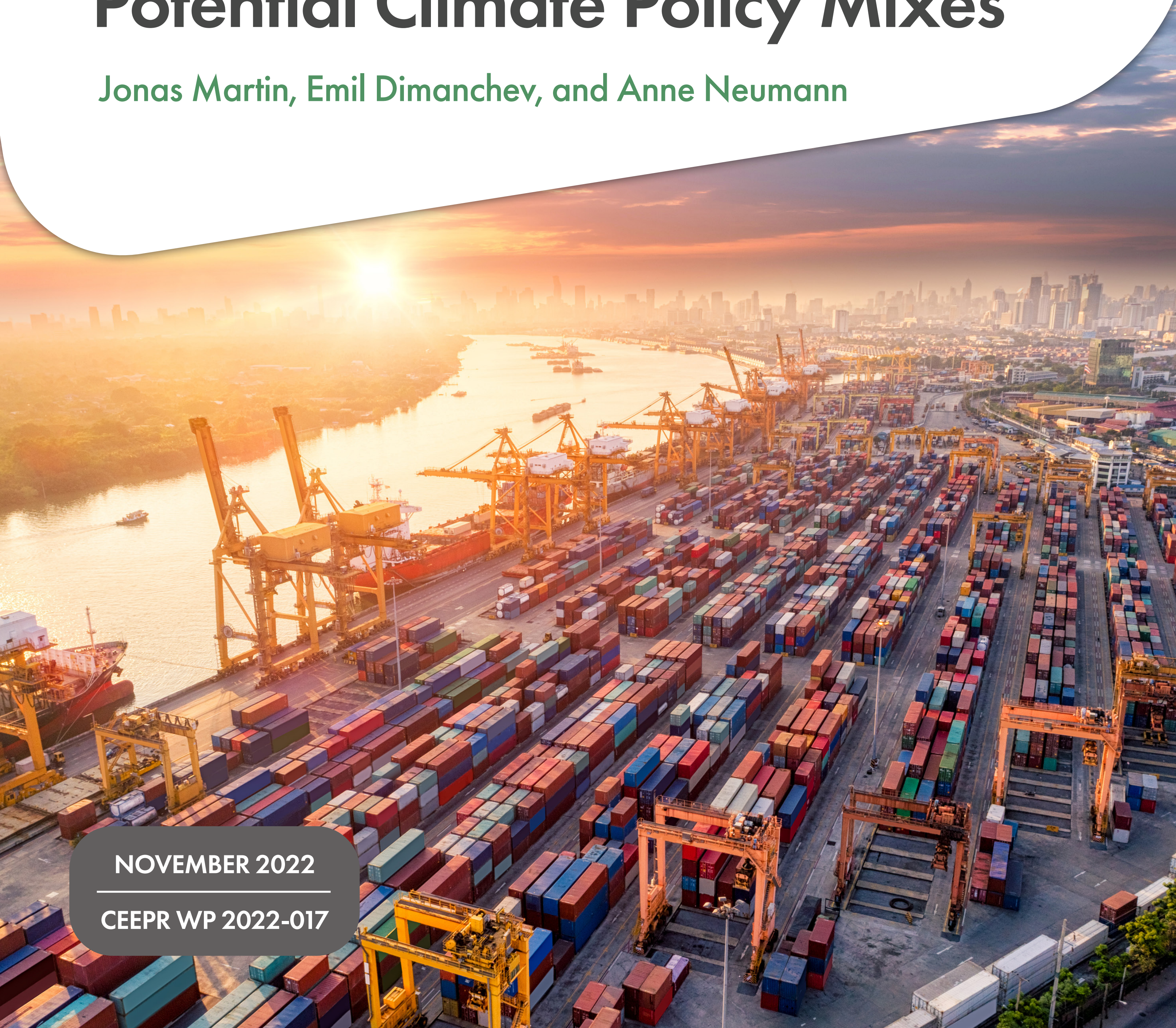
MIT Center for Energy and Environmental Policy Research

Working Paper Series

Carbon Abatement Costs for Hydrogen Fuels in Hard-to-Abate Transport Sectors and Potential Climate Policy Mixes

Jonas Martin, Emil Dimanchev, and Anne Neumann



NOVEMBER 2022

CEEPR WP 2022-017

Working Paper Series.

Since 1977, the Center for Energy and Environmental Policy Research (CEEPR) has been a focal point for research on energy and environmental policy at MIT. CEEPR promotes rigorous, objective research for improved decision making in government and the private sector, and secures the relevance of its work through close cooperation with industry partners from around the globe. Drawing on the unparalleled resources available at MIT, affiliated faculty and research staff as well as international research associates contribute to the empirical study of a wide range of policy issues related to energy supply, energy demand, and the environment.

An important dissemination channel for these research efforts is the MIT CEEPR Working Paper series. CEEPR releases Working Papers written by researchers from MIT and other academic institutions in order to enable timely consideration and reaction to energy and environmental policy research, but does not conduct a selection process or peer review prior to posting. CEEPR's posting of a Working Paper, therefore, does not constitute an endorsement of the accuracy or merit of the Working Paper. If you have questions about a particular Working Paper, please contact the authors or their home institutions.

Carbon abatement costs for hydrogen fuels in hard-to-abate transport sectors and potential climate policy mixes

Jonas Martin[1], Emil Dimanchev[2,3], and Anne Neumann[1,3]

[1]Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway
[2]Department of Electric Power Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[3]Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA, USA

November 7, 2022

Abstract

Deep decarbonization targets require emission reductions in "hard-to-abate" sectors that have until recently received little attention, including freight trucking, shipping, and aviation. Here, we apply a holistic cost model of hydrogen value chains to estimate abatement costs of replacing fossil fuels with renewable hydrogen, ammonia, or e-fuel for freight applications across trucking, shipping, and aviation. This work also analyzes how different climate policies - including carbon pricing, subsidies, and de-risking policies that influence the cost of capital - impact the competitiveness of hydrogen fuels. We estimate abatement costs of €530-1,345/tCO_2 in 2020, depending on the electricity source, transport mode, and type of hydrogen fuel. Concerted efforts by governments and industry could decrease these costs to €50-493/tCO_2 in 2050. These values indicate how high carbon prices must be for clean fuel use to break even. Existing carbon prices would play a partial role in incentivizing adoption if they were to be extended to these sectors. We conclude that subsidies across the value chain are likely necessary to incentivize adoption. De-risking has material impacts on economic feasibility, particularly for hydrogen due to its relative capital intensity. E-fuel costs are more sensitive than other hydrogen fuels to fuel production subsidies.

1 Introduction

Additional climate policy efforts are needed for "hard-to-abate" sectors such as heavy-duty trucking, shipping, and aviation, in order for governments to deliver on net zero emission targets and limit global warming within 1.5°C (Rogelj et al. 2018). Trucking, shipping, and aviation are envisioned to be the main sources of residual emissions toward the middle of the century, thus presenting a challenge for net zero goals (Creutzig et al. 2015; IEA 2020; Luderer et al. 2018; Rogelj et al. 2018). While electrification plays a primary role in 1.5°C and 2°C decarbonization pathways for light vehicles (Dimanchev, Qorbani, and Korpås 2022), other sectors - aviation, parts of heavy-duty transport, and maritime transport - may be impractical or very difficult to electrify, even in the long term. One abatement strategy in these sectors is the replacement of fossil fuels with renewable hydrogen fuels (Green et al. 2019; Rogelj et al. 2018). In this context, European and national hydrogen plans have declared hydrogen technology to be of strategic interest and an integral part of plans to decarbonize hard-to-abate sectors (European Commission 2020; Rossum et al. 2022). Governments are also making concerted efforts to develop hydrogen supply chains, as exemplified by the Australia-Germany Hydrogen Accord.

To design climate policy, governments rely on estimates for the costs of alternative abatement options. Abatement costs allow decision makers to understand how alternative solutions compare, how much a policy will cost, or what options can be implemented within a given budget. However, it is currently unclear how economically feasible different hydrogen fuels are as abatement options in the trucking, shipping, and aviation sectors (IPCC 2022). Martin, Neumann, and Ødegård (2022) showed that the hydrogen fuels are far from cost-competitive on a total cost of ownership basis. Here we explore the abatement cost of using hydrogen fuels and how climate policy influences their cost-competitiveness.

Previous research has modeled abatement costs in hard-to-abate sectors (Tomaschek 2015) but has omitted technological or empirical detail specific to heavy-duty trucking, shipping, or aviation. Some researchers have used relatively detailed bottom-up models to estimate the costs of reducing emissions within the hydrogen supply chain, by replacing steam methane reforming with cleaner alternatives (Parkinson et al. 2019), or by using carbon capture and storage (Longden et al. 2022). However, these estimates do not address the cost of replacing fossil fuels with cleaner fuels. Recent research has analyzed abatement costs for different e-fuel types and hydrogen but excluded consumer costs (such as vehicle costs), which are an important driver of the total cost of ownership (Ueckerdt et al. 2021). Other work has estimated shipping costs for a single year and used exogenous fuel costs without modeling the fuel value chain (Wahl and Kallo 2022), which does not directly capture how important parameters such as the cost of capital impact final costs.

This paper's first contribution is to fill these gaps by estimating the abatement costs of replacing fossil fuel use in freight trucking, shipping, and aviation with renewable hydrogen fuels (section 3.1). Specifically, this work focuses on long-haul trucking, short-sea shipping and short-haul aviation (hereafter, short-form sector names, such as "trucking", are used to denote their respective specific sector segments). We use a detailed bottom-up techno-economic cost model (Martin, Neumann, and Ødegård 2022). The model's high level of detail allows us to compare abatement across sectors (trucking, shipping, and aviation), fuels (hydrogen, ammonia and e-fuels), and across time (2020, 2035, 2050). Our estimates across these dimensions are internally consistent and allow inter-sector and inter-fuel comparisons that set this work apart from previous studies on hydrogen fuel costs more narrowly focused on a given sector or fuel (Fasihi et al. 2021; Glenk and Reichelstein 2019; Ueckerdt et al. 2021; Wahl and Kallo 2022).

We quantify abatement costs by calculating the Levelized Cost of Carbon Abatement (LCCA) across sectors and fuels (this paper therefore uses the terms "abatement cost" and LCCA interchangeably). Our LCCA estimates can be interpreted as long-run marginal abatement costs (covering a horizon long enough to allow changes in the capital stock) (Reichelstein and Rohlfing-Bastian 2015). From a policy perspective, our LCCAs represent the carbon price required for an abatement action to break even, or the carbon price at which an abatement action may be assumed to be taken.

This paper's second contribution is to explore how subsidies (i.e. additional policies other than carbon pricing) can contribute to reducing clean transport costs (section 3.2). European and national hydrogen strategies show that governments are considering a variety of policy instruments beyond carbon pricing to support hydrogen technology. In this paper, we model how subsidies on different parts of the value chain impact the relative cost-competitiveness of hydrogen fuels. Previous work studied existing subsidies for road freight across countries (Noll et al. 2022). Our paper differs in that it investigates potential policies over time across the whole value chain and across transport modes.

As a third contribution to the literature, we explore the role of de-risking hydrogen investments in future policy. Specifically, this paper tests how the cost of capital (i.e. WACC) impacts the cost-competitiveness of hydrogen fuels across sectors. This allows us to indicate how policies (such as Contracts for Differences) that improve the financial risk profile of hydrogen investments, can improve hydrogen economics.

Our fourth contribution is to explore how different government policies including carbon pricing and subsidies may interact to make hydrogen fuels cost-competitive. Here we consider how different combinations of carbon pricing and hydrogen subsidies may impact the competitiveness of clean transport.

Our analysis finds that if carbon prices remain at current levels (€84/tCO_2 in Europe in the first half of 2022 and generally lower in other jurisdictions), cost-competitive renewable hydrogen fuels require governmental incentives across their value chains, which could include subsidies on different processes along the fuel value chain, incentives for clean vehicle purchasing, or the exemption of clean vehicles from public fees, or higher taxation on fossil-based transport. De-risking investments has material impact on economic feasibility, particularly for hydrogen value chains due to its relative capital intensity on the consumer side. E-fuel costs are more sensitive than other hydrogen fuels to fuel production subsidies.

2 Methodology

This work applies a holistic cost model of hydrogen value chains in the transport sector developed in Martin, Neumann, and Ødegård (2022). Here we briefly describe our model before introducing this paper's analytical extensions. The model estimates the levelized cost (in €/tkm) of using renewable hydrogen fuels in freight applications (equivalent to the total cost of ownership). A key feature of the model is its holistic representation of the whole value chain of each hydrogen fuel, which includes the following process steps: renewable electricity generation, fuel production, fuel distribution, and fuel use[1]. This allows us to explore how final costs change in reaction to a large number of individual inputs (the model consists of 140 parameters) and potential policies. The sectors covered include long-haul trucking, short-sea shipping and short-haul aviation for freight transport. Levelized costs are estimated from 2020 (meant to represent present-day values) to 2050. Future values are based on a review of estimates in peer-reviewed literature and industry reports, validated through company interviews. Another feature is the consideration of mode-specific factors specific to freight transport operational costs such as cargo handling expenses and freight-specific fees for use of airports, ports, and roads. Costs represent values without government intervention (taxes or subsidies), which are analyzed in this paper. The model uses global data for component and process costs. However electricity costs are influenced by location-specific renewable capacity factors, which are based on locations in Norway. Our analysis below explores how costs change under different electricity cost assumptions. Input parameters for the costs of individual components and processes represent central values from the literature. Therefore, levelized costs estimated by the model should be seen as central estimates. This paper refers to the model's central estimates or assumptions as "Base Case" values to differentiate it from values derived after introducing policy incentives.

[1]The hydrogen value chain covers: Electricity generation (onshore / offshore wind, hydropower), water electrolysis, cavern storage, liquefaction, distribution (tank ship / tank truck), liquid buffer storage, mode-specific refueling infrastructure, long-haul semi-truck (700 bar tank, fuel cell), short-sea ship (cryogenic tank, fuel cell), short-haul aircraft (cryogenic tank, jet engine). The ammonia value chain uses hydrogen from cavern storage (see hydrogen value chain) and additionally covers ammonia synthesis including nitrogen direct air capture and liquefaction, liquid buffer storage, distribution (tank ship), direct fuel bunkering (ship to ship), short-sea ship (cooling tank, fuel cell). The e-fuel value chain uses hydrogen from cavern storage (see hydrogen value chain) and additionally covers e-fuel synthesis including CO_2 direct air capture, distribution (tank ship / tank truck), e-fuel buffer storage, mode-specific refueling infrastructure, long-haul semi-truck (state of the art, internal combustion), short-sea ship (state of the art, internal combustion), short-haul aircraft (state of the art, jet engine)

In this paper, we quantify hydrogen-related abatement costs using the LCCA metric. Our approach is similar to levelized metrics in previous literature on abatement costs in other sectors (Friedmann et al. 2020; IPCC 2022; Vogt-Schilb, Meunier, and Hallegatte 2018). LCCAs can equivalently be interpreted as long-run marginal abatement costs. The LCCA for a given technology is calculated using the following equation.

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

Equation 1 calculates the levelized cost of carbon abatement in €/tCO_2 by dividing the annual costs of technology change by the CO_2 abatement achieved by switching fuels. $LCOT^O$ represents the levelized cost of the originally used transport; $LCOT^A$ represents the levelized cost of transport for a low-carbon 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 from the low-carbon alternative. CO_2 emissions are collected from Statistics Norway (2021) and shown in Table 1. We only consider combustion-related CO_2 emissions 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 consumption 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 hydrogen, ammonia and e-fuel to be net zero. We calculate the relative CO_2 emissions per tonne-kilometer based on the maximum payload capacity, which is 25 t for long-haul trucking, 9,450 t for short-sea shipping and 20 t for short-haul aviation in our application (Martin, Neumann, and Ødegård 2022).

Table 1: CO_2 emissions per fossil fuel type applied for trucking, shipping and aviation. Source: (Statistics Norway 2021)

Fuel type	CO_2 intensity [tCO_2/tfuel]	Fuel economy [l/km]	CO_2 emission [g/tkm]
Truck: Diesel	3.17	0.32	48.24
Ship: Heavy fuel oil	3.20	44.19	15.11
Aircraft: Jet fuel	3.15	4.00	778.73

The levelized costs of transport ($LCOT^A$ and $LCOT^O$) are estimated using the following equations for each fuel throughout its value chain in the three transport modes. First, as shown in equation 2, levelized costs are sum totals of the levelized cost of individual processes along the value chain, denoted by $LCOX_i$ for process i.

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

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

LCOX 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 annual outcome quantity of i, 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, shown below.

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

WACC is the weighted average cost of capital over N as the specific lifetime of i. Changes in the WACC impact the investment cost of all capital expenditures along the value chain (with the sole exception of a relatively low capital cost associated with fuel distribution which our model does not separate out), allowing us to holistically capture its impact on the cost of using hydrogen fuels.

We further use the model to test the impact of different government subsidies. 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 the following equation.

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

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; 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.

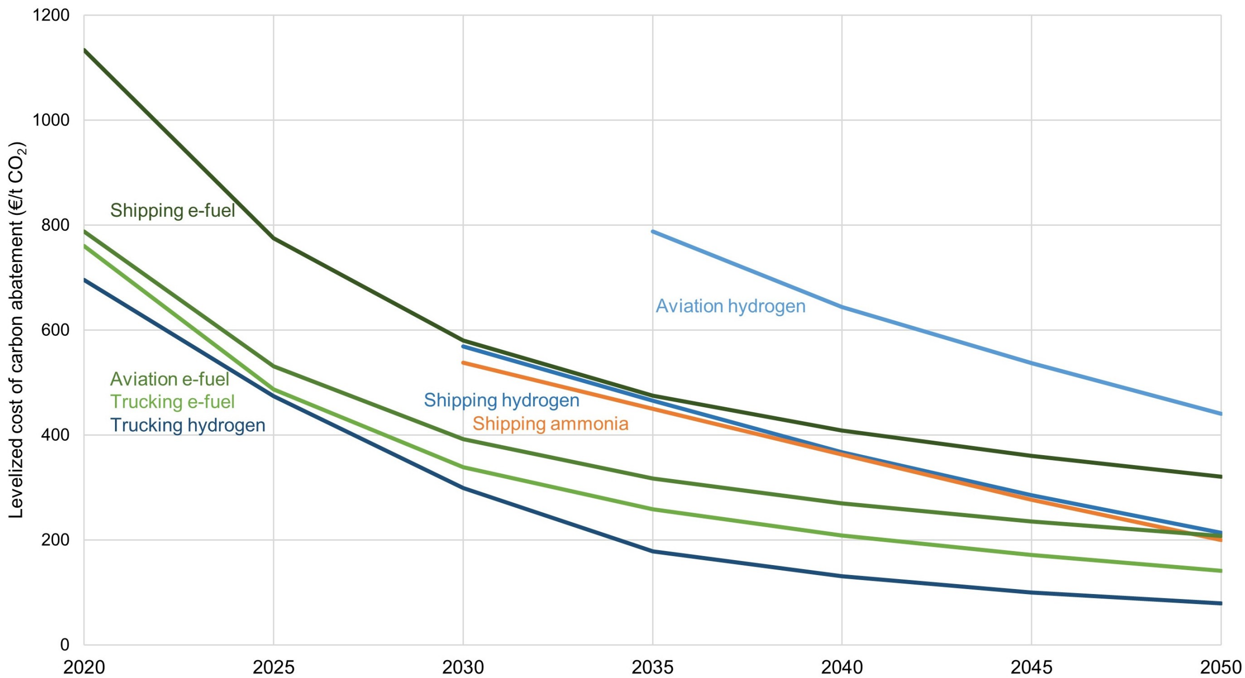


Figure 1: Abatement cost for the renewable hydrogen fuels produced by onshore wind and used in three transport modes towards 2050.
Each line shows the cost of using a given hydrogen fuel instead of a fossil fuel benchmark.

3 Results and discussion

3.1 Abatement costs for hydrogen fuels

Figures 1 and 2 present all estimated abatement costs, quantified using the LCCA metric as discussed in the Methodology section. LCCAs represent the long-term CO_2 price that would be necessary for each abatement technology to break even. The results for 2020 show that hydrogen fuels require relatively high CO_2 prices to break even.

All LCCAs decline over time as a result of technological innovation and adoption-driven learning (Martin, Neumann, and Ødegård 2022). We assume the cost of all production and vehicle components at industrial scale and increasing market diffusion. We assume an interaction between governmental incentives leading to technology competitiveness and increasing sales volume as well as scaling and learning effects through industrial product optimization. In other words, the expected cost reductions can only be achieved with political and industrial commitment starting today.

The cheapest abatement options within each sector are those that use the lowest-cost technologies in terms of €/tkm (as abatement costs are calculated relative to the same fossil fuel

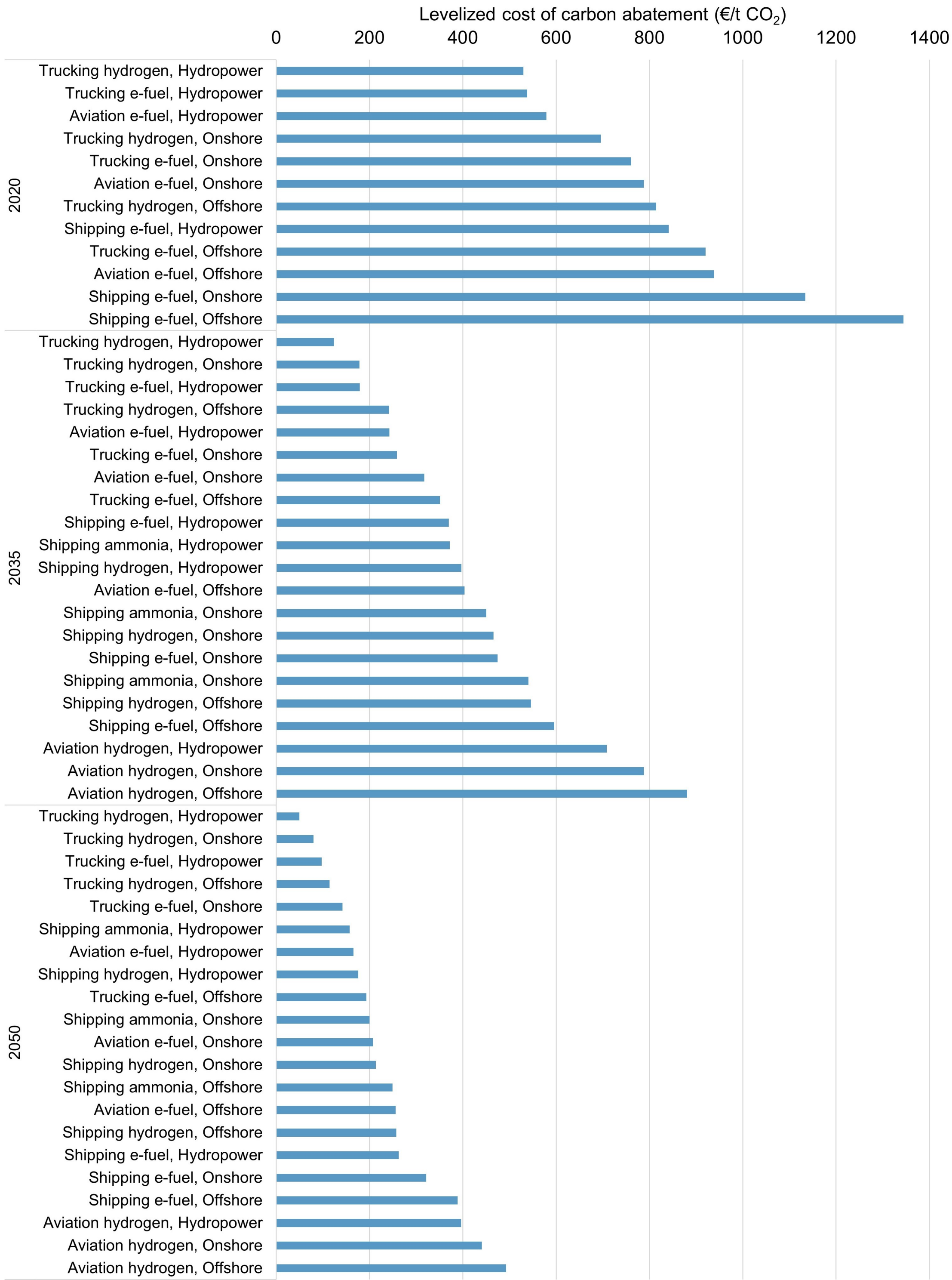


Figure 2: Abatement cost in ascending order for the renewable hydrogen fuels produced by onshore wind, hydropower and offshore wind and used in three transport modes for 2020, 2035 and 2050.

benchmark in each sector) which is discussed in detail in Martin, Neumann, and Ødegård (2022). As shown in Figure 1 (based on electricity from onshore wind) in the trucking sector, the cheapest abatement is via hydrogen, which is estimated to be €696/tCO_2 in 2020 and €80/tCO_2 in 2050. Abatement cost for e-fuels in trucking are higher because the comparably low vehicle Capex cannot offset higher fuel cost combined with a lower engine efficiency. In shipping, ammonia and hydrogen are assumed to become available in 2030 (Martin, Neumann, and Ødegård 2022). In 2030 and beyond, ammonia exhibits the lowest abatement cost, starting with €538/tCO_2 and €200/tCO_2 in 2050. In aviation, e-fuel use costs €788/tCO_2 in 2020; e-fuel use is a cheaper abatement option compared to hydrogen all the way to 2050, when it is estimated to cost €208/tCO_2.

Figure 2 presents the LCCA for fuel and transport options in ascending order for 2020, 2035 and 2050 respectively. Comparing across sectors and electricity sources, we find the lowest abatement costs in 2020 in the trucking sector, equal to €530/tCO_2 for hydrogen and €760/tCO_2 for e-fuel, both produced from hydropower. Trucking remains the lowest cost abatement out of the options we studied also in the following years until 2050 (if electricity comes from hydro or onshore wind). This is due to the fact that the trucking sector exhibits the lowest cost premium on a €/tkm basis (Martin, Neumann, and Ødegård 2022) and the relative emission intensity of diesel-powered trucks (Table 1). This implies that trucking could serve as an early niche market for the development of hydrogen technologies that could drive cost reductions in electrolysis, having in mind the fast developments in battery truck technology (Plötz 2022).

The third-lowest abatement costs are found for e-fuel in the aviation sector based on hydropower equal to €579/tCO_2 in 2020, this option loses its rank in the total cost order until 2050 with a cost of €166/CO_2. The higher cost premium for e-fuel-powered aviation compared to hydrogen-powered trucking (Martin, Neumann, and Ødegård 2022) is offset by the high CO_2 intensity of fossil-based aviation (which exceeds that of trucking by a factor 16, Table 1), especially in the early years. The results show that aircraft and trucks have similar CO_2 abatement cost. Decarbonizing shipping with e-fuel starting in 2020 (minimum €842/tCO_2) and ammonia in 2030 (minimum €435/tCO_2) has comparably high abatement cost. Our cross-sector differences are in contrast to results by Ueckerdt et al. (2021) who present equal abatement costs for the use of e-fuel across sectors. However, our results show shipping to be economically harder to decarbonize than the other two transport modes (in a mid-term perspective). This can be explained by the large influence of fuel costs in the total cost of ownership in shipping (which is more thoroughly captured by our holistic model) and the large fuel cost difference between low-cost heavy fuel oil and clean shipping fuels. In addition, shipping has a relative low CO_2 intensity (a third of that of trucking). In 2050 however, ammonia for shipping economically beats e-fuel for aviation if the same electricity sources are compared. The results reveal that 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 modes at the same time.

3.2 Impact of subsidies on different points on the value chains for hydrogen fuels from onshore wind power

Figure 3 shows how changes in individual input costs (on the x-axes) impact total 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, a 2021 bill in the U.S. House of Representatives proposed a tax credit for hydrogen fuel equivalent to a subsidy of $3/kg (Collins 2021), or approximately €2.5/kg (based on the 2021 exchange rate). Such a subsidy would bring the abatement cost of hydrogen for trucking to €512/tCO_2 in 2020 (as shown in panel d in Figure 3), requiring a carbon price of the same amount to make it cost-competitive (down from €696/tCO_2 under Base Case costs).

Within sectors, we find that subsidy impacts differ between technologies. In trucking and shipping, subsidies on the hydrogen cost, or on the electricity cost, lower the cost of e-fuel-powered transport more than 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 marginal because both fuels are burned in jet engines with the same efficiency assumed. Here, the difference is due to energy losses in the e-fuel synthesis.

Over time, the impact of electricity costs decrease, due to efficiency improvements in the electrolysis process. For vehicles working with 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 fully parallel over time for both fuel types (no efficiency gains expected).

Comparing slopes for vehicle cost changes (panels g-i in Figure 3), trucking and shipping fuel options run parallel, whereas aviation using hydrogen is more sensitive (steeper slope). Vehicle cost sensitivities are the same within a transport mode because across fuel options payload capacities are assumed to be the same. Hydrogen-powered aviation is an exception and is relatively more sensitive to vehicle costs because the cryogenic tanks in hydrogen airplanes leave less space for cargo (only 75 percent).

A general result across sectors is that in the near term, subsidizing any individual input is insufficient to bring the abatement costs of hydrogen fuels in line with current carbon prices. This is because the high cost of hydrogen fuels results from expensive components and processes along a long value chain. Cost changes at any individual play a limited role in lowering final abatement costs.

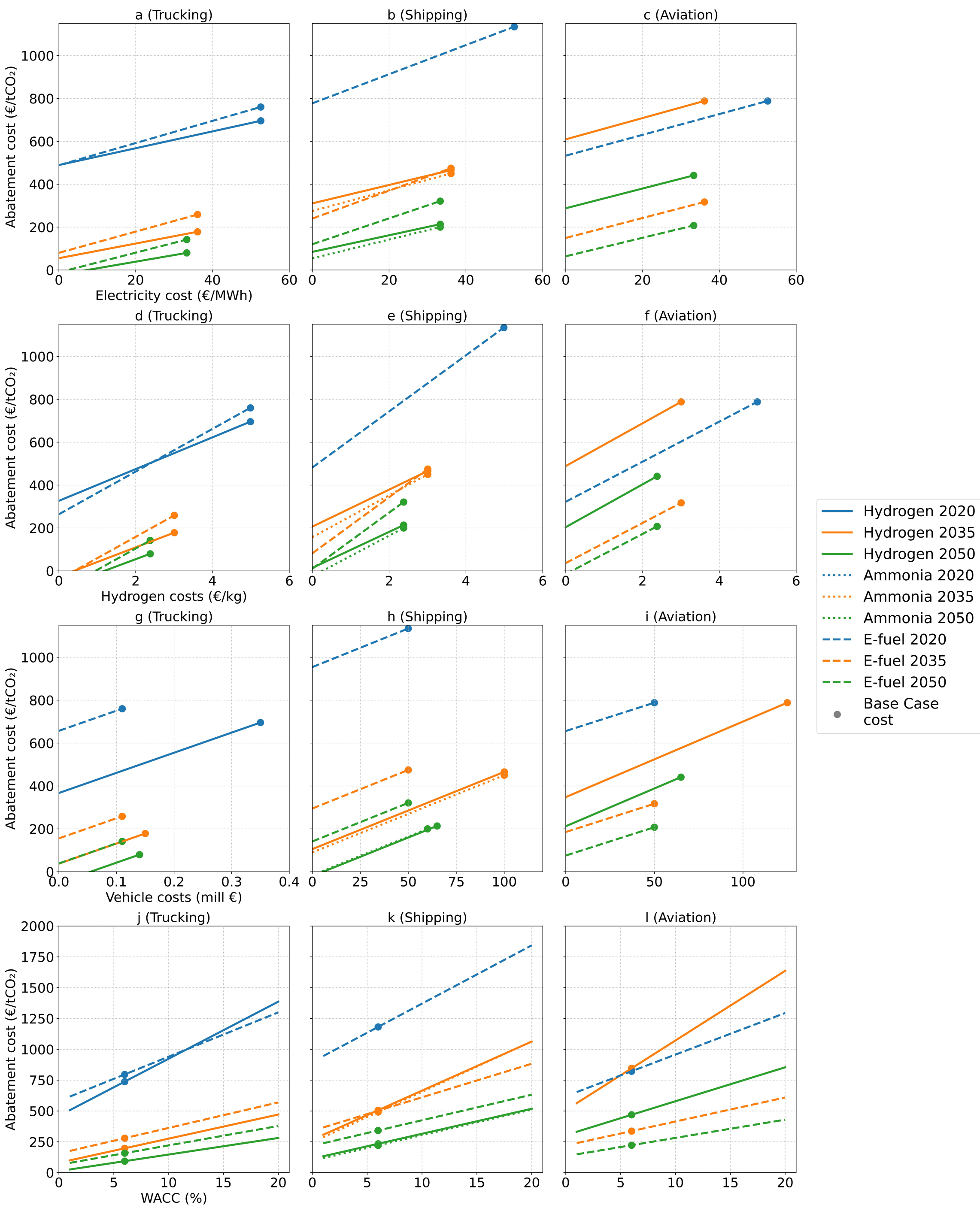


Figure 3: Impact of process and component costs on hydrogen abatement costs
Each line shows the abatement cost of using a given hydrogen fuel instead of a fossil fuel benchmark.

Next, we quantify the impact of policies that impact the Weighted Average Cost of Capital (WACC) across hydrogen value chains (panels j-l in Figure 3. Such policies may include interventions that decrease uncertainty regarding future profitability, 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% (Newbery 2016). Our model's assumes a WACC of 6% across all hydrogen 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 hydrogen development (BEIS 2021).

This analysis estimates that a 1% point change in the WACC changes hydrogen abatement costs by €46/tCO_2 in trucking in 2020, and by €40/tCO_2 and €56/tCO_2 in 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 contrasts with previous work which emphasized the importance of OPEX costs and suggested that policy makers prioritize OPEX subsidies to trucking companies (Noll et al. 2022). This difference is due to the more holistic scope of our model, which captures all CAPEX costs throughout the value chain.

Varying the WACC has a greater impact on capital intensive technologies (as shown by the steeper slopes in Figure 3). Generally, hydrogen and ammonia value chains are more capital intensive than the e-fuel value chain. This is due to capital cost of new vehicle technologies, particularly in the first years when new vehicles become available. The capital costs of new vehicle technologies outweigh capital expenses related to the synthesis of e-fuel. The impact of the WACC decreases over time (illustrated by the decreasing slopes). This is because all technologies become less capital intensive over time due to learning and scaling effects of new technologies (Martin, Neumann, and Ødegård 2022).

3.3 Policy mixes for hydrogen fuels

The previous section examined the impacts of one type of government intervention at a time. Here we explore the impact of potential policy mixes. Figure 4 presents results specifically for the fuel types found to be lowest-cost in each of the three sectors (Martin, Neumann, and Ødegård 2022), which are hydrogen for long-haul trucking shown in 2020, ammonia for short-sea shipping and e-fuel for short-haul aviation shown in 2035, each with fuels from onshore wind power. The vertical line on the right side of each figure separates the clean transport and possible incentives (left) from the fossil fuel-based counterpart including the impact of CO_2 pricing and fuel cost variation (right). Potential component and process subsidies along the value chain bring the clean transport cost down (left), potential CO_2 pricing bring fossil fuel-based 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 (BEIS 2021; European Commission 2020, c.f.). For illustrative purposes, we subsidize components and processes with the equivalent of 50% of its cost. Although we halve cost of several dominant cost drivers in the value chain, additional carbon pricing remains necessary to close the gap in total cost of ownership for the shown transport modes and years. Importantly, Figure 4 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.

Figure 4 also displays the impact of potential changes in the cost of fossil fuels. The bottom corner of the light grey bar (e.g. €0.7/l for trucking) represents the Base Case fossil fuel cost (Martin, Neumann, and Ødegård 2022). Potential fuel cost changes can be interpreted either as cost volatility or as the impact of taxes or subsidies on fossil fuels. For example, carbon prices would not be necessary if fuel costs were increased by €1.1/l diesel fuel for the hydrogen trucking case (2020), €380/t ton heavy fuel oil for the ammonia shipping case (2035) and €294/t Jet A-1 for the e-fuel aviation case (2035). In comparison, diesel prices of May 2022 including all taxes at European fuel stations equaled approximately €2.25/l in Sweden, €2.04/l in Germany, €1.88/l in France and €1.83/l in Italy (FuelsEurope 2022). At these retail prices, hydrogen fuels would be cost-competitive with fossil fuels without carbon pricing assuming the subsidies shown on the left (and assuming that hydrogen fuels are exempt from taxes included in fossil fuel retail costs). Fuel prices could also increase if policy makers remove existing fossil fuel subsidies, which could include additional pricing of environmental and social damages (Shang 2019).

Figure 4 can also be used to show how subsidies 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, for example, if there are no subsidies on electricity (€53/MWh down to €26/MWh) and fuel stations (€6M down to €3M), keeping everything else equal, would roughly require a 100 percent subsidy on the truck's Capex by reducing vehicle cost from €350k to €0. Many countries such as Norway exempt zero-emission vehicle from governmental interventions that however apply to fossil-based transport. This can include exempting zero-emission vehicles from value-added taxes or additional infrastructure fees. Such taxes are not included in the dark grey bar on the right, but the light grey bar illustrates what their impact could be. Similar interactions between policies can be observed for shipping and aviation in Figure 4, but magnitudes differ due to differences in the cost structures of these transport modes.

4 Conclusions and policy implications

This paper shows that the abatement costs for hydrogen fuels remain substantial. Our analysis estimates costs of €530-1,345/tCO_2 in 2020 depending on the electricity source, transport mode and type of hydrogen fuel. In comparison, the CO_2 price in the EU Emissions

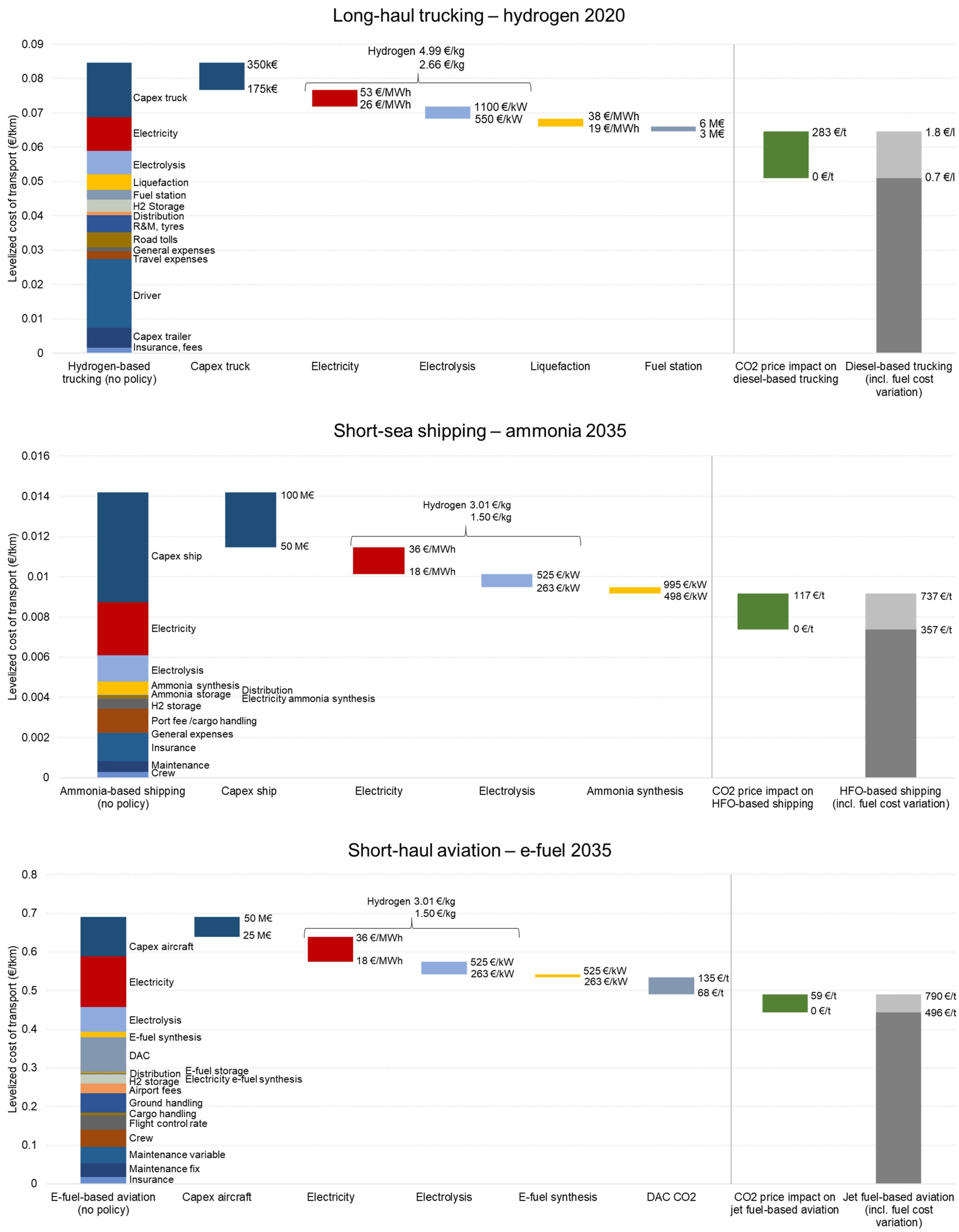


Figure 4: Policy mixes closing the cost gap to fossil-based transport with additional CO_2 pricing. Hydrogen 2020 for long-haul trucking, ammonia 2035 for short-sea shipping, e-fuel 2035 for short-haul aviation (HFO: Heavy fuel oil, DAC: Direct air capture).

Trading System (EU ETS) averaged €84/tCO_2 in the first half of 2022 (Ember 2022). Carbon prices in other jurisdictions are also relatively low; average pricing across countries has been estimated to be €7.90/tCO_2 (Finch and Bergh 2022). This discrepancy shows that existing carbon pricing is far from a sufficient incentive to trigger any of the studied abatement options, even if the sectors were included in the EU ETS or other carbon pricing systems. Of the sectors we focus on, only intra-EU aviation is currently covered by the EU ETS.

For hydrogen fuels to be competitive, either carbon prices have to be several times larger than they are today (relative to EU's carbon price), technology costs have to decline, or some combination of both has to occur. Cost declines appear plausible, based on our cost model, but require government support to incentivize innovation and to drive learning-by-doing effects by encouraging deployment. However, projected cost declines should 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 (HFP Advisory Council 2005). 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 clean hydrogen to $1/kg within a decade (DOE 2021). Still, the future level of policy ambition remains to be seen and the technical potential for innovation is yet to be demonstrated.

One way governments can further incentivize hydrogen adoption is by implementing Carbon Contracts for Differences (CCfD), currently being discussed in the EU (European Commission 2020) and in Norway (ZERO 2022). CCfDs 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 (European Commission 2020). The abatement costs estimated in this paper indicate the general magnitude of the required CCfD strike levels for different abatement options to break even. The indicative magnitude of CCfD payments would then equal the difference between these strike levels and actual carbon prices covering the respective sectors. Even under the assumption that transport is included in existing carbon pricing systems, our results show that the remaining payments that have to be made through potential CCfD contracts are substantial. Contracts for Differences (CfDs) are also being discussed as a way to support hydrogen development (BEIS 2021). 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 CCfD and CfD is the mitigation of risk for hydrogen providers that stems from volatility in the carbon price (in the case of CCfDs) or hydrogen price (in the case of CfDs); however, an important consideration is that this risk is not eliminated but is instead transferred to the government. De-risking achieved through CCfDs or CfDs could allow hydrogen companies to secure financing at lower costs. As our results show, the WACC for hydrogen developers may be an important target for future policy. The cost of capital has been shown to be a strong determinant of levelized renewable costs (Ondraczek, Komendantova, and Patt 2015). We similarly show that reductions in the WACC can materially improve the relative cost-competitiveness of hydrogen applications.

Direct government subsidies, in the form of grants and tax credits for example, are also being implemented or discussed (BEIS 2021; Collins 2021; European Commission 2022). Our analysis quantified the potential impacts of subsidies on hydrogen abatement costs. The results show that for hydrogen fuels to be economically feasible, 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 (Grubb, Hourcade, and Neuhoff 2014; Stern 2006). Such technology support requires not only "market pull" (e.g. through carbon pricing), but also "technology push" through producer subsidies (Grubb, Hourcade, and Neuhoff 2014; Harvey, Orvis, and Rissman 2018). We show that subsidizing the €/kg cost of hydrogen has a relatively large impact out of the interventions we tested, which suggests that innovation policy targeting hydrogen costs could be seen as a focal point of future hydrogen policy. The U.S. House of Representatives proposed a tax credit for hydrogen fuel equivalent to a subsidy of $3/kg (Collins 2021). Our results showed that with current costs, hydrogen use in 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 €200/tCO_2, or a lower carbon price paired with a hydrogen subsidy could be enough to incentivize hydrogen adoption. As governments seek to support hydrogen technology, our cross-sector comparison can help in the identification of potential niches. For example, the use of hydrogen exhibits the lowest abatement cost in the trucking sector, followed by shipping.

Our analysis also has implications for discussions to include the studied sectors in existing carbon markets such as the EU ETS or in new markets such as the proposed "ETS2" in Europe. In the near term, the studied abatement options are unlikely to be the marginal source of abatement in a large carbon market such as the EU ETS. The EU ETS CO_2 price will thus likely be lower than the abatement costs we estimate. This means that companies in the studied sectors will either be resorting to other abatement options, or simply covering CO_2 costs by purchasing and retiring CO_2 permits. In the long term, as other abatement options become exhausted, emission reductions may have to come from the sectors we studied here. The abatement costs we calculate can be interpreted as the long-run equilibrium level for the CO_2 price in a carbon market where the given abatement option is the marginal source of abatement. Therefore, if these sectors are covered by carbon markets, our abatement cost values are indicative of the level of future CO_2 prices when all cheaper abatement options are exhausted (under the strong assumptions behind these values including significant future cost declines).

A limitation of this paper is the omission of strategies for decarbonizing transport other than fuel switching, such as mode shifting and demand reduction. The cost model used does not model consumer behavior, which could mean the adoption and learning effects assumed for future cost figures do not materialize. This is described in Martin, Neumann, and Ødegård (2022) who show the significant uncertainty in cost estimates by introducing best- and worst case scenarios. For example, costs for hydrogen use in trucking in 2035 varied between 1.33 and 1.74 €/tkm (around a Base Case value consistent with our results in this paper of 1.49 €/tkm). We explore conditions under which clean fuels are cost-competitive, but omit factors that influence fuel use other than cost. Life-cycle emissions other than the ones during vehicle operation are neglected in our model. Thus emissions for both fossil-based transport and clean transport value chains (the latter assumed to be zero) are lower than in reality. We show carbon abatement cost and policy instruments for specific use cases and transport modes and do not represent applications other than long-haul trucking, short-sea shipping and short-haul aviation. Analyzing the transport market was beyond our scope and we do not model interactions between adopting one or the other technology, which could produce a different learning behavior.

Future research is needed to address mode shifting and demand reduction as decarbonization options. 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 clean 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 in aviation). 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.

5 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: Conceptualization, Writing - Original Draft, Writing - Review & Editing

6 Declaration of competing interest

This research was financed by Mobility Zero Emission Energy Systems (MoZEES), a Norwegian Centre for Environment friendly Energy Research (FME), co-sponsored by the Research Council of Norway (project number 257653) and 40 partners from research, industry and public sector. The research was also funded by CINELDI – Centre for intelligent electricity distribution, an 8 year Research Centre under the FME-scheme (grant number: 257626/E20). 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.

7 Acknowledgement

This research was financed by Mobility Zero Emission Energy Systems (MoZEES), a Norwegian Centre for Environment friendly Energy Research (FME), co-sponsored by the Research Council of Norway (project number 257653) and 40 partners from research, industry and public sector. The research was also funded by CINELDI – Centre for intelligent electricity distribution, an 8 year Research Centre under the FME-scheme (grant number: 257626/E20).

References

BEIS (2021). *Low Carbon Hydrogen Business Model: consultation on a business model for low carbon hydrogen*. Tech. rep. UK Department of Business, Energy & Industrial Strategy.

Collins, L. (2021). "New clean hydrogen production tax credit of up to $3/kg approved by US House, paving way for cheap green H2". *Recharge*. URL: `https://www.rechargenews.com/energy-transition/new-clean-hydrogen-production-tax-credit-of-up-to-3-kg-approved-by-us-house-paving-way-for-cheap-green-h2/2-1-1102245` (visited on 07/22/2022).

Creutzig, F., P. Jochem, O. Y. Edelenbosch, L. Mattauch, D. P. v. Vuuren, D. McCollum, and J. Minx (2015). "Transport: A roadblock to climate change mitigation?" *Science* 350.6263, p. 911. URL: `http://science.sciencemag.org/content/350/6263/911.abstract`.

Dimanchev, E., D. Qorbani, and M. Korpås (2022). "Electric Vehicle Adoption Dynamics on the Road to Deep Decarbonization". *The 4Ds of Energy Transition*. John Wiley & Sons, Ltd, pp. 177–205. URL: `https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527831425.ch8` (visited on 07/22/2022).

DOE (2021). *Hydrogen Shot*. URL: `https://www.energy.gov/eere/fuelcells/hydrogen-shot` (visited on 07/27/2022).

Ember (2022). *EU Carbon Price Tracker*. URL: `https://ember-climate.org/data/data-tools/carbon-price-viewer/` (visited on 07/29/2022).

European Commission (2020). *A hydrogen strategy for a climate-neutral Europe - Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. Tech. rep. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301 (visited on 07/14/2022).
– (2022). *EU funding programmes and funds 2021-2027*. URL: https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds_en (visited on 07/27/2022).
Fasihi, M., R. Weiss, J. Savolainen, and C. Breyer (2021). "Global potential of green ammonia based on hybrid PV-wind power plants". *Applied Energy* 294, p. 116170. URL: https://www.sciencedirect.com/science/article/pii/S0306261920315750 (visited on 07/13/2022).
Finch, A. and J. van den Bergh (2022). "Assessing the authenticity of national carbon prices: A comparison of 31 countries". *Global Environmental Change* 74, p. 102525. URL: https://www.sciencedirect.com/science/article/pii/S0959378022000632 (visited on 07/27/2022).
Friedmann, J., Z. Fan, Z. Byrum, E. Ochu, A. Bhardwaj, and H. Sheerazi (2020). *Levelized Cost of Carbon Abatement: An Improved Cost-Assessment Methodology for A Net-Zero Emissions World*. Tech. rep. New York, NY: Columbia Center on Global Energy Policy.
FuelsEurope (2022). *Statistical report 2022*. Brussels: FuelsEurope. URL: https://www.fuelseurope.eu/wp-content/uploads/FE_2022SR-Final.pdf.
Glenk, G. and S. Reichelstein (2019). "Economics of converting renewable power to hydrogen". *Nature Energy* 4.3, pp. 216–222. URL: https://www.nature.com/articles/s41560-019-0326-1 (visited on 07/13/2022).
Green, W. H., R. C. Armstrong, M. Ben-Akiva, J. Heywood, C. Knittel, S. Paltsev, B. Reimer, C. Vaishnav, J. Zhao, E. Gross, J. Moody, E. Dimanchev, E. Gençer, A. Ghandi, I.-Y. L. Hsieh, I. Miller, J. Morris, E. Murphy, A. Nunes, J. B. Oke, R. Sridhar, and D. Weigl (2019). *Insights Into Future Mobility: A Report from the Mobility of the Future Study*. Report. MIT Energy Initiative. URL: http://energy.mit.edu/research/mobilityofthefuture/.
Grubb, M., J. C. Hourcade, and K. Neuhoff (2014). *Planetary economics : energy, climate change and the three domains of sustainable development*. Routledge. URL: https://www.routledge.com/Planetary-Economics-Energy-climate-change-and-the-three-domains-of-sustainable/Grubb-Hourcade-Neuhoff/p/book/9780415518826.
Harvey, H., R. Orvis, and J. Rissman (2018). *Designing Climate Solutions*. Island Press. URL: https://link.springer.com/book/10.5822/978-1-61091-957-9 (visited on 05/10/2022).
HFP Advisory Council (2005). *European Hydrogen & Fuel Cell Technology Platform - Deployment Strategy*. Tech. rep. European Hydrogen and Fuel Cell Technology Platform. URL: https://www.fch.europa.eu/sites/default/files/documents/hfp_ds_report_aug2005.pdf.

IEA (2020). *Energy Technology Perspectives 2020*. Paris: OECD Publishing. URL: https://doi.org/10.1787/d07136f0-en.

IPCC (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by P. Shukla, J. Skea, R. Slade, A. A. Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley. Cambridge, UK and New York, NY, USA: Cambridge University Press.

Longden, T., F. J. Beck, F. Jotzo, R. Andrews, and M. Prasad (2022). "'Clean' hydrogen? – Comparing the emissions and costs of fossil fuel versus renewable electricity based hydrogen". *Applied Energy* 306, p. 118145. URL: https://www.sciencedirect.com/science/article/pii/S0306261921014215 (visited on 05/10/2022).

Luderer, G., Z. Vrontisi, C. Bertram, O. Y. Edelenbosch, R. C. Pietzcker, J. Rogelj, H. S. De Boer, L. Drouet, J. Emmerling, O. Fricko, S. Fujimori, P. Havlík, G. Iyer, K. Keramidas, A. Kitous, M. Pehl, V. Krey, K. Riahi, B. Saveyn, M. Tavoni, D. P. Van Vuuren, and E. Kriegler (2018). "Residual fossil CO2 emissions in 1.5–2 °C pathways". *Nature Climate Change* 8.7, pp. 626–633. URL: http://10.1038/s41558-018-0198-6.

Martin, J., A. Neumann, and A. Ødegård (2022). *Sustainable Hydrogen Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Dynamic Cost Model*. Tech. rep. WP 2022-010. Cambridge, MA: MIT CEEPR. URL: https://ceepr.mit.edu/sustainable-hydrogen-fuels-versus-fossil-fuels-for-trucking-shipping-and-aviation-a-dynamic-cost-model/ (visited on 07/27/2022).

Newbery, D. M. (2016). "Towards a green energy economy? The EU Energy Union's transition to a low-carbon zero subsidy electricity system – Lessons from the UK's Electricity Market Reform". *Applied Energy* 179, pp. 1321–1330. URL: https://www.sciencedirect.com/science/article/pii/S0306261916300265 (visited on 07/22/2022).

Noll, B., S. del Val, T. S. Schmidt, and B. Steffen (2022). "Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe". *Applied Energy* 306, p. 118079. URL: https://www.sciencedirect.com/science/article/pii/S0306261921013659 (visited on 07/14/2022).

Ondraczek, J., N. Komendantova, and A. Patt (2015). "WACC the dog: The effect of financing costs on the levelized cost of solar PV power". *Renewable Energy* 75, pp. 888–898. URL: https://www.sciencedirect.com/science/article/pii/S0960148114006806 (visited on 05/10/2022).

Parkinson, B., P. Balcombe, J. F. Speirs, A. D. Hawkes, and K. Hellgardt (2019). "Levelized cost of CO2 mitigation from hydrogen production routes". *Energy & Environmental Science* 12.1, pp. 19–40. URL: https://pubs.rsc.org/en/content/articlelanding/2019/ee/c8ee02079e (visited on 05/10/2022).

Plötz, P. (2022). "Hydrogen technology is unlikely to play a major role in sustainable road transport". *Nature Electronics* 5.1, pp. 8–10. URL: https://www.nature.com/articles/s41928-021-00706-6 (visited on 07/27/2022).

Reichelstein, S. and A. Rohlfing-Bastian (2015). “Levelized Product Cost: Concept and Decision Relevance”. *The Accounting Review* 90.4, pp. 1653–1682. URL: https://www.jstor.org/stable/26550579 (visited on 05/10/2022).

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M. Vilariño (2018). *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.*

Rossum, R. van, J. Jens, G. La Guardia, A. Wang, L. Kühnen, and M. Overgaag (2022). *European Hydrogen Backbone: A European Hydrogen Infrastructure Vision Covering 28 Countries*. Tech. rep. EHB. URL: https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf (visited on 07/14/2022).

Shang Ian W. H. Parry, N.-P. L. B. D. C. (2019). *Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates*. IMF Working Paper Working Paper No. 2019/089. International Monetary Fund. URL: https://www.imf.org/en/Publications/WP/Issues/2019/05/02/Global-Fossil-Fuel-Subsidies-Remain-Large-An-Update-Based-on-Country-Level-Estimates-46509 (visited on 07/27/2022).

Statistics Norway (2021). *Emission factors used in the estimations of emissions from combustion*. Ed. by Statistics Norway. URL: https://www.ssb.no/_attachment/404602/.

Stern, N. (2006). *The Economics of Climate Change. The Stern Review*. Vol. 30. October. Cambridge University Press.

Tomaschek, J. (2015). “Marginal abatement cost curves for policy recommendation – A method for energy system analysis”. *Energy Policy* 85, pp. 376–385. URL: https://www.sciencedirect.com/science/article/pii/S0301421515002141 (visited on 05/10/2022).

Ueckerdt, F., C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, and G. Luderer (2021). “Potential and risks of hydrogen-based e-fuels in climate change mitigation”. *Nature Climate Change* 11.5, pp. 384–393. URL: https://www.nature.com/articles/s41558-021-01032-7 (visited on 07/14/2022).

Vogt-Schilb, A., G. Meunier, and S. Hallegatte (2018). “When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment”. *Journal of Environmental Economics and Management* 88, pp. 210–233. URL: https://www.sciencedirect.com/science/article/pii/S0095069617308392 (visited on 05/10/2022).

Wahl, J. and J. Kallo (2022). “Carbon abatement cost of hydrogen based synthetic fuels – A general framework exemplarily applied to the maritime sector”. *International Journal of Hydrogen Energy* 47.6, pp. 3515–3531. URL: https://www.sciencedirect.com/science/article/pii/S0360319921044219 (visited on 07/14/2022).

ZERO (2022). *Slik når vi klimamålene*. Tech. rep. Oslo, Norway: ZERO. URL: https://zero.no/wp-content/uploads/2022/04/Rapport_ZERO2030_3.pdf.

Contact.

MIT CEEPR Working Paper Series
is published by the MIT Center for Energy and Environmental Policy Research from submissions by affiliated researchers.
For inquiries and/or for permission to reproduce material in this working paper, please contact:

General inquiries: ceepr@mit.edu
Media inquiries: ceepr-media@mit.edu

MIT Center for Energy and
Environmental Policy Research

MIT Center for Energy and
Environmental Policy Research
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139-4307
USA

ceepr.mit.edu

MASSACHUSETTS INSTITUTE OF TECHNOLOGY