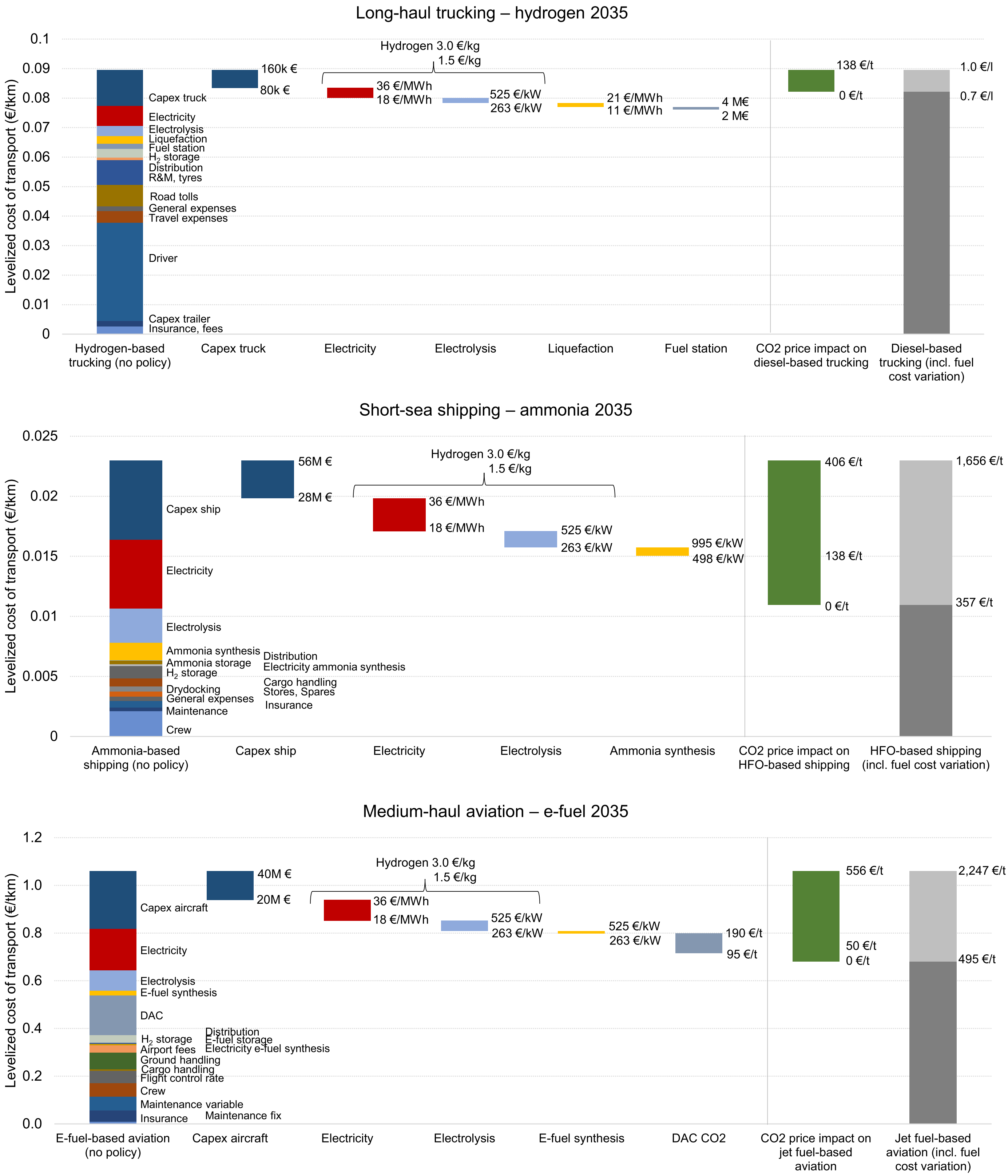

Fig. 6. Policy mixes closing the cost gap to fossil fuel-powered transport with additional CO_2 pricing. Hydrogen for long-haul trucking, ammonia for short-sea shipping, e-fuel for medium-haul aviation in 2035 (HFO: Heavy fuel oil, DAC: Direct air capture).

Fig. 6 can also be used to show how cost reduction and subsidy impacts may interact. The relationship between the absolute cost change per component or process and the change in the resulting transportation costs is linear. This means that, in the case of shipping for example, cost parity would roughly require a 100 percent subsidy on the ship's Capex, reducing vehicle cost from 56M € to 0 € or a 100 percent subsidy on the electricity cost. Many countries such as Norway exempt carbon-neutral vehicles from governmental interventions that however apply to fossil fuel-powered transport. This can include exempting carbon-neutral vehicles from value-added taxes or additional infrastructure fees. Such taxes are not included in the dark gray bar on the right, but the light gray bar illustrates their potential impact. Similar interactions between cost reductions and policies can be observed for all three sectors in Fig. 6, but magnitudes differ due to differences in the cost structures of transport sectors.

4. Policy implications

The future cost reductions presented in this paper assume technological innovation which will in part depend on government incentives for research and development and on deployment subsidies encouraging learning-by-doing effects. The projected cost declines should thus be interpreted with caution. Previous European efforts to support wide scale hydrogen diffusion have been largely unsuccessful; for example the European Hydrogen and Fuel Cell Technology Platform founded in 2003 set a number of aspirational goals for hydrogen use by 2020, which were not met [52]. Today, government support for hydrogen is broader. In addition to continued support in Europe, the US Department of Energy launched an Energy Earthshot initiative in 2021 aiming to reduce the cost of renewable hydrogen to 1 $/kg within a decade [53]. Still, the future level of policy ambition remains to be seen and the technical potential for innovation is yet to be demonstrated.

Several implications for policy making follow from our analysis. From a cost-benefit perspective, our abatement cost estimates can be compared to the marginal benefit of carbon abatement. A commonly used estimate of marginal benefit is the Social Cost of Carbon. There is disagreement on the magnitude of the Social Cost of Carbon [54]. A recent estimate places the 2020 Social Cost of Carbon at 185 $/tCO$_2$ (with a 5–95% range of 44–413 $) [55]. Recent work adopts target-based approaches to valuing the marginal benefit of abatement [56,57]. For example, UK BEIS [57] determine carbon values of 120–361 UK pounds per ton in 2020 and 189–568 in 2050. Relative to these values for the Social Cost of Carbon, our abatement cost estimates suggest that renewable hydrogen, ammonia and e-fuels could be welfare-improving (benefits of abatement exceeding abatement costs) by 2050. Battery-electric trucking could be justified as an abatement option sooner due to its potentially lower cost. However, whether abatement costs are in fact justified by marginal benefits will depend strongly on the exact marginal benefit values, which are in turn subject to the inter-temporal value judgments (i.e. preferred discount rates) and risk preferences [58] of any given jurisdiction.

One way governments can improve hydrogen economics is by de-risking capital-intensive parts of the value chain, for example by implementing Carbon Contracts for Differences, currently being discussed in the EU [12] and in Norway [59]. Carbon Contracts for Differences may be designed as contracts with a public counterpart that pay out the difference between actual carbon prices and a pre-determined carbon price strike level [12]. Contracts for Differences are also being discussed as a way to support hydrogen development [48]. Such contracts could offer compensations equal to the difference between a pre-determined hydrogen strike price necessary for hydrogen producers to recover costs (potentially set through an auction) and actual hydrogen market prices (for example in €/kg). A key feature of long-term contracts such as Carbon Contracts for Differences and Contracts for Differences is the mitigation of risk for hydrogen providers that stems from volatility in the carbon price (in the case of Carbon Contracts for Differences) or hydrogen price (in the case of Contracts for Differences); however, an important consideration is that this risk is not eliminated but is instead transferred to the government. De-risking achieved through Carbon Contracts for Differences or Contracts for Differences could allow hydrogen companies to secure financing at lower costs. Our findings show that the WACC for renewable fuel value chains could potentially emerge as a significant focal point for future policy considerations. The cost of capital has been highlighted to be a strong determinant of levelized renewable cost [60]. We similarly show that reductions in the WACC can materially reduce the abatement costs of hydrogen-powered transport in particular.

Direct government subsidies, in the form of grants and tax credits for example, are also being considered and implemented [48,61,62]. Our analysis quantifies the potential impacts of subsidies on carbon abatement costs for renewable fuels. The results show that for renewable fuels to be at cost parity with fossil fuels, governments support is necessary at multiple points on the value chain. Government support for research, development, and deployment is likely to play an important role in overcoming path dependencies and internalizing knowledge spillovers that may otherwise hinder technological development [63,64]. Such technology support requires not only “market pull” (e.g. through carbon pricing), but also “technology push” through producer subsidies [64,65]. The sensitivity of abatement costs to the €/kg cost of hydrogen suggests that hydrogen costs could be a focal point for future hydrogen-related innovation policy. The U.S. Inflation Reduction Act provides a tax credit for clean hydrogen of up to 3 $/kg. Our results show that with current costs, hydrogen-powered trucking would still require a high carbon price or other incentives to be cost-competitive. However, potential cost declines of components and processes across the value chain alleviate the need for subsidies. By 2035, the cost model we use suggests a potential hydrogen cost of 3 €/kg. This suggests that either a carbon price of 138 €/tCO$_2$, or a lower carbon price paired with a hydrogen subsidy would make hydrogen-based trucking cost-competitive with fossil fuels. As governments seek to support hydrogen technology, our cross-sector comparison can help in the identification of potential niches. Among the hydrogen-based fuel applications we considered, long-haul trucking is the lowest-cost abatement option. However, the economic feasibility of hydrogen in this sector is subject to competition from battery-electric trucks, and the extent to which the energy density disadvantages of battery-electric trucks will be overcome. Another early hydrogen market could be the use of e-fuel for shipping and aviation (also as fuel blending).

5. Results relative to prior research

Table 3 validates this study’s results against literature values. The variety in model set-ups and carbon intensity of fuels make it hard to compare study results [15]. However, tendencies and deviations stand out. Overall, the study’s abatement costs largely align with existing estimates.

Compared to this study’s results for hydrogen-powered trucking, the lower abatement costs in [21] could result from excluding additional vehicle costs for fuel cells and hydrogen tanks. Hence, the disparity in value is more pronounced in 2020 as compared to 2035 and 2050 values, when the influence of vehicle costs diminishes [16]. For e-fuel use, [21] assumes lower e-fuel costs in 2020 of 210 €/MWh compared to 313–460 €/MWh in this study, and a steeper cost decrease towards 2050, which may explain their lower abatement cost. In [30] for e-fuel use in trucking, results are presented based on fixed carbon costs of either 20 or 500 €/t_{CO2} over all investigated years (compared to 600 €/t_{CO2} in 2020, decreasing to 90 €/t_{CO2} in 2050 in this study), which results in a wider range of abatement costs. Our results show that carbon neutrality in shipping and aviation is economically harder to achieve than in trucking, which is in line with the findings in [15]. This can be explained by the large impact of fuel costs in the total cost of ownership in shipping and aviation (which becomes obvious through the total cost of ownership analysis in [16]). Wahl and Kallo [31] report a median abatement cost of 661 $/tCO$_2$ for renewable fuel-powered shipping. In [67] a carbon price of 350–450 €/tCO$_2$ is estimated to induce a fuel transition towards hydrogen, methanol and ammonia in the shipping sector. Lagouvardou et al. [26] estimate comparably low carbon abatement cost of 200–700 €/tCO$_2$ to make e-fuel-powered shipping a cost competitive option today. For 2040, [68] assume lower abatement costs for hydrogen-powered than for e-fuel-powered aviation, which stands in contrast to the findings in [15] and our results.

Table 3
Comparing the results with values reported in the literature. This study's result ranges encompass fuel from hydro (lower bound) and offshore wind (upper bound).

€/t_{CO2}	This study	Literature
Trucking battery-electric 2020	446 – 574	470 – 705 [66], 120 – 190_{2025} [30]
Trucking battery-electric 2035	-49 – -4	-120 – 110_{2030} [15], -100 – -30_{2030} [30]
Trucking battery-electric 2050	-49 – -22	-250 – -180_{2040} [30]
Trucking hydrogen 2020	793 – 1,163	580 – 647 [66], 200 – 300 [21], 580 – 780_{2025} [30]
Trucking hydrogen 2035	68 – 549	200 – 375_{2030} [15], 50 – 130 [21], 300 – 400_{2030} [30]
Trucking hydrogen 2050	-11 – 57	-10 – 50 [21], -50 – 80_{2040} [30]
Trucking e-fuel 2020	914 – 1,463	750 – 850 [21], 1,300 [66], 1,150 – $1{,}650_{2025}$ [30]
Trucking e-fuel 2035	299 – 549	200 – 350 [21], 300 – $1{,}200_{2030}$ [15], 80 – $1{,}080_{2030}$ [30]
Trucking e-fuel 2050	126 – 269	10–70 [21], -20 – 890_{2040} [30]
Shipping hydrogen 2035	345 – 519	320 – 800_{2030} [15], 350 – 450 [67]
Shipping hydrogen 2050	188 – 285	
Shipping ammonia 2035	301 – 493	270 – 900_{2030} [15], 350 – 450 [67]
Shipping ammonia 2050	167 – 274	
Shipping e-fuel 2020	1,005 – 1,526	200 – 700 [26]
Shipping e-fuel 2035	421 – 659	300 – $1{,}200_{2030}$ [15]
Shipping e-fuel 2050	257 – 393	
Aviation hydrogen 2035	1,162 – 1,410	490 – 950_{2030} [15]
Aviation hydrogen 2050	533 – 675	170_{2040} [68]
Aviation e-fuel 2020	1,041 – 1,598	
Aviation e-fuel 2035	417 – 671	400 – $1{,}200_{2030}$ [15]
Aviation e-fuel 2050	241 – 387	200_{2040} [68]

6. Strengths and limitations of this work

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

The strength of this study lies in its ability to disaggregate fuel and transport value chains. The advantage of this disaggregation is the ability to analyze the sensitivity of costs to a variety of policy instruments in the form of parameter variation. Martin, Neumann, and Ødegård [16] already outline the limitations of the underlying model approach. The following limitations are particularly relevant to this paper.

- The model includes several location-specific assumptions, here tailored to Norway. These include renewable availabilities (which impacts the levelized cost of electricity), renewable fuels being carbon-neutral, infrastructure limitations (no fuel pipelines), and infrastructure fees (on roads, ports and airports). However, these location-specific assumptions play a relatively small role in our model. The results are applicable to any region with similar renewable potential and the model is broadly usable by adjusting input variables. The sensitivity analysis shown in Fig. 5 offers insights into cost changes (e.g., electricity costs or WACC) that can also be interpreted as regional variations. The examples of national policies and fossil fuel costs provide context.
- We show carbon abatement cost and policy instruments for specific electricity production, fuels, and transport sectors. Analyzing the whole fuel and transport market was beyond our scope. Data specific to other use cases need to be updated for transferability. However, the model is easily adjustable to expand to further renewable potentials, fuels and transport sectors.
- We only consider scope-1-emissions (vehicle operation). Upstream emission and life-cycle emission should be considered in a more detailed approach. Thus emissions for both fossil fuel-powered transport and carbon-neutral transport value chains are lower than in reality.
- We do not investigate different fossil fuels per sector. Considering renewable fuels relative to less emissions-intensive maritime diesel oil could result in higher abatement costs for the shipping sector. The same holds for natural gas use in trucking.
- We focus on Norway as a closed system and neglect fuel import from other countries, which could compete with government incentives to make domestic fuel production cost competitive.
- Not explicitly calculated in our model are the following components: electricity grid, tank ship distribution, direct air capture, hydrogen storage, fuel buffer storage, and refueling infrastructure at ports and airports. Varying the WACC as a policy instrument may have a higher impact, especially on the hydrogen value chain.
- Vehicle operation is simplified with average parameters. A system model approach could extend the investigation to other abatement strategies such as mode shifting and demand reduction.
- We explore conditions under which renewable fuels are cost-competitive, but omit factors that influence fuel use other than cost, such as synergies with other sectors or security of fuel handling.

7. Conclusions

This paper shows that the abatement costs for carbon-neutral transport remain substantial and long-term incentives are required across sectors and fuels. Our analysis estimates costs of 793–1,598 €/tCO_2 in 2020 depending on the electricity source, transport sector and type of renewable fuel. The lowest abatement costs for 2020 are in battery-electric trucking 446–574 €/tCO_2, and the costs of this abatement option turn negative in 2030–2035 and beyond. Shipping, known for its cost sensitivity in adopting renewable fuels caused by the dominance of today's low-cost heavy fuel oil, offset the cost premium with the high carbon intensity, leading to lower carbon abatement costs compared to aviation. However, aviation with the highest abatement costs, could be an early market for e-fuel since alternatives are limited and fuel blending in existing infrastructures reduces upfront investments. Overall for 2050, our cost model estimates carbon abatement costs for renewable fuels of -11–675 €. We show that these abatement costs are driven by differences in electricity costs, the energy efficiency of renewable fuel value chains, and the type of fossil fuel replaced. Differences between value chains along these factors further mean that the effect of government intervention varies across fuel value chains. We show that e-fuel costs are particularly sensitive to subsidies on electricity costs. We further find that the weighted average cost of capital has a material impact on economic feasibility, particularly for the hydrogen value chains due to the relative capital intensity of fuel production assets (e.g. electrolysis) and new vehicle technologies. This suggests that policies that

Table 4
Data input used for battery-electric trucking for 2020, 2035 and 2050, extending the data base of [16]. The upper and lower bounds in parentheses represent the uncertainties used in Fig. 4. Data on energy content always refer to the low heating value. Data placed solely in the central column is relevant for all years.

Battery-electric trucking	2020	2035	2050	Source
Charging station				
Capex [€]	470,000 (+/-25%)	350,000 (+/-25%)	300,000 (+/-25%)	[40]
Max. output [GWh_{el}/a]		11		[40]
Utilization rate [%]	70%	85%	100%	[16]
Lifetime [a]		15		[40]
Opex [% of Capex]		1		[40]
WACC [%]		6		[16]
Electricity grid fee [ct/kWh_{el}]		4		[69]
Battery-electric semi-truck				
Capex [€]	420,000 (+/-15%)	150,000 (+/-5%)	150,000 (+/-5%)	[40]
Fuel economy [kWh/km]	1.52 (+/-5%)	1.21 (+/-5%)	1.15 (+/-5%)	[40]
Max. Payload [t]		25		[16]
Payload loss (market+fuel) [%]		57%		[8,46]
Insurance [% of Capex/a]		2%		[16]
Repair & maintenance [€/a]		15,000		[16]
Annual mileage [km]		120,000		[16]

Table 5
Changes in data input since [16]. The upper and lower bounds in parentheses represent the uncertainties used in Fig. 4. Data on energy content always refer to the low heating value. Data placed solely in the central column is relevant for all years.

Data changes since [Martin et al. 2023]	2020	2035	2050	Source
Diesel-powered trucking				
Fuel economy [kWh/km] (old)		3.2 (32 l/100 km)		[16]
Fuel economy [kWh/km] (new)		3.0 (30 l/100 km)		[40]
Hydrogen-powered trucking				
Capex [€] (old)	350,000 (+/-14%)	150,000 (+33%/-13%)	140,000 (+14%/-29%)	[16]
Capex [€] (new)	450,000 (+/-15%)	160,000 (+/-5%)	155,000 (+/-5%)	[40]
Fuel economy [kWh/km] (old)	2.98 (+/-0.161)	2.75 (+/-0.161)	2.69 (+/-0.161)	[16]
Fuel economy [kWh/km] (new)	2.53 (+/-5%)	1.90 (+/-5%)	1.79 (+/-5%)	[40]
Ammonia-powered shipping				
Payload loss (market+fuel) [%] (old)		57		[16]
Payload loss (market+fuel) [%] (new)		60		[8,41]

reduce financial risks associated with emerging transport technology could play an important role going forward.

Future research is needed to address mode shifting and demand reduction as options to achieve carbon neutrality. The interaction of cost reduction potential and consumer behavior should also be investigated. The decision process over time should also include non-economic criteria. Our work has not considered the potential scale of renewable fuel use. Additional research is needed to assess the potential scale of future hydrogen markets and the magnitude of emissions abatement. Our comparison of abatement options also raises the question whether national strategies should focus on individual options (for example, those with the lowest abatement costs), or an “all of the above” approach covering all sectors. A consideration for the latter approach is that some early abatement options are particularly sensitive to electricity costs (for example e-fuel use). If these options are to be pursued, future work could consider how policies could plan for or stimulate availability of low-cost electricity for such harder-to-abate transport sectors.

CRediT authorship contribution statement

Jonas Martin: Conceptualization, Methodology, Data collection, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, Validation.

Emil Dimanchev: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Visualization.

Anne Neumann: Writing - Review & Editing, Supervision.

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.

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Appendix A. Data assumptions

This section outlines the data assumptions for battery-electric trucking (Table 4) and provides a list of data updates (Table 5) in comparison to the information presented in [16].

In line with the assumptions made for long-haul trucking in [16], we consider a 40-tonne semi-truck comprising a truck unit and a cargo semi-trailer. The mode-specific costs (e.g. salary, fees, average load factor) associated with operating the truck are consistent with those outlined for other fuel options in [16]. In addition, we assume a payload loss of 5% due to the lower energy density of the battery system

[8]. For Capex and fuel economy, we use data from [40] (shown in Table 2). In line with the assumption in [16], we consider an uncertainty range of $+/-15\%$ for Capex values from 2020 to 2030 and $+/-5\%$ thereafter. For the fuel economy, an uncertainty range of $+/-5\%$ is assumed throughout the investigated time period. Charging electricity from hydro, onshore wind, and offshore wind is distributed and balanced by the Norwegian grid, with a grid fee of 4 ct/kWh [37,69]. For simplicity, one charging station exemplifies levelized costs with a maximal electricity output of 11 GWh_{el}/a [40]. We assume Capex, lifetime and Opex as used in [40]. In addition, we incorporate utilization rates of 70%, 85%, and 100% for the years 2020, 2035, and 2050, respectively, taking into account initial lower charging demand due to limited availability of battery-electric trucks [16]. All calculations adhere to the same methodology as outlined in [16].

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