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Modeling cost-optimal fuel choices for truck, ship, and airplane fleets: The impact of sustainability commitments

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ABSTRACT

For the next 25 years, numerous transport operators have introduced sustainability commitments to mitigate carbon emissions. However, static goals to reduce fossil fuel usage and adopt renewable fuel technologies pose economic risk. This study analyzes the costs of strategic fleet replacement through a mixed integer linear program. Comparing three Norwegian transport operators, we determine cost-optimal investments in fossil and renewable fuel technologies for two approaches: One integrating and the other neglecting sustainability commitments. Our findings reveal that the truck operator's sustainability commitments incur minimal additional costs, with battery-electric trucks proving cost-effectiveness early. In contrast, ship and airplane operators exhibit significant differences in fleet replacement decisions, resulting in additional costs ranging from +6% to +31% for ships and +4% to +11% for airplanes, across fuel cost and carbon price scenarios. Norwegian carbon price regulations fall short in incentivizing a cost-competitive technology transition for ships and airplanes. Additional policies are needed to encourage gradual fleet replacement.

1. Introduction

Within the next 25 years, transport operators[1] must drastically reduce the use of fossil fuels to meet international carbon emission targets [3]. This requires identifying suitable fuel technologies [4], building up new infrastructures [5], and replacing vehicle fleets early enough to accommodate system inertia [6]. Similar to other countries, Norway has pledged to decrease its total greenhouse gas emissions to 50%–55% of 2005 levels by 2030 and achieve carbon neutrality by 2050 [7]. While the country has made remarkable progress in electrifying passenger vehicles with renewable electricity [3], the challenge of decarbonizing truck, ship, and air transport remains significant [8]. Here, a current fossil oil dependency of close to 100% creates a homogeneous picture[2] [1]. The future fuel mix, however, is assumed to differ substantially [3]. For long-haul road freight, battery-electric trucks, supplemented by hydrogen, are estimated to be the dominant renewable fuel technology[3] [9]. Bio-based fuels, hydrogen, and synthetic hydro-carbons (e-fuel) are assumed to coexist in a future maritime and aviation market, where today's battery technology reaches technical limits [3,4].

While governments define decarbonization strategies on a macro level [10], for transport operators, the optimal timing to decarbonize their vehicle fleets is challenging [5]. A wait-and-see approach might already jeopardize emission targets for 2050, with asset lifespans of up to 25 years for airplanes [11] or 30 years for ships [12]. Thus, investing too long in fossil fuel technologies might result in high emission costs, the need for short-term depreciation, and low residual values for vehicles to be sold in shrinking secondary markets. Investing too early in renewable fuel technologies, however, might lead to high fuel technology costs and dependencies on inadequate supply chains.

In recent years, many transport operators present fleet replacement strategies to mitigate carbon emissions, defined as sustainability commitments. Such commitments schedule exit dates for fossil fuels [13],

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[1] A transport operator is a company that manages and operates a commercial fleet of vehicles, such as trucks, ships or airplanes.

[2] Norwegian rail transport accounts for only 1% of total transport energy demand, with 80% already electrified and therefore excluded from this study for simplification [1].

[3] We consider "fuel" to be any type of energy being used to power a vehicle, "fuel technology" encompassing the fuel and associated vehicle technology, and "renewable fuels" being produced from climate-friendly electricity sources, such as hydropower and wind, which accounts for 92% of Norwegian grid electricity (2020) [2].

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Nomenclature

Set and index	
$a \in \mathcal{A}$	Group of vehicle age classes (Age of purchase 0, 1, 2, ..., age of retiring a_{max})
$y \in \mathcal{Y}$	Timesteps in years (2020, 2021, ..., 2055)
$t \in \mathcal{T}$	Fuel technologies (Diesel, Battery, Ammonia, Hydrogen, Biofuel_{10}, Efuel_{10-100})
$r \in \mathcal{R}$	Renewable fuel technologies (Battery, Hydrogen, Ammonia, Efuel_{100})
$s \in \mathcal{S}$	Scenarios (Expect, Optimistic, Pessimistic, Expect/Carbon^{++})
Decision variables	
$n^{act}_{a,y,t}$	Active vehicles in operation [#]
$n^{buy}_{a,y,t}$	Buying of vehicles [#]
$n^{conv}_{a,y,t}$	Fuel conversion of existing vehicles [#]
$n^{pas}_{a,y,t}$	Passive vehicles not used [#]
$n^{sell}_{a,y,t}$	Selling of vehicles [#]
$n^{tot}_{a,y,t}$	Total fleet (active + passive vehicles) [#]
$tr^{oper}_{y,t}$	Fleet's transport operation [tkm]
Parameters	
$c^{cap}_{y,t}$	Capital expenditures [€]
$c^{fuel}_{y,t,s}$	Fuel cost [€/tkm]
$n^{init}_{a,y,t}$	Initial vehicles of the fleet [#]
$c^{fix}_{y,t}$	Fixed operational expenditures [€/tkm]
$p^{carb}_{y,t,s}$	Carbon emission price [€/t_{CO2}]
tr^{cap}_{t}	Transport capacity per vehicle [tkm/a]
tr^{dem}_{y}	Fleet's transport demand [tkm]
$v^{resi}_{y,t}$	Residual value of vehicles [€]
$\epsilon_{y,t}$	Carbon emission factor [t_{CO2}/tkm]
γ_y	Fleet's share of renewable fuel technologies [%]
ω_y	Emission reduction goal [%]
Others	
#	Number of vehicles [integer]
i	Interest rate [%]
tkm	Tonne-kilometer
V_y	Respective value per year (Sigmoid function)
y_0	Start year [2020]
y_h	Year of half-time growth (Sigmoid function)
α	Parameter 1 (Sigmoid function)
β	Parameter 2 (Sigmoid function)

renewable fuel shares in a fleet [14], or generalized emission reduction targets over time[4] [15]. Although knowing that implementing sustainability commitments can come with high cost, its quantification compared to an uncommitted approach is often non-transparent.

Among the various cost parameters influencing the technology transition, fuel costs stand out as the most significant and uncertain factor, exerting a substantial influence on the future expenses of commercial transport [16,17]. That uncertainty surrounding both future renewable and fossil fuels poses a challenge to the fleet replacement process. On the other hand, carbon pricing, which places a premium on fossil fuel use, is regarded as an efficient policy tool to foster cost-competitiveness of renewable fuel technologies [8].

[4] In practice, sustainability commitments can involve additional measures to mitigate environmental impact, such as the reduction of resource consumption, noise pollution or waste, which are not considered in this study.

Against this background, this paper aims to answer the following research questions: (i) What are cost-optimal fuel technology choices for transport operators following sustainability commitments for emission reduction?, (ii) How expensive is their realization?, (iii) How sensitive are decisions to different fuel cost and carbon price scenarios?, and (iv) How does an approach free of sustainability commitments differ?

To analyze this, the paper proposes a *mixed integer linear program* solved by a deterministic optimization model (hereafter abbreviated as "model"). Its objective is to replace an initial vehicle fleet with fossil and renewable fuel technologies over time — aligned to sustainability commitments while minimizing the operator's total fleet costs. The model is designed to be adaptable to different transport sectors, fleet structures, and sustainability commitments. We apply it to three Norwegian transport operators in long-haul trucking, short-sea shipping, and medium-haul aviation — transport sectors, which are of similar importance in other European countries [4,16].

The paper is structured as follows: Section 2 provides an overview of relevant literature, presenting both the current state of the art and the novelties of this study. Section 3 delves into the model's methodology, while Section 4 presents a numerical example along with the utilized data. Section 5 unveils the results, which are discussed in Section 6 alongside limitations of this work. Finally, Section 7 concludes the paper and makes suggestions for future work.

2. State of the art and this study's progress beyond

Strategic fleet replacement is important for transport operators to ensure cost-efficiency and reliability, aligned to a variety of frameworks. The complexity of this task has initiated a rich body of literature, originating from the classical equipment replacement problem and evolving into strategic fleet replacement [5].

The classical equipment replacement problem aims to strike a balance between the increasing operational cost and decreasing residual value of aging equipment, relative to the expenses involved in investing in and operating new equipment [18]. This approach optimizes the timing of investment, focusing on a 1-to-1 substitution of the same technology [19]. In contrast, the renewal problem allows for the replacement of single components to extend the asset's lifespan [20]. A combination of the replacement and renewal problem is explored in [21]. Expanding on this, [22] integrate the adoption of alternative technologies. In the context of sustainability in transport, alternative technologies include the integration of renewable or low-carbon fuels and the enhancement of fuel efficiency [5]. Often, uncertainty is associated with renewable fuel technologies, covering aspects such as investment costs [23], fuel costs [22], or the policy landscape [24]. Its impact is investigated through deterministic approaches combined with sensitivity analyses [25] or in a stochastic manner [22]. With growing attention, the strategic alignment of fleet replacements with climate regulations is investigated [5].

Hence, strategic fleet replacement models span a variety of applications, analyzing different transport sectors, technology portfolios, and policy regulations. In the context of road transport, [23] develop an optimization framework to achieve sustainable urban freight transport, considering uncertainty in fuel and investment costs. A mixed integer linear program is developed by [26], that combines vehicle purchase, retrofit, and task assignment decisions to reduce emissions from transit bus fleets. In [27], the authors optimize the fleet integration of electric buses. For the national car fleet of Germany, [28] simulate long-term vehicle fleet replacements driven by varies carbon price scenarios. A stochastic multi-period setting is used by [29] to minimize cost and risk while decarbonizing a company's car fleet. Cost-optimal fuel choices for truck fleets are analyzed by [30] with a real options analysis framework driven by fuel price dynamics. In [5], the authors develop a stochastic mixed integer program to cost-optimize a strategic transition plan for trucks and charging infrastructure under uncertainty.

For the maritime sector, [31] provide a comprehensive review of relevant literature related to fleet planning for ships. Investigating fleet replacement decisions concerning fossil fuel alternatives, [32] propose a real option model, considering uncertainties in demand and fuel prices within the context of different policies. A two-stage stochastic optimization model is developed by [22], considering uncertainties in fuel and carbon emission prices, and assessing their impact on retrofitting and new purchase. Furthermore, [33] minimize the total system costs of the Danish ship fleet, transitioning to carbon neutrality under various deterministic scenarios.

For the aviation sector, strategic fleet replacement literature primarily centers around addressing the uncertainty of demand, specifically focusing on achieving a cost-optimal expansion of fleet capacity. Thus, literature exploring sustainability aspects is relatively limited. A three-step airline fleet planning methodology is introduced by [34], aiming to identify fleets that remain robust to stochastic demand realizations. Additionally, [35] optimize dynamic airline decisions concerning the purchase, leasing, or disposal of airplanes over time under uncertain demand. Airplane fleet renewal is employed in [36], specifically investigating the impact of policy incentives financed by a carbon emission tax.

While not exhaustive, the cited references underscore the relevance of strategic fleet replacement within the scope of this study. The reviewed literature predominantly focuses on strategic fleet replacement models for road transport, with limited coverage of sustainability aspects in shipping and aviation. Sustainability commitments by the private sector play a minor role compared to national emission targets. In addition, the literature lacks connections between transport modes, which limits comparability across road, sea, and air transport. Here, harmonized data assumptions and a uniform model framework are crucial, as emphasized by [37]. To address these gaps, this work aims to advance beyond the current state of the art in the following dimensions:

- Developing a universal framework for strategic fleet replacement for trucks, ships, and airplanes, and applying it to Norwegian transport operators with harmonized input data and cost assumptions.
- Studying sustainability commitments of transport operators by quantifying their economic and operational impact on fleet replacement decisions.
- Exploring different fuel cost scenarios, considering value chain efficiencies to ensure cost proportionality across fuel types and transport modes.
- Informing policymakers about the pivotal years of peak demand for renewable fuel technologies and demonstrating the impact of carbon pricing across transport sectors.

3. Methodology

To address our research questions, we formulate a *mixed integer linear program* designed to optimize fleet replacement decisions over a specified time period. The primary objective of the model is to minimize overall fleet costs, taking into account various constraints such as the sustainability commitments of transport operators and government regulations aimed at achieving carbon neutrality by 2050. Section 3.1 provides a general overview of the model's structure, while Section 3.2 delves into the model's detailed formulation.

3.1. Model overview

Fig. 1 provides a comprehensive overview of the model's structure. The general input data includes annual transport demand, a portfolio comprising both fossil and renewable fuel technologies, and scenarios of fuel cost and carbon price variation. Specific to fuel technologies, the model considers capital and operational costs, annual transport capacities (based on average payload and annual mileage of vehicles), and carbon emission factors. Operator-specific sustainability commitments are integrated, constraining the deployment of fossil fuel technologies over time.

The initial fleet encompasses the existing vehicles in the starting year, categorized by fuel technology and vehicle age. We assume that the initial fleet uniformly operates on fossil fuel. The total fleet is differentiated by active vehicles, engaged in transport operations, and passive vehicles that are temporarily out of use, assumed not to age during that period. Employing a total cost of ownership approach, the model aims to minimize the overall costs of the fleet over the investigated period. Fleet replacement decisions are executed annually, offering the flexibility to buy new vehicles, sell used vehicles, or retain vehicles with remaining lifetime in the fleet. A yearly fleet update is conducted, incrementing a vehicle's age to simulate a natural aging process. The decision-making process is bound by several constraints. Vehicles reaching the end of their life must be sold and replaced if transportation is required. However, vehicles may be sold earlier if their transport capacity or fuel technology becomes outdated. The fleet's transport capacity must at least cover the predetermined transport demand. In addition to economic considerations, each purchase decision must also adhere to current sustainability commitments, potentially limiting the utilization or acquisition of fossil fuel technologies.

For each investigated year, the model outputs the new fleet composition. The results provide detailed insights into the fuel technology mix, associated emission reduction, timing of investments, disposals, and annual costs for the operator. Furthermore, differences in the fleet's net present value among different scenarios can be evaluated.

3.2. Model formulation

This section provides a detailed description of the formulated methodology. The model, a *mixed integer linear program*, optimizes fleet replacements over time by minimizing the objective function, treating the number of vehicles as discrete and the transport demand as continuous variables. The following outlines the model's sets, objective function, decision variables, parameters, and constraints.

3.2.1. Sets

The model optimizes across four dimensions. Each vehicle n is characterized by its fuel technology t and its age class a in the time-step y. Renewable fuel technologies r represent a subset of t, excluding the blending of fossil with renewable fuels, as carbon neutrality is unattainable in such cases. The sets are defined as follows:

Fuel technologies	{Fossil fuel technologies, Renewable fuel technologies} [t]
Renewable fuel technologies	{Battery-electric, Hydrogen, Ammonia, E-fuel100} [r]
Time steps	{2020, 2021, …, 2055} [y]
Age classes	{0, …, a_{max}} [a]
Scenarios	{Expect, Optimistic, Pessimistic, Expect/Carbon^{++}} [s]

3.2.2. Objective function

Eq. (1) to (5) aim to minimize the transport operator's expenses, covering both the capital and operational costs of the vehicle fleet for a specific scenario:

$$min \sum_{y} \sum_{t} \frac{1}{(1+i)^{y-y_0}} * (Capex_{y,t} - Value_{y,t} + Opex^{fix}_{y,t} + Opex^{var}_{y,t,s}) \quad (1)$$

with

$$Capex_{y,t} = \sum_{a} n^{buy}_{a,y,t} * c^{cap}_{y,t} \quad (2)$$

$$Value_{y,t} = \sum_{a} n^{sell}_{a,y,t} * v^{resi}_{y,t} \quad (3)$$

$$Opex^{fix}_{y,t} = \sum_{a} (n^{act}_{a,y,t} + n^{pas}_{a,y,t}) * c^{fix}_{y,t} \quad (4)$$

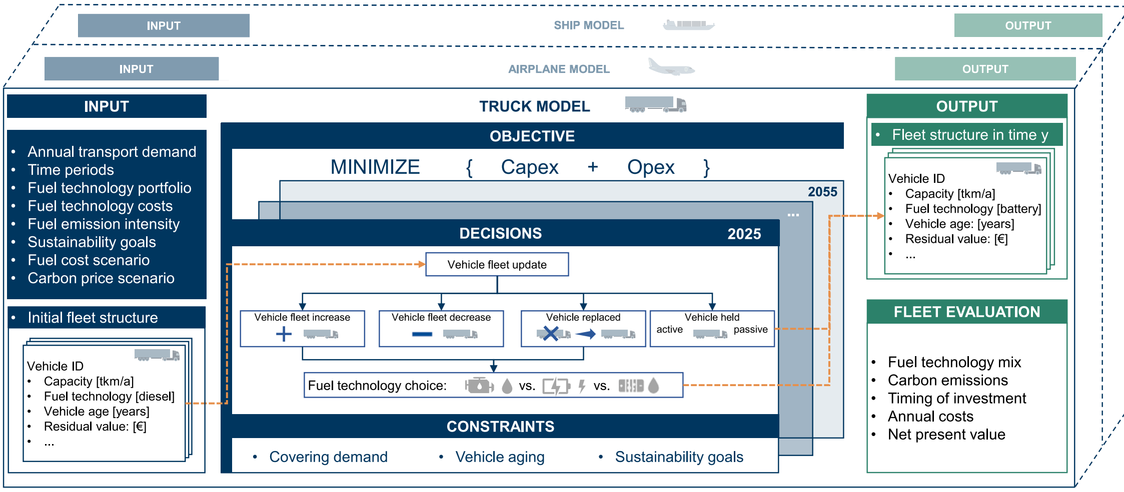


Fig. 1. Overview of the model's structure. Figure inspired by [28].

$$Opex^{var}_{y,t,s} = tr^{oper}_{y,t} * c^{fuel}_{y,t,s} + tr^{oper}_{y,t} * \epsilon_{y,t} * p^{carb}_{y,t,s} \quad (5)$$

where $n^{buy}_{a,y,t}$ and $n^{sell}_{a,y,t}$ represent the purchased or sold vehicles of age class a, in year y, of technology t. Additionally, $n^{act}_{a,y,t}$ and $n^{pas}_{a,y,t}$ denote the active vehicles in operation or passive vehicles not in use. The variable $tr^{oper}_{y,t}$ represents the transport operation carried out to meet the transport demand. Capital expenditures are denoted by $c^{cap}_{y,t}$, fixed operating expenses by $c^{fix}_{y,t}$, fuel costs by $c^{fuel}_{y,t,s}$, and carbon prices by $p^{carb}_{y,t,s}$, with scenarios s distinguishing the latter two. The residual value of sold vehicles is covered by $v^{resi}_{y,t}$, and the technology-specific emission factor by $\epsilon_{y,t}$. The interest rate is denoted as i, and the starting year is y_0 (set to 2020).

3.2.3. Decision variables

The variables influenced by the operators' decisions are consolidated into the decision variable vector d as shown in Eq. (6). These variables encompass the buying, selling, and operation (active or passive) of vehicles. Furthermore, the operator has the option to convert fossil fuels to biofuel or e-fuel blending, represented by $n^{conv}_{a,y,t}$:

$$d = [n^{buy}_{a,y,t}, n^{sell}_{a,y,t}, n^{conv}_{a,y,t}, n^{act}_{a,y,t}, n^{pas}_{a,y,t}] \quad (6)$$

3.2.4. Parameters

The techno-economic parameters, presented in the parameter vector p in Eq. (7), define the characteristics of both the transport operator and fuel technologies:

$$p = [c^{cap}_{y,t}, v^{resi}_{y,t}, c^{fix}_{y,t}, c^{fuel}_{y,t,s}, \epsilon_{y,t}, p^{carb}_{y,t,s}, n^{init}_{a,0,t}, \omega_y, tr^{cap}_t, tr^{dem}_y] \quad (7)$$

where $n^{init}_{a,0,t}$ represents the operator's initial fleet in time-step 0, ω_y defines a percentage of emission reduction regulated by sustainability commitments, tr^{cap}_t is the vehicle's transport capacity of fuel technology t, and tr^{dem}_y is the transport demand in time-step y. Future fossil and renewable fuel costs, as well as carbon prices, are assumed to be uncertain. Indexed by s, $c^{fuel}_{y,t,s}$ and $p^{carb}_{y,t,s}$ are considered in our scenario analysis, encompassing a range of input data.

3.2.5. Constraints

Eq. (8) defines the total fleet $n^{tot}_{a,y,t}$ by summing up the overall number of vehicles, encompassing both active and passive vehicles.

$$n^{tot}_{a,y,t} = n^{act}_{a,y,t} + n^{pas}_{a,y,t} \quad (\forall a, y, t) \quad (8)$$

Eq. (9) quantifies the fleet's transport operation carried out by the active vehicles and their technology-specific transport capacity, represented as the sum across all age classes.

$$tr^{oper}_{y,t} = \sum_a n^{act}_{a,y,t} * tr^{cap}_t \quad (\forall a, y, t) \quad (9)$$

Eq. (10) ensures the coverage of transport demand by the sum of all active vehicles.

$$\sum_t tr^{oper}_{y,t} \geq tr^{dem}_y \quad (\forall y, t) \quad (10)$$

Eq. (11) ensures the attainment of sustainability commitments, specifying that the emissions resulting from the actual transport operation across all fuel technologies must be equal to or lower than the percentage ω_y of those in the reference year y_0.

$$\sum_t tr^{oper}_{y,t} * \epsilon_t \leq \omega_y * \sum_t tr^{oper}_{y_0,t} * \epsilon_t \quad (\forall y, t) \quad (11)$$

Eq. (12) guarantees that renewable fuel technologies (R) fulfill the predefined share γ_y of all purchased vehicles in time-step y, as outlined in the operator's sustainability commitments.

$$\sum_r n^{buy}_{a,y,t} \geq \gamma_y * \sum_t n^{buy}_{a,y,t} \quad (\forall y, t) \quad (12)$$

Eq. (13) defines the aging process of the fleet's vehicles of fuel technology t over the years y. A vehicle with an age of 0 is newly bought, a_{max} represents the age of the last year of operation, and a_{max+1} signifies the age at which the vehicle must be sold and exit the fleet. Further explanations for each equation line can be found in Appendix A.

$$n^{tot}_{a,y,t} = \begin{cases} n^{init}_{a,y,t} + n^{buy}_{a,y,t} - n^{sell}_{a,y,t} & : \forall a = 0, y = 0, t \\ n^{init}_{a,y,t} - n^{sell}_{a,y,t} & : \forall a \in \{1, \dots, a_{max-1}\}, y = 0, t \\ n^{init}_{a,y,t} - n^{sell}_{a,y,t} & : \forall a = a_{max}, y = 0, t \\ n^{init}_{a,y,t} - n^{sell}_{a,y,t} & : \forall a = a_{max+1}, y = 0, t \\ n^{buy}_{a,y,t} + n^{pas}_{a,y-1,t} & : \forall a = 0, y > 0, t \\ n^{act}_{a-1,y-1,t} + n^{pas}_{a,y-1,t} - n^{sell}_{a,y,t} - n^{conv}_{a,y,t} & : \forall a \in \{1, \dots, a_{max-1}\}, y > 0, t \\ n^{act}_{a-1,y-1,t} + n^{pas}_{a,y-1,t} - n^{sell}_{a,y,t} - n^{conv}_{a,y,t} & : \forall a = a_{max}, y > 0, t \\ n^{act}_{a-1,y-1,t} - n^{sell}_{a,y,t} & : \forall a = a_{max+1}, y > 0, t \end{cases} \quad (13)$$

With:

$$n^{conv}_{a,y,t} = \begin{cases} n^{efuel10}_{a,y,t} + n^{efuel50}_{a,y,t} + n^{efuel100}_{a,y,t} & : \forall a \in \{1, \dots, a_{max}\}, y > 0, t = fossils \\ n^{efuel50}_{a,y,t} + n^{efuel100}_{a,y,t} & : \forall a \in \{1, \dots, a_{max}\}, y > 0, t = efuel10 \\ n^{efuel100}_{a,y,t} & : \forall a \in \{1, \dots, a_{max}\}, y > 0, t = efuel50 \end{cases} \quad (14)$$

Table 1
The transport operators' sustainability commitments considered in the analysis, in addition to the mandatory government goal of achieving carbon neutrality by 2050.

Sector	Sustainability commitment (2030)	Government policy (2050)
Long-haul trucking	50% carbon-neutral trucks of new purchases	Carbon-neutral
Short-sea shipping	50% emission reduction (compared to 2008 levels) and 100% carbon-neutral ships of new purchases	Carbon-neutral
Medium-haul aviation	25% emission reduction (compared to 2010 levels) through the use of sustainable aviation fuels	Carbon-neutral

$n^{conv}_{a,y,t}$ denotes vehicles that have been converted from fossil fuel or a lower e-fuel blending to a (higher) e-fuel blending. In the case of aviation, this entails replacing the blending of e-fuel10 with biofuel10.

Eq. (15) ensures the clearance of the group of retired vehicles, compelling the sale of vehicles that have reached the end of life (a_{max+1}).

$$n_{a,y,t} = 0 \quad (\forall a = a_{max+1}, y > 0, t) \tag{15}$$

4. Numerical example

We apply our model to Norwegian transport operators in long-haul trucking, short-sea shipping, and medium-haul aviation. In Section 4.1, we outline the three Norwegian transport operators and their sustainability commitments. Appendix D details the study's techno-economic data, while Sections 4.3 and 4.4 present the applied renewable fuel cost and carbon price scenarios.

4.1. Norwegian transport operators and their sustainability commitments

Norwegian operators in trucking [38], shipping [39], and aviation [14] are at the forefront of carbon emissions mitigation, driven by government policies and regulations [40]. Focusing on three specific Norwegian transport operators and their sustainability commitments, we utilize publicly available fleet data, modified to avoid providing direct advice while ensuring the data represents typical fleet characteristics of each transport sector. The sustainability commitments considered in this analysis are detailed in Table 1.

The truck operator manages a fleet of 100 vehicles with an average age of 2.5 years. Situated in Norway, the company adheres to the "National Transport Plan 2022–2033" [40], which mandates that, from 2030 onward, 50% of newly acquired long-haul trucks must be carbon-neutral.

The ship operator oversees a fleet of 5 vessels with an average age of 14.6 years. Situated in Norway, the operator aligns with the emission targets of the Norwegian Shipowner's Association, which stipulate a 50% reduction in carbon emissions by 2030 compared to the 2008 levels[5] [13]. Additionally, starting in 2030, newly purchased ships must be carbon-neutral.

The airplane operator manages a fleet of 45 aircraft with an average age of 9 years. Situated in Norway, the operator aligns with representative emission targets set by the Norwegian aviation industry [41]. Its goal is to achieve a 16%–28% reduction in emissions by 2030 compared to 2010 levels, accomplished through the utilization of sustainable aviation fuels [14]. For our analysis, we apply a reduction target of 25% of the initial fleet.

In our analysis, the Norwegian government's policy of achieving carbon neutrality in all sectors by 2050 is mandatory and cannot be influenced by operators [42]. For a detailed age structure of the operators' fleets, refer to Appendix B.

4.2. Fossil and renewable fuel technologies considered

Approximated to current market shares [1], we assume that today's transport exclusively relies on fossil fuels. The fossil fuel technologies considered encompass diesel for trucks, marine gas oil (MGO) for ships, and kerosene for airplanes. As alternatives, renewable fuel technologies include battery-electric, hydrogen and e-fuel[6] for trucks, hydrogen, ammonia and e-fuel for ships, and biofuel, e-fuel, and hydrogen for airplanes, as illustrated in Fig. 2.

We exclude other low-carbon technologies, such as liquefied natural gas, across all sectors, as achieving carbon neutrality is unattainable [4]. While the blending of fossil fuels with renewable fuels can vary in practice,[7] we limit the resolution of blending shares for biofuel to 10% (due to limited availability) and for e-fuel to 10%, 50%, and 100% for the sake of simplification. In interpreting the results, it should be noted that in practice, the share of biofuel and e-fuel will be distributed across the entire fleet rather than being consumed in individual vehicles.

In Appendix D, we outline the techno-economic assumptions to characterize vehicle configurations across different fuel technologies. For simplicity, we assume that all vehicles within a fleet belong to the same type, ensuring uniform technical parameters such as annual mileage and maximum payload. The selected vehicle types serve as representative examples of both Norwegian and European transport [4, 16]. The assumed data is presented in Table D.5 to Table D.7 and the methodology of interpolating between today's and future values explained in Appendix C.

4.3. Fossil and renewable fuel costs

Fuel cost stands out as the most dominant and uncertain parameter influencing the future costs of commercial transport [16,17]. The uncertainty in the costs of emerging, renewable fuel technologies poses a particular risk for decision-makers that requires careful consideration. Additionally, the uncertainty in future oil prices, affecting the costs of fossil fuels, can either bolster or jeopardize the cost-competitiveness of a potential transition. Therefore, we undertake a comprehensive scenario analysis to quantify the impact of this uncertainty. In the case of renewable fuels, electricity emerges as the primary cost lever [16]. To develop scenarios for renewable fuel costs, we employ the existing cost model from [8] and input it with a projected range of future electricity prices for Norwegian market zones, as estimated by [43]. The impact of electricity prices on renewable fuel costs is determined by the process efficiency of the fuel value chains. Resulting in Fig. 3, fuel types respond similarly, though not identically, to variations in electricity prices, as represented by [8]. For fossil fuels, the international oil price serves as the major cost lever. We use the future price estimates for

[5] We consider the fleet's carbon emissions in 2020 as benchmark since the youngest ships date back to 2008.

[6] In this paper, we harmonize the costs and energy densities of e-fuels across sectors, simplifying variations among e-diesel, e-MGO, and e-kerosene (11.5 kWh/kg and 10 kWh/l) as detailed by [16]. While absolute cost values may vary slightly, the cost differences compared to their respective fossil counterparts dominate operators' investment decisions.

[7] At present, Fischer–Tropsch e-fuel is certified for blending with fossil kerosene at up to 50%, with anticipated future increases to reach 100% [4].

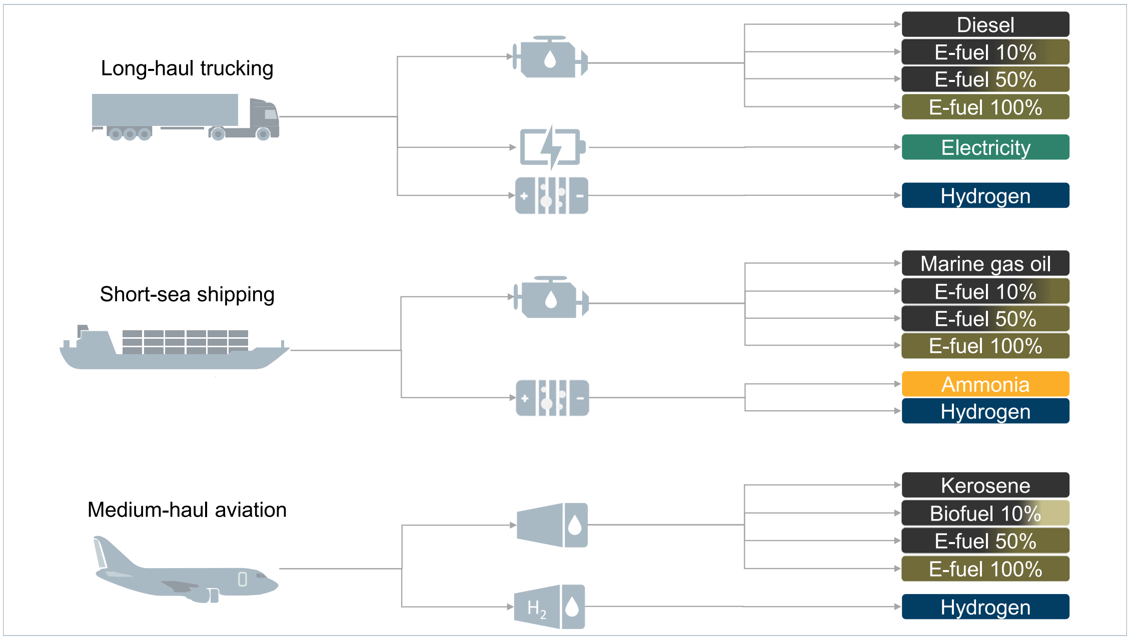


Fig. 2. Fossil and renewable fuel technologies considered in this analysis.

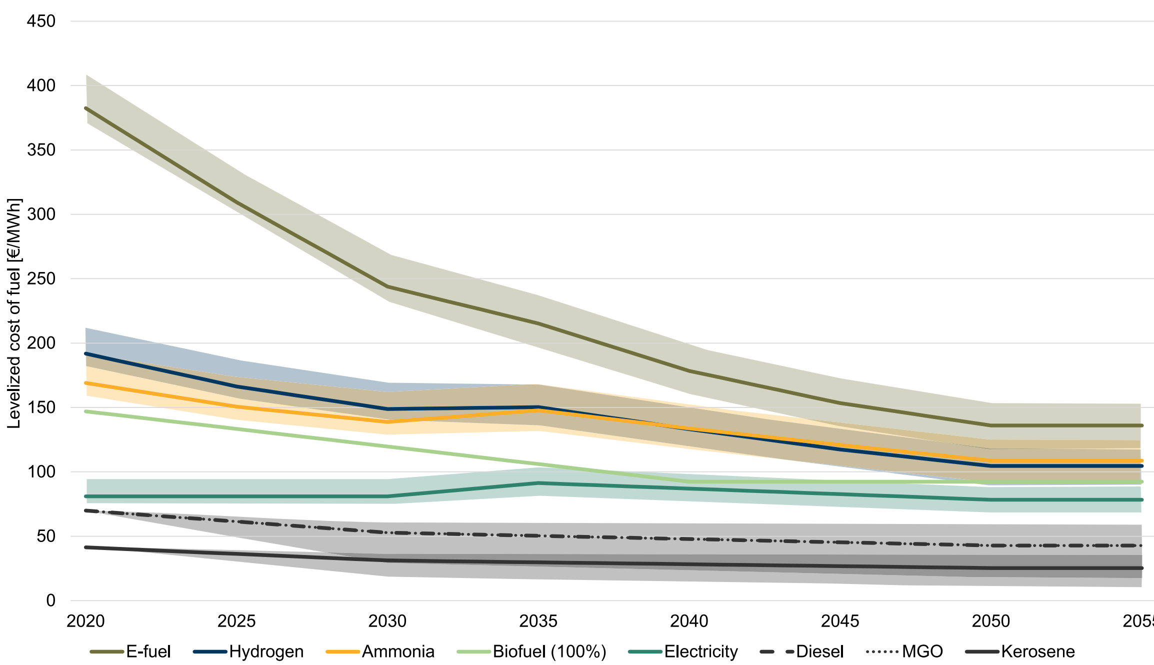


Fig. 3. Range of fossil and renewable fuel costs considered for scenario generation. Baseline with high and low cost ranges.

fossil crude oil provided by [44] as an index to generate scenarios for all considered fossil fuels. These assumptions can be considered conservative, hindering the cost-competitiveness of renewable fuels due to a tendency for general price decline. Fig. 3 illustrates the high and low ranges of fossil and renewable fuel costs alongside baseline developments. Table 2 outlines the generated fuel cost scenarios.

Table 2
Scenario definition based on the different input data.

Scenario	Renewable fuel cost	Fossil fuel cost	Carbon prices
Expect	Baseline	Baseline	Baseline
Optimistic	Low	High	Baseline
Pessimistic	High	Low	Baseline
Expect/Carbon^{++}	Baseline	Baseline	High

The *Optimistic* scenario depicts a situation where low-cost renewable fuels compete with relatively high-cost fossil fuels, supporting the cost-competitiveness of renewable fuels. Conversely, the *Pessimistic* scenario acts in the opposite direction.

4.4. Carbon price scenarios and emission costs

Carbon pricing emerges as an efficient policy tool for fostering the cost-competitiveness of renewable fuel technologies [44]. To assess the model's decisions under different carbon prices, we examine three price scenarios, illustrated in Fig. 4. We align with two scenarios proposed by the Norwegian government [45]. The "Baseline Norwegian Regulation" scenario escalates to 223 €/t in 2030 and remains stable thereafter — the minimum price level guaranteed by the government. We apply this

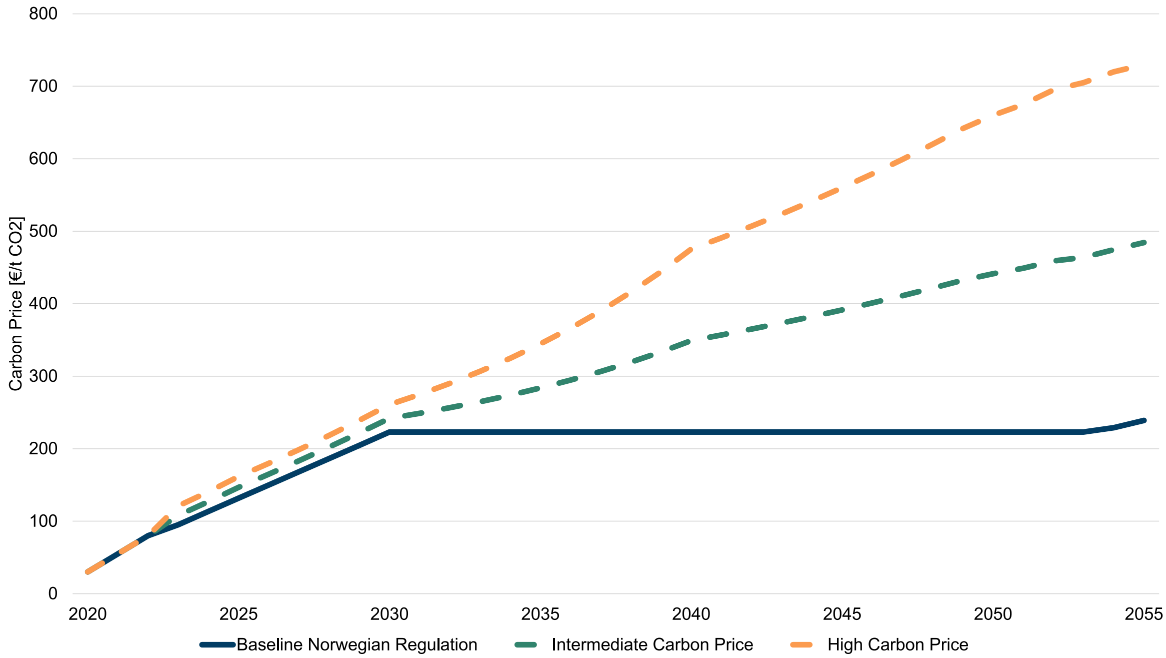


Fig. 4. Range of carbon prices considered for scenario generation.

development in our analysis for the Scenarios *Expect*, *Optimistic*, and *Pessimistic*, as presented in Table 2.

The "IPCC 1.5 °C pathway-median" scenario, as outlined by the Norwegian government [45], quantifies a carbon price of 1,106 €/t in 2050, necessary to align with the climate goals of the Paris Agreement [46]. We use this value to formulate an average with the base carbon price, creating the *High Carbon Price* development, escalating to 665 €/t in 2050 and used in this study's Scenario $Carbon^{++}$ (Table 2).

We analyze all fuel technologies based on scope 1 emissions, taking into account tailpipe carbon emissions during consumption. For fossil fuels, we utilize emission factors from [47], reflecting each fuel's carbon content. For renewable fuels, we assume zero carbon emissions due to the low carbon content of Norwegian grid electricity (below 0.022 $kgCO_2/kWh_{el}$ in 2022) [48] which is assumed to decrease further. The carbon utilized for e-fuel production is obtained through direct air capture [16], indicating that the same amount of carbon emitted into the atmosphere during combustion was previously captured from the atmosphere in a closed carbon cycle.

5. Numerical results

In this section, we describe numerical results based on the data assumptions outlined. In Section 5.1, we present strategic fleet replacement decisions aligned with sustainability commitments for the Scenario *Expect*. Variations of fuel costs and carbon prices are analyzed in Section 5.2. In Section 5.3, we present fleet replacement decisions neglecting sustainability commitments, and Section 5.4 determines the associated cost differences between a committed and uncommitted approach.

5.1. Baseline fleet replacement decisions aligned with sustainability commitments

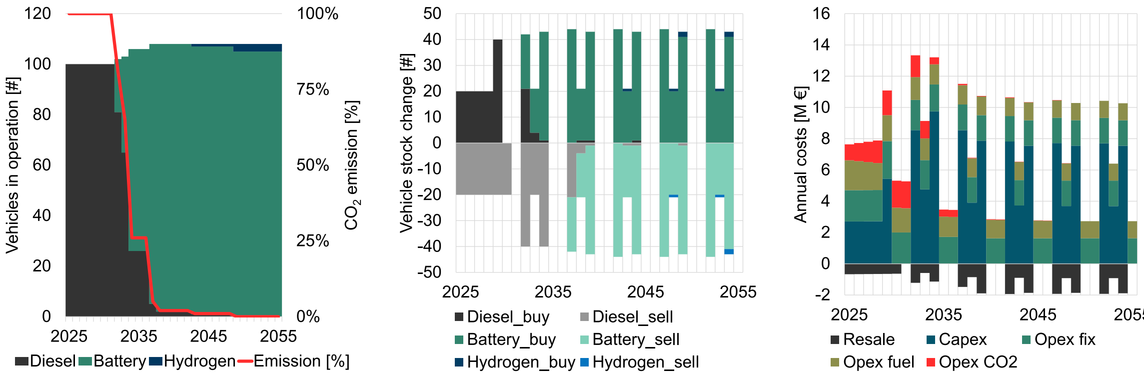
For the Scenario *Expect*, Fig. 5(a) depicts the truck operator's fuel choices in line with sustainability commitments. Between 2025 and 2031, a fleet of 100 diesel trucks is used. From 2032, a gradual shift to battery-electric trucks reduces diesel trucks to 5% by 2037, with the total fleet expanding to 108 vehicles to accommodate battery-electric limitations in transport capacity. By 2049, three hydrogen trucks replace all remaining diesel trucks. The final preference for hydrogen over battery-electric trucks might be caused by the comparably beneficial transport capacity of hydrogen trucks. Although more expensive than battery-electric trucks in general, this behavior points to potential business cases of hydrogen trucks in certain future fleet structures. Carbon emissions are mostly eliminated by 2037 (a 95% reduction from 2025 levels), achieving carbon neutrality by 2049.

Fig. 5(b) outlines the operator's investment strategy. After a period of consistent truck purchases until 2028, there is a significant peak in 40 diesel truck investments in 2029. This stockpiling strategy enables the postponement of investments in still unprofitable renewable fuel technologies, considering restrictions starting in 2030. By 2032, the operator achieves its sustainability commitments with 42 truck purchases, 50% being battery-electric. Annual costs in Fig. 5(c) show peak years due to grouped investments. Emission costs initially rise with stable diesel use and increasing carbon prices but drop by 2037 with the integration of renewable fuel technologies. Fuel costs for battery-electric trucks prove significantly lower compared to diesel trucks in initial years.

For the Scenario *Expect*, Fig. 6(a) presents the ship operator's fuel choices in line with sustainability commitments. Between 2025 and 2029, the operator utilizes five MGO ships. In 2030, the replacement of MGO with ammonia ships reduces its share to 33%. Simultaneously, the fleet expands to six ships to accommodate the limited transport capacity of ammonia ships. By 2041, two hydrogen ships are added, completely phasing out fossil fuel. Despite sustainability commitments aiming for only -50% emission reduction by 2030, the odd initial fleet size and the increase via ammonia ships lead to a -60% emission reduction by 2030. Carbon neutrality is achieved by 2041.

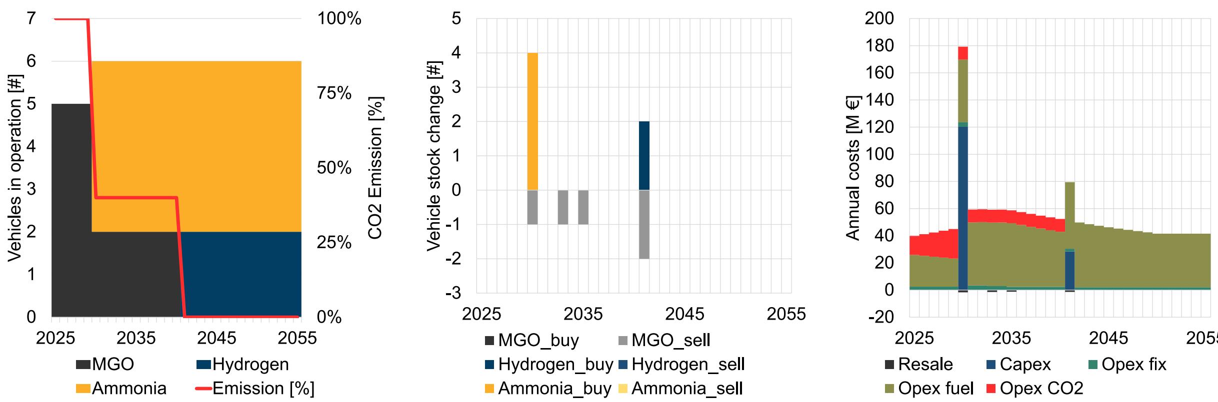
Fig. 6(b) outlines the operator's investment strategy. Following a period of no ship purchases until 2029, the operator makes a significant investment in 4 ammonia ships by 2030, surpassing its sustainability commitment of a 50% emission reduction. As the replaced MGO ships have not yet reached the end of their life, the operator stores them in a stockpile to use as spares for aging MGO fleets in operation (2033 and 2035). This strategy circumvents prohibited investments in new MGO ships.[8] In 2041, hydrogen ships replace the remaining MGO ships which

[8] In our model, passive ships do not age; they only incur fixed operational costs, making them potential for later use.



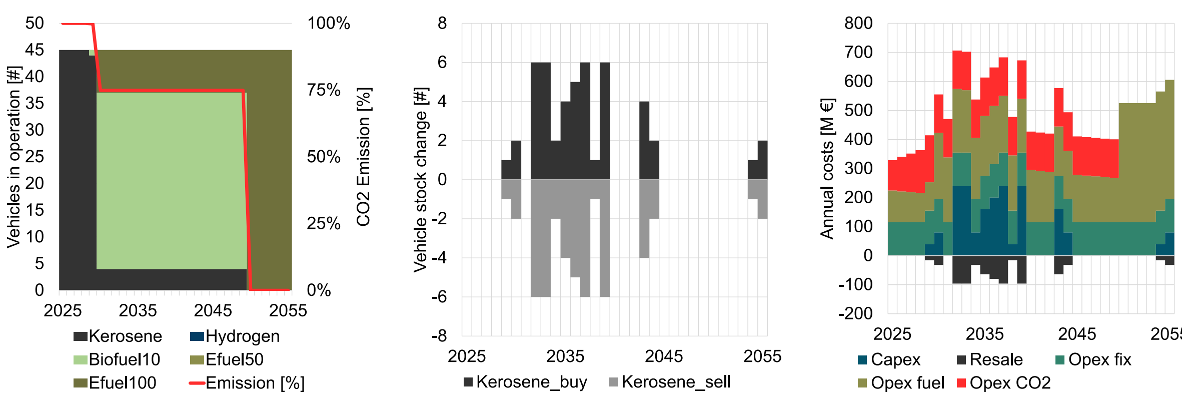
(a) Fuel technology choices (b) Investment strategy (c) Annual costs

Fig. 5. Truck operator: Fuel technology choices, associated investment strategy and its annual costs to align with sustainability commitments under the Scenario *Expect*.



(a) Fuel technology choices (b) Investment strategy (c) Annual costs

Fig. 6. Ship operator: Fuel technology choices, associated investment strategy and its annual costs to align with sustainability commitments under the Scenario *Expect*.



(a) Fuel technology choices (b) Investment strategy (c) Annual costs

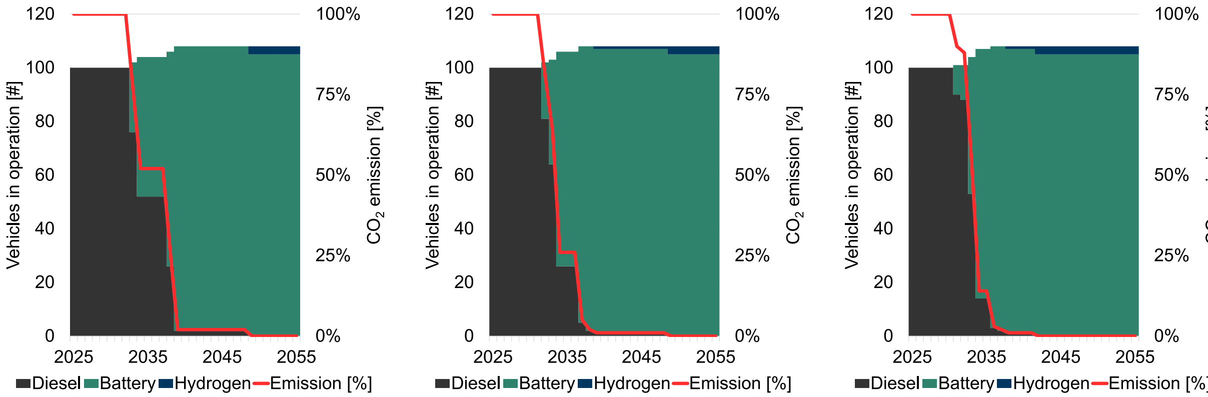
Fig. 7. Airplane operator: Fuel technology choices, associated investment strategy and its annual costs to align with sustainability commitments under the Scenario *Expect*.

reach the end of life. Hydrogen ships are still unprofitable at this point, but the replacement is unavoidable as old MGO ships exit the fleet.

Annual costs in Fig. 6(c) exhibit peaks during single years of investment. Emission costs rise initially with stable MGO use and increasing carbon prices, eliminated by 2041 with renewable fuel integration. Between 2031 and 2041, an operational cost disadvantage through renewable fuel use is visible compared to the cost level during earlier years of pure MGO use, which turns into a cost advantage after 2041.

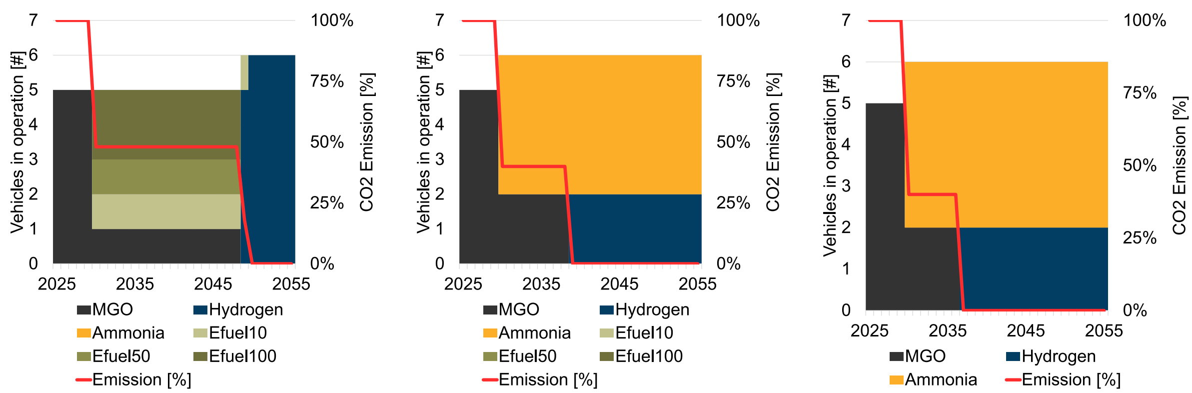
Fig. 7(a) illustrates the airplane operator's fuel technology choices in line with sustainability commitments. Between 2025 and 2029, the operator uses 45 kerosene airplanes. In 2030, a partial replacement of kerosene with biofuel and e-fuel reduces its share in operation by 25%. The fleet size remains stable as the fuel technology choice does not impose payload limitations. Until 2049, the share of kerosene remains constant, eventually replaced by e-fuel in 2050, driven solely by government regulation that enforce carbon neutrality.

Fig. 7(b) outlines the operator's investment strategy, which aligns with the fleet's natural aging process as fuel blends are used in conventional airplanes. This strategy is not influenced by fuel technology choices.



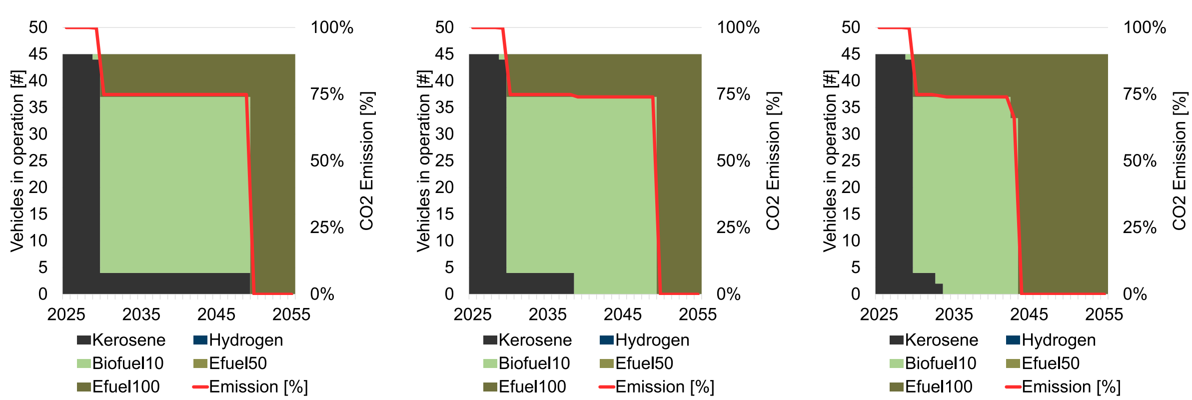
(a) Scenario *Pessimistic*. (b) Scenario *Optimistic*. (c) Scenario *Expect/Carbon*$^{++}$.

Fig. 8. Truck operator: Fuel technology choices to align with sustainability commitments under different scenarios.



(a) Scenario *Pessimistic*. (b) Scenario *Optimistic*. (c) Scenario *Expect/Carbon*$^{++}$.

Fig. 9. Ship operator: Fuel technology choices to align with sustainability commitments under different scenarios.



(a) Scenario *Pessimistic*. (b) Scenario *Optimistic*. (c) Scenario *Expect/Carbon*$^{++}$.

Fig. 10. Airplane operator: Fuel technology choices to align with sustainability commitments under different scenarios.

The annual costs illustrated in Fig. 7(c) exhibit peak years between 2030 and 2039, as well as in 2050 and beyond. In the first period, the operator faces multiple economic challenges, including a significant cost increase for renewable fuels, rising emission costs, and the necessary replacement of aging airplanes. In the second period, the mandatory transition to e-fuel by 2050 results in significantly higher operating costs compared to previous years.

5.2. Fuel cost and carbon price analysis aligned with sustainability commitments

In this section, we illustrate how the model's decisions vary under different fuel cost and carbon price scenarios while adhering to sustainability commitments. Figs. 8 to 10 present scenario results considering: (a) high-cost renewable fuels and low-cost fossil fuels under baseline carbon prices, (b) low-cost renewable fuels and high-cost fossil fuels under baseline carbon prices, and (c) baseline fuel costs under high carbon prices.

For the truck operator, Figs. 8(a) to 8(c) demonstrate a fairly consistent behavior across scenarios. The unfavorable cost relationship between high-cost renewable and low-cost fossil fuels results in a postponed cost-competitiveness of battery-electric trucks. As a response, the operator continues to invest three years after 2030 in 50% diesel trucks, aligning with sustainability commitments, before benefiting from the lower cost of battery-electric trucks. Conversely, a beneficial setting of fuel costs (Fig. 8(b)) and higher carbon prices (Fig. 8(c)) exhibit an early transition to battery-electric trucks. In both scenarios, the operator is stimulated to adopt battery-electric trucks sooner to capitalize on cost advantages.

For the ship operator, Figs. 9(a) to 9(c) exhibit significant differences. The unfavorable cost relationship between high-cost renewable and low-cost fossil fuels leads to investments in new MGO ships to replace parts of the aging fleet in 2029. The lower costs of fossil MGO seem to outweigh the cost increase of e-fuel, making a 50% fleet-wide e-fuel blending and preservation of the existing fleet profitable compared to ammonia or hydrogen technology. Consequently, the ship operator skips ammonia as a potential fuel technology and begins investing in hydrogen technology in 2049, one year before the mandatory decarbonization. In contrast, both a cost-beneficial relation of fuels (Fig. 8(b)) and higher carbon prices (Fig. 8(c)) stimulate the achievement of carbon neutrality based on ammonia and hydrogen technologies, two and four years earlier compared to the Scenario *Expect*.

For the airplane operator, Figs. 10(a) to 10(c) show partial differences. In the case of the unfavorable cost relationship between high-cost renewable and low-cost fossil fuels (Fig. 10(a)), the operator follows the same strategy as in the Scenario *Expect*. However, the high fossil fuel prices applied in Fig. 10(b) result in higher shares of biofuel use by 2039 compared to the base case. The most substantial impact among all scenarios is observed with high carbon prices in Fig. 10(c), allowing the operator to achieve carbon neutrality cost-beneficially by 2044.

5.3. Fuel technology choices without sustainability commitments

In this section, we present the model's decisions across scenarios, but for transport operators neglecting sustainability commitments. This implies that all investment decisions before 2050 are solely driven by cost considerations. However, achieving carbon neutrality by 2050 remains mandatory. Figs. 11 to 13 depict the fuel technology choices over time and per transport mode under different scenarios, considering: (a) both baseline fuel costs and baseline carbon prices, (b) baseline fuel costs and high carbon prices, and (c) low-cost renewable fuels and high-cost fossil fuels under baseline carbon prices.

For the truck operator, Fig. 11(a) illustrates the main transition from diesel to battery-electric trucks starting in 2034 and concluding in 2038 (compared to 2032 to 2037 under sustainability commitments). In the Scenario *Expect/Carbon*$^{++}$ (Fig. 11(b)), the main transition period is 2032 to 2036, and for *Optimistic* (Fig. 11(c)) it is 2033 to 2037. Hence, the fleet replacement decisions for the truck operator appear robust, with little variation across scenarios and even compared to its behavior under sustainability commitments.

For the ship operator, Fig. 12(a) depicts a rapid and last-minute transition from MGO to hydrogen technology in a single year, 2050 (compared to 2030 to 2041 under sustainability commitments, with a mix of ammonia and hydrogen technology). In the Scenario *Expect/Carbon*$^{++}$ (Fig. 12(b)), the entire transition occurs in 2037, and for *Optimistic* (Fig. 11(c)) in 2046, with the purchase of hydrogen technology. Hence, the fleet replacement decisions for the ship operator appear very sensitive to the scenarios investigated, and sustainability commitments being a significant driver.

Table 3
Net present value per scenario of fleet replacement with and without sustainability commitments. The percentage quantifies its cost difference.

[M€]	Expect	Optimistic	Pessimistic	Expect/Carbon^{++}
Truck operator				
Committed	104.9	105.3	101.9	107.0
Uncommitted	104.1	104.8	100.7	106.7
	+0.7%	+0.5	+1.2%	+0.3%
Ship operator				
Committed	779	759	768	811
Uncommitted	668	698	586	762
	+15.6%	+8.8%	+31.0%	+6.4%
Airplane operator				
Committed	6,332	6,367	6,117	7,119
Uncommitted	5,888	6,015	5,522	6,848
	+7.6%	+5.9%	+10.8%	+4.0%

For the airplane operator, Fig. 13(a) shows a rapid and last-minute transition from kerosene to e-fuel technology in a single year, 2050 (compared to 2030 to 2050 under sustainability commitments, with a mix of biofuel and e-fuel technology). In the Scenario *Expect/Carbon*$^{++}$ (Fig. 13(b)), the transition period is 2030 to 2044, with an increasing share of biofuel blending and a rapid integration of e-fuel in 2044. In the Scenario *Optimistic* (Fig. 11(c)), the transition period is 2030 to 2050, where the cost ratio between fossil and renewable fuels is not efficient for e-fuel competitiveness before 2050. Hence, the timing and volume of fuel switch appears very sensitive to the scenarios investigated, and the initial operator's sustainability commitments as well as government restrictions in 2050 to be important drivers.

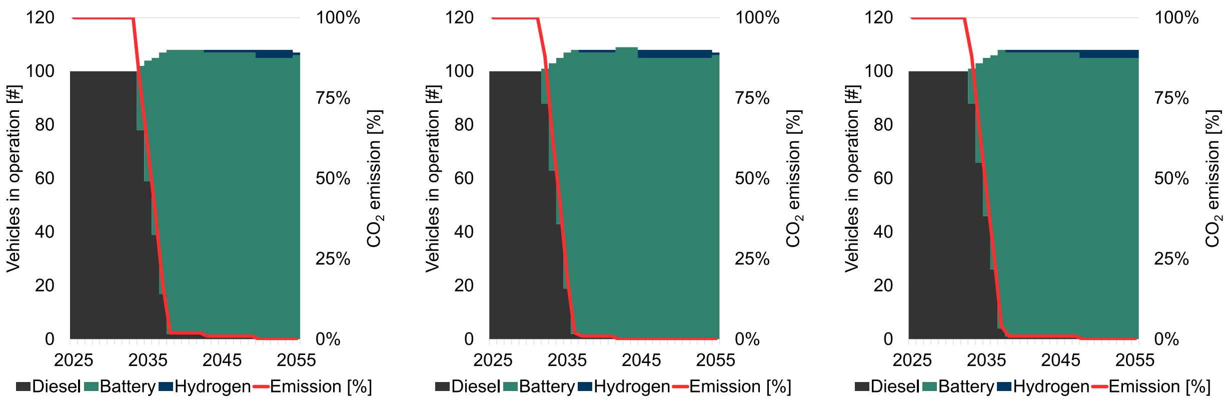
5.4. The costs of implementing sustainability commitments

In this section, we compare the net present values (NPV) of the transport operators' decisions with and without the consideration of sustainability commitments across scenarios. Table 3 provides an overview of results, quantifying the additional expenses caused by implementing sustainability commitments.

For the truck operator, the NPVs of the committed and uncommitted approach exhibit a deviation below 1.5%. The limited additional costs to implement the sustainability commitments underline the similar investment decisions found in Section 5.3. In other words, the operator's sustainability commitments seem robust and economically reasonable.

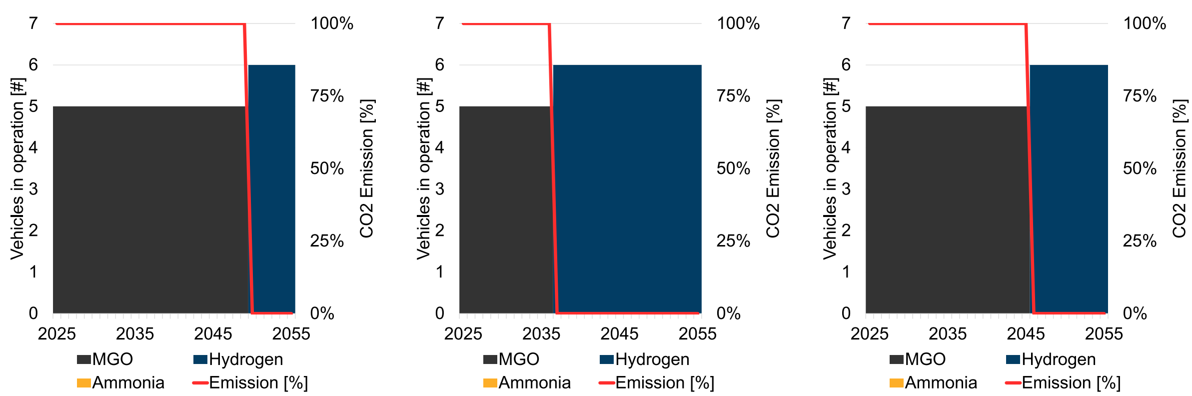
In contrast, the ship operator faces a significant cost-burden from sustainability commitments, as the required investments would not be executed in an uncommitted approach. The cost-optimal postponement and restructuring of uncommitted investments, shown in Fig. 12, lead to cost differences ranging from 6% to 31% across scenarios. The largest cost gap is observed in the *Pessimistic* scenario, where the operator suffers from high-cost renewable fuels and low-cost fossil fuels, being compelled to invest early in renewable fuel technologies. The *Optimistic* and *Expect/Carbon*$^{++}$ scenarios notably reduce the cost gap between the committed and uncommitted approach (compared to *Expect*) due to high-cost fossil fuels or high-cost carbon emissions, supporting a transition towards renewable fuel technologies. Considering the magnitude of additional costs, the set sustainability commitments appear overambitious.

For the airplane operator, additional costs for achieving sustainability commitments range from +4% to +11%, showing relatively uniform impacts across scenarios. The most sensitive scenario is *Pessimistic* (+11%), where the committed share of e-fuel in 2030 contrasts with the uncommitted use starting 20 years later. The *Optimistic* and *Expect/Carbon*$^{++}$ scenarios reduce the cost gap between the committed and uncommitted approach (compared to *Expect*) due to high-cost fossil fuels or high-cost carbon emissions, supporting a transition towards renewable fuel technologies. In general, the flexible fuel blending as a



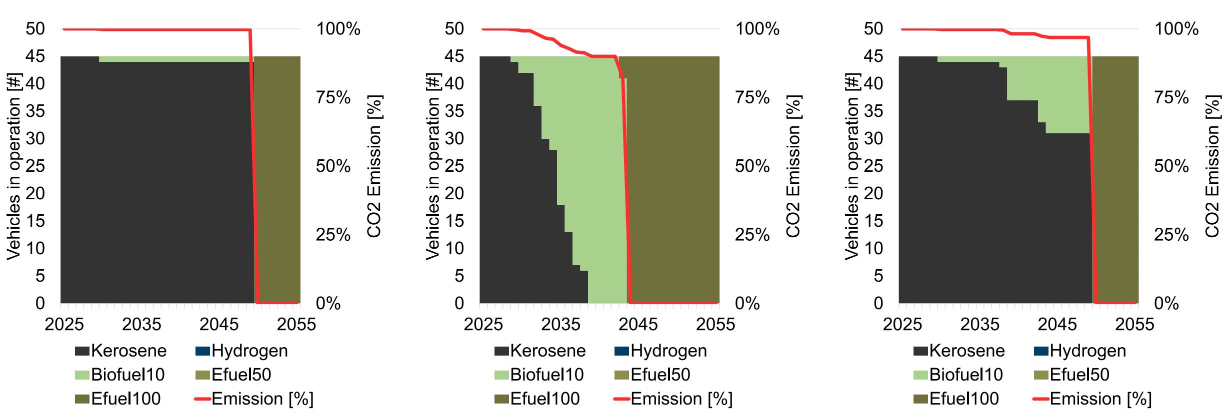
(a) Scenario *Expect*. (b) Scenario *Expect/Carbon*$^{++}$. (c) Scenario *Optimistic*.

Fig. 11. Truck operator: Fuel technology choices without sustainability commitments under different scenarios.



(a) Scenario *Expect*. (b) Scenario *Expect/Carbon*$^{++}$. (c) Scenario *Optimistic*.

Fig. 12. Ship operator: Fuel technology choices without sustainability commitments under different scenarios.



(a) Scenario *Expect*. (b) Scenario *Expect/Carbon*$^{++}$. (c) Scenario *Optimistic*.

Fig. 13. Airplane operator: Fuel technology choices without sustainability commitments under different scenarios.

reaction to cost developments while operating the same airplane fleet in both committed and uncommitted approaches leads to smaller cost differences compared to the shipping sector.

6. Discussion and policy implications

Our analysis guides cost-optimal fleet replacement decisions towards decarbonization, translating sustainability commitments into concrete actions. Significant variations in fuel technology transitions are observed among the truck, ship, and airplane operators. Our findings underscore the importance of regulatory frameworks for policymakers.

For the committed truck operator, battery-electric trucks emerge as the primary fuel technology up to 2050. Despite their lower payload capacity leading to a fleet size increase, the use of low-cost electricity compensates for additional costs, which is crucial in commercial transport [17]. The operator adopts a *successive replacement* of diesel trucks, following the fleet's age structure. Sustainability commitments initiate the transition, but battery-electric trucks become cost-competitive with diesel shortly after. Similar investment decisions are observed in an uncommitted approach, reflected in comparable NPVs across scenarios. The short asset lifespan allows flexible fleet adjustments to different cost scenarios. The suggested strategy for truck operators involves timely manufacturer agreements to avoid supply shortfalls. Policymakers should provide early incentives to build up required charging infrastructure and support related industries to realize assumed cost reductions. The trucking sector, as previously debated [8], could pioneer carbon neutrality in hard-to-abate transport sectors.

For the committed ship operator, ammonia initially emerges as the most cost-effective renewable fuel technology in the mid-term, later surpassed by hydrogen ships. The technology shift should be interpreted with caution as building infrastructures for two fuel technologies incurs additional costs, neglected in this study. The rapid replacement of most MGO ships in 2030, driven by sustainability commitments, is not cost-beneficial under assumed carbon prices. The goal of investing solely in renewable fuel technologies by 2030 discriminates against fleets with assets reaching their end of life between 2030 and 2040 and creates a lock-in effect with little flexibility. Uncommitted investments significantly differ, indicating the over-ambitious nature of sustainability commitments. Without additional policy incentives or optimistic fuel cost developments, abandonment of sustainability commitments in practice seems likely. Government incentives on fuel costs or carbon prices can be impactful, as seen in Scenarios *Optimistic* and *Expect/Carbon*$^{++}$. The variety in fuel technology choices underscores the current uncertainty in maritime fleet management, emphasizing the need for early knowledge acquisition through pilot projects supported by policies.

For the committed airplane operator, the shown dependency on biofuel and e-fuel shares reflects current efforts by airlines to reserve limited volumes from emerging pilot projects [49]. The rapid replacement of 25% kerosene in 2030 and the last-minute replacement of the remaining kerosene in 2050, driven by sustainability commitments, is not cost-beneficial under assumed carbon prices. An uncommitted approach significantly differs, postponing e-fuel utilization until 2050. Although additional costs for implementing sustainability commitments are expected, fuel blending provides flexibility for adjusting to different cost scenarios. However, even under optimistic cost assumptions, the use of e-fuel remains non-competitive. Government incentives remain crucial, such as renewable fuel subsidies or fossil fuel taxes combined with higher carbon prices. Our results underscore the risk of carbon-neutral aviation remaining a subsidy-dependent sector. While the airplane operator can achieve carbon neutrality without vehicle replacement, outsourcing responsibility to renewable fuel suppliers reduces control over sustainability improvements. However, optimizing the fleet's fuel efficiency through continuous technology adoption remains a controllable cost lever through fleet management. Policy makers should encourage industry agreements between airplane operators and renewable fuel suppliers, promoting early scaling of e-fuel production to avoid fossil kerosene lock-in. Additionally, biofuel expansion should be evaluated considering land use and food conflicts [4].

Overall, our model results reveal three decarbonization approaches: *successive*, *rapid*, and *last-minute replacement*. Successive replacement occurs when renewable fuel technologies gradually become cost-competitive with fossil fuels, aligning with the fleet's natural aging process. This is exemplified by the investigated truck operator. Rapid replacement arises when the lack of cost-competitiveness conflicts with ambitious sustainability commitments, forcing implementation in a specific year. In uncommitted approaches, sudden cost-benefit shifts can also lead to rapid fleet replacements. Policymakers should be aware of the risks associated with rapid and last-minute replacements, including potential strain on emerging supply chains, market price escalation, and a lack of early innovation. Sufficient policy support is crucial to achieve early cost reductions in renewable fuel technologies assumed in this study, leveraging learning and scaling effects. In this context, [8] examine the effects of subsidizing and taxing fuel value chains, including fuel production, consumption, and vehicle investments.

In addition, decoupling sustainability commitments from pivotal years helps technology suppliers prepare for increasing demand. Against this background, in 2023 the European Union enacted renewable fuel mandates, progressively increasing the share of sustainable aviation fuels to a minimum of 2% in 2025, 20% in 2035, and 70% in 2050 [50]. Similar mandates apply to the maritime sector, targeting emission reductions of at least 2% in 2025, 14.5% in 2035, and 80% in 2050 [50]. Additionally, a comparable trajectory is planned for commercial road transport, with emissions aimed to decrease by 45% in 2030, 65% in 2035, and 90% by 2040 [51].

This study provides a comprehensive examination of fleet replacement decisions for Norwegian truck, ship, and airplane operators, encompassing various transport modes, fuel technologies, and sustainability commitments. However, it is important to acknowledge certain limitations in the model. Fleet behavior is simplified using average parameters, and the detailed modeling of actual operating patterns, which may influence the suitability of specific fuel technologies, is beyond the study's scope. Additionally, the study utilizes techno-economic data specific to fuel technologies and transport operators in Norway, each for a specific product group. While the results are relevant for similar applications in other countries, data should be updated to ensure transferability to specific use cases. Only scope-1 carbon emissions from vehicle operations are considered, omitting other life-cycle emissions and greenhouse gases. Scopes must be regularly updated to align with respective regulations. The study addresses the uncertainty of future cost developments through deterministic scenarios, allowing for a comparison between scenarios with and without sustainability commitments. To analyze robust fleet replacement decisions across scenarios more comprehensively, extending the model to a stochastic, multistage framework is suggested. This also entails a more detailed examination of oil price uncertainty and its impact on fleet replacement.

7. Conclusion and outlook

This paper guides truck, ship, and airplane operators in strategic fleet replacement decisions, minimizing costs while achieving sustainability commitments. Using a newly developed mixed integer linear program, we analyze three Norwegian cases. The study compares fleet replacement decisions under varied fuel cost and carbon price scenarios, examining both approaches — one incorporating sustainability commitments and the other that does not. It highlights the impact of sustainability commitments on fleet decisions and associated costs, identifying pivotal transition years towards carbon-neutral transport.

We find that the truck operator's sustainability commitments incur minimal additional costs as battery-electric trucks become cost-effective between 2030 and 2036. In contrast, the ship operator faces uncertainty in choosing hydrogen or ammonia across scenarios, increasing fleet costs of +6% to +31% compared to an uncommitted approach. The airplane operator experiences additional costs of +4% to +11% caused by e-fuel and biofuel use, being depend on policy support even beyond 2050. Existing Norwegian carbon price regulations are insufficient to drive the technology transition for ship and airplane operators in the expected future.

Transport operators should carefully assess their sustainability commitments, ensuring timely procurement of fuel technologies and access to capital to manage significant cost increases in pivotal years. Industry stakeholders should be aware that peak demand for renewable fuel technologies in certain years may strain emerging supply chains. Policymakers, aligning with European initiatives, should incentivize early technology innovation and gradually increase demand for fuel technologies. Reducing fuel costs or imposing taxes on carbon emissions has demonstrated effectiveness in shaping fleet replacement decisions.

Future work may address: (i) policies promoting a gradual technology transition, (ii) employing a multi-stage stochastic approach to cover uncertainty, and (iii) analyzing the effects of strategic fleet replacements on national transport systems including modal shift.

CRediT authorship contribution statement

Jonas Martin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonia Golab:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Goran Durakovic:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Sebastian Zwickl-Bernhard:** Writing – review & editing, Methodology, Conceptualization. **Hans Auer:** Writing – review & editing, Methodology, Conceptualization. **Anne Neumann:** 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.

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

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

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Appendix A. Equations in words

(13).1	The subgroup of the total fleet (vehicle age of 0; starting year 0; specific technology t), encompasses new vehicles of the operator's initial fleet, plus new vehicles bought, minus new vehicles sold again.
(13).2	The subgroup of the total fleet (vehicles with the age lower than the last year of operation and older than 0; starting year 0; specific technology t), encompasses the corresponding vehicles of the operator's initial fleet, minus corresponding vehicles sold.
(13).3	The subgroup of the total fleet (vehicles with the age equal to the last year of operation; starting year 0; specific technology t), encompasses the corresponding vehicles of the operator's initial fleet, minus corresponding vehicles sold.
(13).4	The subgroup of the total fleet (vehicles with the age equal to the retiring year; starting year; specific technology t), encompasses the corresponding vehicles of the operator's initial fleet, minus corresponding vehicles sold.
(13).5	The subgroup of the total fleet (vehicles with the age of 0; all years beyond the starting year; specific technology t), encompasses the vehicles newly bought, plus passive vehicles from the previous year.
(13).6	The subgroup of the total fleet (vehicles with the age lower than the last year of operation and older than 0; all years beyond the starting year; specific technology t), encompasses the active vehicles from the previous year, plus passive vehicles from the previous year, minus the vehicles sold, minus the vehicles converted to another fuel technology (fuel blending).
(13).7	The subgroup of the total fleet (vehicles with the age equal to the last year of operation; all years beyond the starting year; specific technology t), encompasses the active vehicles from the previous year, passive vehicles being from the previous year, minus the vehicles sold, minus the vehicles converted to another fuel technology (fuel blending).
(13).8	The subgroup of the total fleet (vehicles with the retiring age; all years beyond the starting year; specific technology t), encompasses the active vehicles from the previous year, minus vehicles sold.

Appendix B. Age distribution of initial fleets

See Table B.4.

Table B.4
Age classes of the initial fleets assumed in the numerical example (end of life: eol).

Age class	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	...	25	...	30
Truck	0	20	20	20	20	20 (eol)																
Ship	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	2	0	0	0	0 (eol)
Airplane	0	2	4	0	0	0	6	1	6	5	4	2	6	6	0	2	1	0	0	0 (eol)		

Appendix C. Parameter interpolation

The selected techno-economic parameters are subject to changes over time, capturing factors like economies of scale and technological innovation. We use Eq. (C.1) for interpolation.

$$S(a) = V_{2020} + (V_{2055} - V_{2020}) \cdot \left(\frac{1}{1 + \exp(-\alpha(y - y_h))^{\beta}} \right) \tag{C.1}$$

where, V_{2020} and V_{2055} represent the start and end values, α and β determine the speed of change, and y_h denotes the year of half-time growth. See Tables D.5 to D.7 for specific parameter values.

Appendix D. Vehicle configuration and techno-economic data

For the truck fleet, we analyze a tractor-trailer combination, such as the Scania R450 or a similar model, with a maximum payload of 25 tonnes in the diesel version, assumed to operate at 60% capacity [4]. The annual mileage is set at 100,000 km [16], resulting in an annual vehicle transport capacity of 1.5M tonne-kilometers [16]. We assume a reduced transport capacity of battery trucks by 15% and hydrogen trucks by 7%, compared to diesel trucks [4,8]. The tractor-trailer composition costs 145T € for diesel, 440T € for battery-electric, and 430T € for hydrogen in 2020, with the cost development detailed in Table D.5 [9]. Fuel economy in 2030 is considered at 2.9 kWh/km for diesel, 1.52 kWh/km for battery-electric, and 2.53 kWh/km for hydrogen, undergoing improvements until 2055 [9]. When multiplied by the specific fuel costs, these values result in $Opex_{fuel}$ as shown in Table D.5. The vehicles' residual values per fuel technology are compiled from sources such as [9,17]. For diesel trucks, the residual value is assumed to decrease (25% in 2020 and 5% in 2055 of Capex), reflecting the expectation of a shrinking market for internal combustion engines [3]. In contrast, secondary markets for renewable fuel technologies exhibit an opposing trend [9]. The vehicle lifespan is set to 5 years on the primary market [52].

For the ship fleet, we examine a short-sea feeder for container freight, such as the Enforcer (IMO: 9255737) or a similar vessel, featuring a payload of 9,450 deadweight tonnes [55]. The MGO version operates at 65% capacity [54]. With an assumed annual mileage of 118,000 km, the vessel's yearly transport capacity is calculated at 726M tonne-kilometers. We assume a reduced transport capacity of hydrogen ships by 9% and ammonia ships by 7.5%, compared to MGO ships [4,8]. The estimated $Capex$ per ship are 20M € for MGO, 35M € for hydrogen, and 35M € for ammonia in 2020, with cost development presented in Table D.6 [12,16,56]. However, hydrogen and ammonia ships are expected to be first available in 2030 [16]. The fuel economy is 647 kWh/km for MGO and 589 kWh/km for hydrogen and ammonia, undergoing improvements towards 2055 [16]. When multiplied by the specific fuel costs, these values determine the $Opex_{fuel}$ shown in Table D.6. In the shipping sector, residual values are comparatively low [57]. For an MGO ship, we assume a residual value of 3.5% of the Capex in 2020, decreasing to 2.5% in 2055 [58]. In contrast, secondary markets for renewable fuel technologies develop in the opposite direction. The vehicle lifespan is set to 35 years on the primary market [4].

For the airplane fleet, we examine a type, such as the Airbus A320neo, with a total payload of 20 tonnes [4]. The kerosene version operates at 75% capacity [11]. The assumed annual mileage is 1,728,000 km [11], resulting in an annual vehicle's transport capacity of 25.9M tonne-kilometers [16]. We assume a reduced transport capacity of hydrogen airplanes by 18% compared to the kerosene version [4,8]. Estimated costs for the airplane are 40M € for kerosene and 100M € for hydrogen in 2020, with cost development detailed in Table D.7 [16]. However, hydrogen airplanes are anticipated to be first available in 2035 [59]. The fuel economy is stable at 38.8 kWh/km for both kerosene and hydrogen [16]. When multiplied by the specific fuel costs, these values determine the fuel costs shown in Table D.7. For a kerosene airplane, we assume a residual value of 40% of the Capex in 2020 and decreasing to 30% in 2055 [3], assuming stable secondary markets. The high value is attributed to a mandatory, intensive maintenance program [11]. The vehicle lifespan is set to 25 years on the primary market [11].

The $WACC$ is set to 6% for all technologies. All applied data, including Capex, residual values, operational expenditures, fuel costs, emission factors, transport capacity per vehicle, and annual transport demand per fleet, are shown in Table D.5 (trucking), Table D.6 (shipping), and Table D.7 (aviation).

Table D.5
Techno-economic data for a long-haul truck considered in our analysis. All energy-related data applies the low heating value.

Capex [T€]	**2020**	**2055**	**a$_h$**	β	α	**Source**
Diesel/e-fuel	135	145	15	0.9	0.4	[9]
Battery-electric	430	175	11	0.9	0.4	[9]
Hydrogen	420	185	12	0.9	0.4	[9]
Residual value [T€]	**2020**	**2055**	**a$_h$**	β	α	**Source**
Diesel/e-fuel	34	22	15	0.9	0.4	[17]
Battery-electric	65	44	11	0.9	0.4	[9,17]
Hydrogen	63	46	12	0.9	0.4	[9,17]
Opex fix [T€/a]	**2020**	**2055**	**a$_h$**	β	α	**Source**
Diesel/e-fuel	20	20	15	0.9	0.4	[9]
Battery-electric	15	15	11	0.9	0.4	[9]
Hydrogen	26	19	12	0.9	0.4	[9]
Fuel (baseline) [€/kWh]	**2020**	**2055**	**a$_h$**	β	α	**Source**
Diesel	0.075	0.048	For details Fig. 3			[53]
E-fuel10	0.107	0.058	For details Fig. 3			[16,16,53]
E-fuel50	0.232	0.095	For details Fig. 3			[16,16,53]
E-fuel100	0.388	0.142	For details Fig. 3			[16]
Battery-electric	0.088	0.082	For details Fig. 3			[16]
Hydrogen	0.216	0.113	For details Fig. 3			[16]
Fuel economy [kWh/tkm]	**2020**	**2055**	**a$_h$**	β	α	**Source**
Diesel/e-fuel	0.19	0.16	15	0.9	0.4	[8,9]
Battery-electric	0.11	0.09	11	0.9	0.4	[8,9]
Hydrogen	0.17	0.12	12	0.9	0.4	[8,9]

(continued on next page)

Table D.5 (*continued*).

Emission factor [g/tkm]	2020	2055	a_h	β	α	Source
Diesel	51.54	51.54				[4,8,47,54]
E-fuel10	46.39	46.39				[4,8,47,54]
E-fuel50	25.77	25.77				[4,8,47,54]
E-fuel100	0	0				[4,8,54]
Battery-electric	0	0				[4,8,47,54]
Hydrogen	0	0				[4,8,47,54]
Transport capacity [Mtkm/a]	**2020**	**2055**	a_h	β	α	**Source**
Diesel/e-fuel	1.5	1.5				[4,8,54]
E-fuel10	1.5	1.5				[4,8,54]
E-fuel50	1.5	1.5				[4,8,54]
E-fuel100	1.5	1.5				[4,8,54]
Battery-electric	1.39	1.39				[4,8,54]
Hydrogen	1.49	1.49				[4,8,54]
Transport demand [Mtkm/a]	**2020**	**2055**	a_h	β	α	**Source**
All fuel technologies	150	150				[4,8,54]

Table D.6
Techno-economic data for a short-sea ship considered in our analysis. All energy-related data applies the low heating value.

Capex [M€]	2020	2055	a_h	β	α	Source
MGO/e-fuel	20	20	20	0.90	0.40	[12,16,56]
Ammonia	35	20	20	0.90	0.40	[12,16,56]
Hydrogen	35	20	20	0.90	0.40	[12,16,56]
Residual value [M€]	**2020**	**2055**	a_h	β	α	**Source**
MGO/e-fuel	2	1	20	0.90	0.40	[12]
Ammonia	1.8	2.3	20	0.90	0.40	[12]
Hydrogen	1.8	2.5	20	0.90	0.40	[12]
Opex fix [T€/a]	**2020**	**2055**	a_h	β	α	**Source**
MGO/e-fuel	488	488	20	0.90	0.40	[12]
Ammonia	339	339	20	0.90	0.40	[12]
Hydrogen	339	339	20	0.90	0.40	[12]
Fuel (baseline) [€/kWh]	**2020**	**2055**	a_h	β	α	**Source**
MGO	0.07	0.043	For details Fig. 3			[16,44]
E-fuel10	0.101	0.052	For details Fig. 3			[16,44]
E-fuel50	0.226	0.089	For details Fig. 3			[16,44]
E-fuel100	0.382	0.136	For details Fig. 3			[16,44]
Ammonia	0.169	0.109	For details Fig. 3			[16]
Hydrogen	0.192	0.105	For details Fig. 3			[16]
Fuel economy [kWh/tkm]	**2020**	**2055**	a_h	β	α	**Source**
MGO/e-fuel	0.11	0.10	20	0.9	0.4	[8]
Ammonia	0.10	0.09	20	0.9	0.4	[8]
Hydrogen	0.10	0.09	20	0.9	0.4	[8]
Emission factor [g/tkm]	**2020**	**2055**	a_h	β	α	**Source**
MGO	29.32	29.32				[4,8,47,54]
E-fuel10	26.38	26.38				[4,8,47,54]
E-fuel50	14.66	14.66				[4,8,47,54]
E-fuel100	0	0				[8]
Ammonia	0	0				[8]
Hydrogen	0	0				[8]
Transport capacity [Mtkm/a]	**2020**	**2055**	a_h	β	α	**Source**
MGO/e-fuel	725	725				[4,8,54]
E-fuel10	725	725				[4,8,54]
E-fuel50	725	725				[4,8,54]
E-fuel100	725	725				[4,8,54]
Ammonia	670	670				[4,8,54]
Hydrogen	660	660				[4,8,54]
Transport demand [Mtkm/a]	**2020**	**2055**	a_h	β	α	**Source**
All fuel technologies	3624	3624				[4,8,54]

Table D.7
Techno-economic data for a medium-haul airplane considered in our analysis. All energy-related data applies the low heating value.

Capex [M€]	**2020**	**2055**	**a_h**	**β**	**α**	**Source**
Kerosene/e-fuel	40	40	25	0.90	0.50	[16]
Hydrogen	100	52	25	0.90	0.50	[16]
Residual value [M€]	**2020**	**2055**	**a_h**	**β**	**α**	**Source**
Kerosene/biofuel, e-fuel	16	16	25	0.90	0.50	[11]
Hydrogen	5	21	25	0.90	0.50	[11]
Opex fix [M€/a]	**2020**	**2055**	**a_h**	**β**	**α**	**Source**
Kerosene/biofuel, e-fuel	2.55	2.55	25	0.90	0.50	[16]
Hydrogen	4.35	2.91	25	0.90	0.50	[16]
Fuel (baseline) [€/kWh]	**2020**	**2055**	**a_h**	**β**	**α**	**Source**
Kerosene	0.041	0.025	For details Fig. 3			[16,44]
Biofuel10	0.052	0.032	For details Fig. 3			[16,44,60]
E-fuel50	0.212	0.081	For details Fig. 3			[16,44]
E-fuel100	0.382	0.136	For details Fig. 3			[16,44]
Hydrogen	0.192	0.105	For details Fig. 3			[16,44]
Fuel economy [kWh/tkm]	**2020**	**2055**	**a_h**	**β**	**α**	**Source**
MGO/bio,e-fuel	2.59	2.59				[8]
Hydrogen	3.15	3.15				[8]
Emission factor [g/tkm]	**2020**	**2055**	**a_h**	**β**	**α**	**Source**
Kerosene	680	680				[4,8,47,54]
Biofuel10	612	612				[4,8,47,54]
E-fuel50	340	340				[4,8,47,54]
E-fuel100	0	0				[8]
Hydrogen	0	0				[8]
Transport capacity [Mtkm/a]	**2020**	**2055**	**a_h**	**β**	**α**	**Source**
Kerosene	26	26				[4,8,54]
Biofuel10	26	26				[4,8,54]
E-fuel50	26	26				[4,8,54]
E-fuel100	26	26				[4,8,54]
Hydrogen	21	21				[4,8,54]
Transport demand [Mtkm/a]	**2020**	**2055**	**a_h**	**β**	**α**	**Source**
All fuel technologies	1166	1166				[4,8,54]

References

[1] DNV. Energy transition Norway 2022: A national forecast to 2050. Oslo: DNV AS; 2022.
[2] IEA. Norway 2022: Energy policy review. Paris: International Energy Agency; 2022.
[3] IEA. World energy outlook 2022. Paris: International Energy Agency; 2022.
[4] Gray N, McDonagh S, O'Shea R, Smyth B, Murphy JD. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Adv Appl Energy 2021;1:100008.
[5] Alp O, Tan T, Udenio M. Transitioning to sustainable freight transportation by integrating fleet replacement and charging infrastructure decisions. Omega 2022;109:102595.
[6] Martin J, Bakker SJ, van Beesten ER, Golab A. Strategic freight transport planning for a carbon-neutral Norway: The uncertainty of electricity and oil prices. 2024, Preprint.
[7] Samferdselsdepartement. Nasjonal transportplan 2022–2033: Meld. St. 20, Melding til Stortinget. Oslo: Det kongelige samferdselsdepartement; 2021.
[8] Martin J, Dimanchev E, Neumann A. Carbon abatement costs for renewable fuels in hard-to-abate transport sectors. Adv Appl Energy 2023;12:100156.
[9] Transport and Environment. How to decarbonise long-haul trucking in Germany. An analysis of available vehicle technologies and their associated costs. Brussels; 2021.
[10] Bakker SJ, van Beesten ER, Brynildsen IS, Sandvig A, Siqveland M, Tomasgard A. STraM: A framework for strategic national freight transport modeling. 2023, Preprint, URL https://arxiv.org/abs/2304.14001. [Accessed 11 October 2023].
[11] Doganis R. Flying off course: Airline economics and marketing. 5th ed. New York: Routledge; 2019.
[12] Drewry. Ship operating costs: Annual review and forecast. London: Drewry Maritime Research; 2013.
[13] NSA. Zero emissions in 2050. Oslo: Norwegian Shipowners' Association; 2020.
[14] Norwegian. Environmental sustainability strategy 2023. Oslo: Norwegian Air Shuttle ASA; 2020.
[15] Posten. Fact booklet: Sustainability at Posten. Oslo: Posten; 2022.
[16] Martin J, Neumann A, Ødegård A. Renewable hydrogen and synthetic fuels versus fossil fuels for trucking, shipping and aviation: A holistic cost model. Renew Sustain Energy Rev 2023;186:113637.
[17] Noll B, Del Val S, Schmidt TS, Steffen B. Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe. Appl Energy 2022;306:118079.
[18] Hartman JC, Tan CH. Equipment replacement analysis: A literature review and directions for future research. Eng Econ 2014;59(2):136–53.
[19] Adkins R, Paxson D. Replacement decisions with multiple stochastic values and depreciation. European J Oper Res 2017;257(1):174–84.
[20] Mohammadi R, He Q, Karwan M. Data-driven robust strategies for joint optimization of rail renewal and maintenance planning. Omega 2021;103:102379.
[21] Stutzman S, Weiland B, Preckel P, Wetzstein M. Optimal replacement policies for an uncertain rejuvenated asset. Int J Prod Econ 2017;185:21–33.
[22] Lagemann B, Lagouvardou S, Lindstad E, Fagerholt K, Psaraftis HN, Erikstad SO. Optimal ship lifetime fuel and power system selection under uncertainty. Transp Res D 2023;119:103748.
[23] Ahani P, Arantes A, Melo S. A portfolio approach for optimal fleet replacement toward sustainable urban freight transportation. Transp Res D 2016;48:357–68.
[24] Xiao L, Zhang J, Wang C, Han R. Optimal fleet replacement management under cap-and-trade system with government subsidy uncertainty. Multimodal Transp 2023;2(2):100077.
[25] Lagemann B, Lindstad E, Fagerholt K, Rialland A, Ove Erikstad S. Optimal ship lifetime fuel and power system selection. Transp Res D 2022;102:103145.
[26] Stasko TH, Oliver Gao H. Reducing transit fleet emissions through vehicle retrofits, replacements, and usage changes over multiple time periods. Transp Res D 2010;15(5):254–62.
[27] Islam A, Lownes N. When to go electric? A parallel bus fleet replacement study. Transp Res D 2019;72:299–311.
[28] Trost T, Sterner M, Bruckner T. Impact of electric vehicles and synthetic gaseous fuels on final energy consumption and carbon dioxide emissions in Germany based on long-term vehicle fleet modelling. Energy 2017;141:1215–25.
[29] Ansaripoor AH, Oliveira FS, Liret A. Recursive expected conditional value at risk in the fleet renewal problem with alternative fuel vehicles. Transp Res C 2016;65:156–71.
[30] Xian H, Karali B, Colson G, Wetzstein ME. Diesel or compressed natural gas? A real options evaluation of the U.S. natural gas boom on fuel choice for trucking fleets. Energy 2015;90:1342–8.
[31] Pantuso G, Fagerholt K, Hvattum LM. A survey on maritime fleet size and mix problems. European J Oper Res 2014;235(2):341–9.

[32] Zheng S, Chen S. Fleet replacement decisions under demand and fuel price uncertainties. Transp Res D 2018;60:153–73.

[33] ben Brahim T, Wiese F, Münster M. Pathways to climate-neutral shipping: A Danish case study. Energy 2019;188:116009.

[34] Sa CA, Santos BF, Clarke J-PB. Portfolio-based airline fleet planning under stochastic demand. Omega 2020;97:102101.

[35] Hsu C-I, Li H-C, Liu S-M, Chao C-C. Aircraft replacement scheduling: A dynamic programming approach. Transp Res E 2011;47(1):41–60.

[36] Dray L, Evans A, Reynolds T, Schäfer AW, Vera-Morales M, Bosbach W. Airline fleet replacement funded by a carbon tax: An integrated assessment. Transp Policy 2014;34:75–84.

[37] Brynolf S, Hansson J, Anderson JE, Skov IR, Wallington TJ, Grahn M, et al. Review of electrofuel feasibility - prospects for road, ocean, and air transport. Progr Energy 2022;4(4):042007.

[38] Norgesgruppen. Annual and sustainability report 2022. Oslo: Norgesgruppen; 2022.

[39] NCL. Zero emission new buildings: We are North Sea Container Line, an integrated container logistics company. Haugesund; 2023, URL https://www.ncl.no/about/sea-change/. [Accessed 11 January 2024],

[40] Norwegian Ministry of Transport. National transport plan 2022–2033: English summary. Oslo: Norwegian Ministry of Transport; 2021.

[41] Larsen OM, Fagernæs A, Johansen KM, Resare LA, Skram T, Hamremoen E, et al. Aviation in Norway: Sustainability and social benefit. Oslo: Avinor; 2020.

[42] Fridstrøm L, Tomasgard A, Eskeland GS, Espegren KA, Rosenberg E, Helgesen PI, et al. Decarbonization of transport: A position paper prepared by FME MoZEES and FME CenSES. Oslo: MoZEES - Mobility Zero Energy Systems; 2018.

[43] Statnett. Langsiktig markedsanalyse: Norge, Norden og Europa 2022–2050. Oslo: Statnett; 2023.

[44] IEA. World energy outlook 2023. Paris: International Energy Agency; 2023.

[45] Norwegian Government. Carbon price trajectories for use in socio-economic analyzes - regjeringen.no. 2022, Oslo; URL https://www.regjeringen.no/no/tema/okonomi-og-budsjett/statlig-okonomistyring/karbonprisbaner-for-bruk-i-samfunnsokonomiske-analyser/id2878113/. [Accessed 10 November 2023],

[46] United Nations. Paris agreement. Bonn: United Nations; 2015.

[47] SSB. Emission factors used in the estimations of emissions from combustion. Oslo: Statistics Norway; 2021.

[48] IRENA. Energy profile Norway. Abu Dhabi: IRENA; 2022.

[49] Norwegian Air Shuttle. Norwegian partners with Norsk e-Fuel to build new e-fuel plant in Norway. 2023, Oslo; URL https://media.uk.norwegian.com/pressreleases/norwegian-partners-with-norsk-e-fuel-to-build-new-e-fuel-plant-in-norway-3247949. [Accessed 24 January 2024],

[50] EU. ReFuelEU aviation and FuelEU maritime explained. 2023, URL https://www.consilium.europa.eu/en/infographics/fit-for-55-refueleu-and-fueleu/. [Accessed 28 May 2023],

[51] European Commission. Reducing CO_2 emissions from heavy-duty vehicles. Brussels; 2024, URL https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en. [Accessed 24 January 2024].

[52] Braun M. Sieben Kandidaten ziehen Bilanz. Stuttgart: trans aktuell; 2016.

[53] FuelsEurope. Statistical report 2022. Brussels: FuelsEurope; 2022.

[54] van der Meulen S, Grijspaardt T, Mars W, van der Geest W, Roest-Crollius A, Kiel J. Cost figures for freight transport – final report: Kostenkengetallen voor Goederenvervoer - eindrapportage. Zoetermee: Panteia; 2020.

[55] Confeeder. Ship data - Enforcer, Encounter, Endeavor, Energizer, Ensemble, Endurance. Rhoon: Confeeder Shipping and Chartering B.V.; 2017.

[56] Ulstein. Vessel business case analysis: 475 TEU container ship. Ulstein: Ulstein international AS; 2019.

[57] Stopford M. Maritime economics. 3rd ed. London: Routledge; 2009.

[58] DNV. Transport in transition: A deep dive into fuels, electricity, and infrastructure. Hovik: DNV AS; 2023.

[59] AIRBUS. Airbus reveals new zero-emission concept aircraft: Press release. Toulouse: AIRBUS; 2020.

[60] Zhou Y, Searle S, Pavlenko N. Current and future cost of e-kerosene in the United States and Europe: Working paper 2022-14. Washington, DC: International council on clean transportation; 2022.