THE POWER OF POLICY TOWARDS A HYDROGEN-POWERED DUTCH INLAND WATERWAY TRANSPORT SECTOR: AN ECONOMIC DECISION-MAKING SIMULATION ON SHIP LEVEL

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Preface

After high school, I pondered whether pursuing a university degree would suit my interests and capabilities. Even more, I was skeptical about the opportunities that student life presumably had to offer. Ironically, it has been quite a journey having studied in Groningen, Vienna, Hongkong, Leiden, Delft and Rotterdam. After my bachelor's in business administration, I wanted to pursue a more technical path where the MSc Industrial Ecology offered the perfect opportunity. I became interested in programming and wanted to use my thesis project to further explore Python. With little prior knowledge this was challenging at times. In the end, I am proud to say that finishing the thesis project has provided me with loads of knowledge, both in terms of content and practical skills.

I have always been fascinated by the energy transition, which will be critical for my and future generations. I have noticed that consumers, businesses, and policymakers all expect the other party to take the lead in the energy transition. Although all parties need to contribute, I believe that most business and consumer decisions come down to an economic trade-off. Policymakers have the means to influence this economic trade-off. I hope this thesis provides insight to people involved in the energy transition in the IWT sector. Potentially, the designed model provides decision-making support for IWT operators by calculating the total costs of hydrogen- and diesel-powered drivetrains given predetermined assumptions. Furthermore, policymakers can test different scenarios and evaluate the aggregate outcome of individual decisions made by IWT operators.

I would not have been able to finish this thesis without the help of my supervisors. Therefore, I would like to thank Dr. E.G.M. Kleijn and Prof. Dr. A.J.M van Wijk for their guidance and eye for practical use of the research. It really triggered me to critically assess my own work. Furthermore, I am grateful for all help from people within the sector that provided me with loads of relevant information. Finally, I would like to thank my family and friends with whom I could share all my process- and content-related challenges and accomplishments.

Abstract

Hydrogen offers opportunities to develop a sustainable energy system and is essential to support the EU's commitment to reaching carbon neutrality by 2050. Hydrogen is a solution for heavy transport sectors that struggle to reduce emissions by direct electrification, such as the Dutch inland waterway transport (IWT) sector. However, the lack of economic viability is one of the most dominant challenges for hydrogen, which calls for a tailored and sectoral policy approach that considers the dynamics involved in the IWT sector. This study simulates the decision-making process of active ships in the Netherlands based on the economic trade-off between diesel- and hydrogen-powered drivetrains to identify policy measures that would catalyze the sector's hydrogen transition.

In the simulated base scenario, NO_x, PM, and CO_2 emission targets are not met. Economic policies must contribute to the realization of these emission targets. Here, quantity-based economic instruments are preferred over price-based economic. Quantity-based economic instruments ensure that emission targets are realized virtually, while the effect of price-based economic instruments is subject to uncertainties related to cost developments, for instance. The introduction of a Renewable Energy (HBE) obligation and the inclusion of the IWT sector in the Emission Trading Scheme (ETS) are effective quantity-based economic instruments. When implementing both these instruments, policymakers must prevent double burdening of the IWT sector.

When introducing an HBE obligation, obligation levels must be set in accordance with the emission goals and a multiplier for hydrogen is recommended to create a level playing field with other renewable fuels. To include the IWT sector in the ETS, the minimum tonnage condition for ships must be removed. In addition to these policies, subsidies must be provided on the large capital investments for hydrogen to compensate for the higher marginal abatement cost in the IWT sector and create a level playing field with other transport modes, countries and fuels. Besides economic policies, the development of relevant regulation and bunkering infrastructure is a prerequisite for the hydrogen transition in the IWT sector.

This research mainly focused on a techno-economic trade-off between hydrogen- and diesel-powered drivetrains. Future research could focus on additional (qualitative) criteria in the decision-making process, such as upcoming legislation, safety, and (bunkering) infrastructure availability.

Keywords: Hydrogen, inland waterway transport, technological transitions, energy systems modeling, policy

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Nomenclature

List of abbreviations

Symbol	**Description**
GTL	Gas to liquid
CCNR	Central Commission for Navigation on the Rhine
CCS	Carbon capture and storage
CH_2	Compressed hydrogen
DPF	Diesel particulate filter
ETS	Emission trading scheme
FC	Fuel cell
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas emissions
HBE	Hernieuwbare brandstof eenheden (translated: renewable energy units)
HHV	Higher heating value
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IMO	International Maritime Organization
IWT	Inland waterway transport
LH_2	Liquid hydrogen
LHV	Lower heating value
LNG	Liquified natural gas
LOHC	Liquid organic hydrogen carrier
PEM	Proton exchange membrane
PGS	Publicatiereeks gevaarlijke stoffen (translated: publication set dangerous substances)
PM	Particulate matter
RED	Renewable energy directive
RPM	Rounds per minute
SCR	Selective catalytic reduction
SMR	Steam methane reforming
SRVB	Subsidieregeling verduurzaming binnenvaartsschepen (translated: subsidy sustainable IWT ships)
TCO	Total cost of ownership
TTW	Tank-to-wake
WTW	Well-to-wake

List of symbols

Symbol	**Description**	**Unit**
AL	Average load	[%]
$ATCO$	Average total cost of ownership	[€]
ATD	Average trip distance	[hours]
CC	Capital cost	[€]
CE	CO_2 emissions	[t]
CF	Cost of fuel	[€]
CP	CO_2 price	[€/ t]
CRF	Capital recovery factor	[%]
D	Degradation	[%]
DCO	Diesel consumption in IWT sector	[kWh / year]
EOH	Effective operational hours	[hours / year]
FCO	Fuel consumption	[kWh/year]
FP	Fuel price	[€/kWh]
$HBEC$	HBE cost	[€]
$HBEP$	HBE price	[€/GJ]
HCO	Hydrogen consumption	[$\mathrm{kwh_{HHV}/kg_{H2}}$]
HD	Hydrogen demand	[PJ/year]
HE	Hypothetical emissions	[kg]
HED	Hydrogen energy density	[$\mathrm{kwh_{HHV}/kg_{H2}}$]
i	Component of drivetrain system	[-]
I	Installation cost	[€]
IC	Investment cost	[€/specific component capacity]
j	Ship	[-]
K	Fixed period	[years]
LT	Economic lifetime	[years]
M	Margin	[%]
ME	Modeled emissions	[kg]
N	Number of system components	[-]
OM	Operational maintenance	[%]
OMC	Operational maintenance cost	[€]
Q	Quantitiy	[specific component capacity]
r	Discount rate	[%]
RE	Real emissions	[kg]
REC	Renewable energy obligation in IWT sector	[GJ/year]
REO	Renewable energy obligation in IWT sector	[GJ/year]
s	Drivetrain system	[-]
SoD	Share of diesel	[%]
$SoGH_2$	Share of green hydrogen	[%]
TCO	Total cost of ownership	[€]
TEP	Total engine power	[kW]
$WACC$	Weighted average cost of capital	[%]
x	Introduction of HBE	[0 or 1]
y	Introduction of CO_2 taxes	[0 or 1]
Z	Total number of ships	[-]
η	Drivetrain efficiency	[%]

1 Introduction

Hydrogen is enjoying growing attention, with hydrogen plans already incorporated in long-term European strategies (European Commission, 2020). Hydrogen offers opportunities to develop a sustainable energy system and is essential to support the EU's commitment to reaching carbon neutrality by 2050 (European Commission, 2020). Recently, the EU even agreed on raising its ambitions to a 55% CO_2 emission reduction by 2030 (European Commission, 2020). In addition, the Netherlands faces a nitrogen crisis and struggles to tackle nitrogen emissions (Boztas, 2021). In the new EU hydrogen strategy, an increased supply of 80 GW is planned to stimulate the hydrogen economy (European Commission, 2020). However, the development of demand must coincide, and hence new markets for hydrogen must emerge. Markets where decarbonizing through direct electrification seems unlikely are suggested as potential hydrogen markets (Schnülle et al., 2016). This is the case in the heavy transport sector where alternative energy carriers do not have the required energy density (Ball & Weeda, 2015; Schnülle et al., 2016).

Within heavy transport, the highest emission intensities are present in air and water transport. The emission intensity is an efficiency indicator representing the emissions per euro added value (CBS, 2020). Aviation and the international maritime sector are global industries, which makes national policy interventions that stimulate a transition complicated in these industries. However, the inland waterway transport (IWT) sector is subject to national policies to a larger extent. The IWT sector shows high potential for a fuel transition towards hydrogen, especially in the Netherlands. The Netherlands is a country renowned for its closely branched waterway network. Waterway transport contributed 43.2% to the freight transport modal split, while the EU's average was 6% in 2018 (Eurostat, 2018). Given the various opportunities and strengths of waterway transport, such as sufficient infrastructure capacity, low infrastructure maintenance, and a high level of safety (CCNR, 2021b; Wiegmans, 2005), the Netherlands seeks to shift its modal split even further towards waterway transport (Rijkswaterstaat, 2020).

In the Netherlands, the emission intensity for water transport was 2.39 [gCO_2-equivalents/€] in 2018, more than 5 times larger than the emission intensity for road transport (CBS, 2019). In 2019, the sector emitted 25.9 kton NO_x, 0.8 kton PM_{10}, and 1914 kton CO_2 into the air (CBS, 2021a). These represent 11.1% (NO_x), 9.4% (PM_{10}), and 4.6% (CO_2) of the the transport sector's total emissions, respectively. Within the Dutch IWT sector, targets have been set to reduce these emissions to zero in 2050 (Green Deal, 2019).

Hydrogen is considered a solid and clean alternative for conventional fuels used in the shipping industry (Deniz & Zincir, 2016; DNV GL, 2019; IRENA, 2020; MariGreen, 2018), especially for shorter distances (DNV GL, 2019). The main advantage of hydrogen is the possibility of being a zero-emission fuel when produced from renewable resources (DNV GL, 2019). Hence, hydrogen fits into a zero-emission scenario for 2050. Hydrogen is nowadays still produced from natural gas, but anticipated future sustainable production capacity shows high potential. However, the introduction of hydrogen faces several challenges, the most dominant one being the lack of economic viability (da Silva Veras et al., 2017; DNV GL, 2019; Gigler & Weeda, 2018; IRENA, 2020). To address these and other challenges, the transition towards green hydrogen calls for tailored and sectoral policy approaches (IRENA, 2020).

Knowledge gap

Many studies have presented transition models for the introduction of hydrogen (Farrell et al., 2003; FCH, 2019; Gigler & Weeda, 2018; Qadrdan et al., 2008; Shafiei et al., 2015). However, these studies lack detail as they describe transitions in global, national, or general (e.g., transport sector) terms. The lack of detail in these studies results in superficial analyses that do not adequately address the dynamics involved in sector-specific technological transitions. McDowall (2012) argues that studies on the hydrogen transition are limited to a broad and generic view, lacking a substantial level of technical detail. While several studies highlight the opportunities of hydrogen in freight transport and the IWT sector (CCNR, 2020b; DNV GL, 2019; EICB, 2020; Farrell et al., 2003; Hansson et al., 2020, MariGreen, 2018; Moriarty & Honnery, 2019), no studies are known that propose a detailed transition model for the introduction of hydrogen in the IWT sector specifically and call for policy action. Additionally, Hansson et al. (2020) call for assessments with a more detailed representation of the shipping sector to increase understanding of the circumstances where renewable fuels are cost-effective.

Aim and research questions

This study simulates the decision-making process of active ships in the Netherlands based on the economic trade-off between diesel- and hydrogen-powered drivetrains to identify policy measures that would catalyze the hydrogen transition in the sector. This aim is formulated in the following main research question: *What policy measures would facilitate the hydrogen transition in the Dutch inland waterway transport (IWT) sector and contribute to reaching emissions targets?*

The main research question is answered using the following sub questions:

- What are the Dutch IWT sector characteristics in terms of the fleet, fuels, emissions and policies?
- What are characteristics of hydrogen applications?
- What is technically required to introduce hydrogen in the Dutch IWT sector?
- How do economic decision-making dynamics for IWT operators affect future emissions and hydrogen demand?
- How does the introduction of policy measures affect future emissions and hydrogen demand?

Thesis outline
The report has the following structure. In Chapter 2, an overview is provided of the hydrogen opportunities in the Dutch IWT sector, considering the sector characteristics, the potential of hydrogen applications, and the technical requirements for producing, distributing, and applying hydrogen. Chapter 3 covers the research approach, which includes the assumptions underlying the transition model. In Chapter 4, a base scenario for the hydrogen transition is developed, policy measures are tested in the model, and alternative scenarios are constructed that meet the emission targets in the Dutch IWT sector. Finally, the results are discussed in Chapter 5, and policy recommendations are provided that facilitate the hydrogen transition towards zero emissions in 2050.

2 Hydrogen opportunities

2.1 Dutch IWT sector characteristics

2.1.1 Overview

The Dutch IWT sector is the largest in the EU, contributing 33% to the total waterway freight transport in the EU in 2019 (CCR, 2019). Within the Netherlands, 43.2% of all freight transport was transported along waterways in 2018 (Eurostat, 2018). In 2018, a total turnover of €2.5 billion was reported with a 16% exploitation coefficient (CCR, 2019). The exploitation coefficient represents the relation between profits and net turnover, also known as the profit margin. Profit margins, however, have been decreasing over the years caused by overcapacity problems that are present since 2008. During the financial crisis, many new ships were commissioned, but demand for freight transport declined.

Most of the assignments (55%) in freight transport on waterways are traded on the spot market and do not involve any long-term relationships between IWT operators and logistics service providers. IWT operators refer to individuals or companies that operate or own the IWT vessels, and are responsible for decision-making. The remaining 45% of freight transport is performed by shippers and logistics service providers themselves, or through long-term agreements with IWT operators (CCNR, 2021d).

2.1.2 Fleet

The Dutch IWT sector is characterized by a high level of small (family) businesses. According to CBS (2021b), 4130 enterprises were active in the sector, of which 3050 were operating in freight transport. In 2021, 9628 ships were registered in the central database of IVR (IVR, 2021a). In the Netherlands, 45% of the businesses own only one ship, 20% of the businesses own 2 or 3 ships, and the remaining business own more than 4 ships (CCNR, 2021d). This indicates a low market concentration given the number of IWT operators. Over the past decade, the number of ships has been decreasing due to the replacement of smaller ships by larger ones.

About 44% of the current Dutch fleet are motor ships designed to ship dry cargo, such as coal, sand, and containers. Ten percent is classified as tankers that ship wet cargo. Table 1 indicates that 12% of the Dutch fleet is categorized as push- and tug boats that are coupled to barges without drivetrains. Furthermore, the fleet consists of passenger ships (12%) and other inland waterway ships (22%) (IVR, 2019). More detailed descriptive statistics about the fleet can be found in Appendix A. Below the most important characteristics for decision-making are described for these different ship types.

Table 1: Dutch fleet classified by ship type

	Dry cargo	**Wet cargo**	**Push and tug**	**Passenger**	**Other**
Registered in NL	4241	924	1155	1185	2123

Cargo vessels

Cargo vessels can either be dry cargo motor ships or wet cargo motor ships. Cargo vessels consider costs as a key criterion in the decision-making process. Noise, vibrations, and emissions, on the other hand, are less relevant criteria (MariGreen, 2018). In the entire fleet, cargo vessels run the longest distances. An extra stop for bunkering would be both costly and inconvenient, so a larger fuel tank is required for cargo vessels (MariGreen, 2018). Cargo vessels usually bunker while the ship is unloaded. Hence, fast bunkering times are not the most important criterion.

Push and tugboats

Push- and tugboats represent similar characteristics as cargo vessels. However, they often run shorter distances and hence, require smaller fuel tanks. When push- and tugboats drop off barges, they are often combined immediately with a new barge to embark on a new trip. Hence, push- and tugboats display high effective operational hours (EICB, 2015). Therefore, short bunkering times are essential to maximize the operational use (MariGreen, 2018). In general, push- and tug boats are classified according to their engine size, which can be <500kW, 500-2000kW, and >2000kW (Dahlke-Wallet et al., 2020). In the remainder of this thesis, push- and tugboats are grouped as push boats.

Passenger ships

The convenience of passengers is a weighty criterion in the decision-making processes of passenger ships. Hence, these ships seek to reduce unpleasant noise, vibrations, and emissions. As opposed to freight transporting ships, passenger ships face more cost factors than only fuel and ship depreciation costs. For instance, they often provide additional services to passengers, which requires personnel costs (MariGreen, 2018). Therefore, costs are considered a less important criterion in the decision-making process. Finally, passenger ships run relatively short distances and have plenty of time for bunkering processes. In general, ferries and cabin vessels are distinguished among passenger ships (Dahlke-Wallet et al., 2020; MariGreen, 2018).

Other ships

Ships classified in this category are waste collection boats, bunker boats, bunker stations, service vessels, patrol vessels, and large recreational vessels. The ship types in this category and their characteristics are heterogeneous. Hence, this group has been left out of the scope of this research.

Based on MariGreen (2018), Table 2 is composed, which shows the importance of decision-making criteria for each ship. The scoring ranges from unimportant to important, indicated by [−−] and [++], respectively. For cargo ships and push boats, costs are an important decision-making criterion. Passenger ships are potentially willing to pay a premium for drivetrains and fuels associated with lower emissions and less noise.

Table 2: Importance of decision-making criteria for ship types

	Cargo	**Push**	**Passenger**
Noise and vibrations	−−	−−	+
Emissions	−−	−−	+
Range	++	o	−
Reliability	+	+	o
Ease of bunkering	−	+	−
Costs	++	++	o

2.1.3 Development of the Dutch fleet

In the coming decades, the Dutch fleet will change in different ways. Firstly, the type of cargo being shipped will change. Coal transport will slowly disappear, and fuels such as hydrogen are being shipped to a larger extent. About 0.7% of the cargo ships are currently used for coal transport, which are often large ships (Panteia, 2019). Secondly, the Dutch government seeks to further shift the modal split towards waterway transport, which would increase the number of active ships (Rijkswaterstaat, 2020). However, the modal split shift has not been considered in this research. Thirdly and most importantly, the fleet composition will change. New ships will be commissioned, engines will be replaced, and some ships will be scrapped. The dynamics relevant to determine the future fleet composition are outlined below.

Commissioning of new ships

Strong peaks in the commissioning of dry cargo ships are present around 1960, 1980, 2000, and 2009, often due to economic prosperity in the years before these peaks. The commissioning of all other ships is relatively stable over the years (CCNR, 2020a). Between 2011 and 2019, 11 new dry cargo ships and 14 tank vessels were commissioned each year in the Netherlands, on average (CCNR, 2020a). IVR (2018) reported 89 commissioned ships in the Netherlands annually over the period 2000-2018. More detailed trends in the commissioning of ships can be found in Appendix C. Over the past years, the aggregate tonnage of all cargo ships in Europe has been increasing, while the total number of active ships has decreased (CCR, 2018). This indicates that the size of new ships increases.

Replacement of engines

The engine lifetime must be determined to predict the replacement year of engines. EICB (2015) estimates the expected engine lifetime based on the engine's effective operational hours and rounds per minute (RPM). They assume that a 750-RPM engine can operate for about 75.000 hours before being revised. Engines of 750–1250 RPM can operate for 62.500 hours, and engines >1250 RPM can operate for 50.000 hours. Currently, most ships are equipped with >1250 RPM engines. After the engine lifetime has passed, the engine can be revised. This means the engine lifetime is extended by the original engine lifetime. The revision takes place when it is financially more attractive than replacing the engine, which is often the case. When revising an engine, the revised engine does not have to comply with new emission standards under current policies. Current policies state that only new engines must comply with the latest Stage-V emission standards. These emission standards are explained in section 2.1.5.

EICB (2015) does not specify engine lifetimes for passenger ships and cargo ships shorter than 38 meters because those ships were exempted from emission regulations back in 2015. However, nowadays, these ships need to satisfy emission regulations. Based on expert interviews, setting effective operational hours for ships shorter than 38 meters at 1200 hours seems reasonable. Often these ships are service vessels that operate about 250 workdays a year, for 8 hours a day. One thousand two hundred effective operational hours would correspond to an engine utilization rate of 60%.

Passenger ships' engine lifetimes are generally shorter than for cargo vessels because passengers ascribe value to clean and new ships (expert consultation). This claim is substantiated by the IVR database, which returns an average age of 39.6 years for passenger ships, while cargo ships have an average age of 48.7. When considering the average lifetime of cargo vessels, the analysis returns an engine lifetime of 30.1 years before revision. Hence, in this study, the engine lifetime for passenger ships is set to 24 years, which is the result of the average engine lifetime of cargo vessel engines multiplied by the ratio between passenger and cargo ship age. Based on the assumptions and sources above, Table 3 was composed.

Table 3: Engine lifetimes based on ship type, RPM, and effective hours

		Estimated lifetime (years)			**After revision (years)**		
Ship class	Effective hours	RPM <750	RPM 750-1250	RPM >1250	RPM <750	RPM 750-1250	RPM >1250
0–38m	1400	54	45	36	107	89	71
39–49m	1683	45	37	29	89	74	59
50–54m	1861	50	42	33	100	84	67
55–66m	1550	48	40	32	97	81	65
67–79m	1662	45	38	30	90	75	60
80–84m	1540	49	41	32	97	81	65
85–86m	1708	44	37	29	88	73	59
87–109m	1886	40	33	27	80	66	53
110–134m	1943	39	32	26	77	64	51
>134m	3467	26	22	18	53	44	35
Coupled convoys	2513	30	25	20	60	50	40
Push boat 500–999kW	3126	28	24	19	57	47	38
Push boat 1000–1999kW	5336	14	12	9	28	23	19
Push boat >2000kW	7258	10	9	7	21	17	14
Passenger ships	1400	24	24	24	48	48	48

The engine's replacement year is based on the engine lifetime after revision. However, the replacement year could be brought forward by several factors, such as new emission regulations, economic benefits, or an early engine breakdown. The probability of early breakdown is assumed equal to the probability of an extended engine lifetime. Hence, potential early engine breakdowns are neglected in this thesis. In the years before 2020, a peak in engine replacements has occurred because new engines need to comply with Stage-V emission standards after 2020 (expert consultation). These Stage-V diesel engines are significantly more expensive, so for some IWT operators it was economically beneficial to replace their engine earlier than necessary.

Scrapping of ships

Ships in the IWT sector often display long lifetimes, which slows down the energy transition in the sector. The IVR annual reports of 2017, 2018, 2019, and 2020 show an average of 68.8 ships being scrapped each year in the entire European database that contained 18.332 ships in 2020 (IVR, 2021b). From expert interviews, it became apparent that it is reasonable to assume that ships are being scrapped after the engine lifetime has been passed four times. Hence, push boats >2000 kW have lifetimes of 28 years, while passenger ships display lifetimes of 96 years. The emissions of scrapped ships must be excluded from the sector's aggregate emissions.

2.1.4 Fuels

Most ships in the Dutch IWT sector are equipped with a diesel combustion engine (Panteia, 2019). Liquified natural gas (LNG) is currently used only on a limited scale because the introduction has been hampered by a strong decline in diesel prices between 2014 and 2017 (Panteia, 2019). In 2019, up to 19 ships were running on LNG (Panteia, 2019). For diesel, multiple types are available that are plain diesel (EN590), diesel with a bio-component (HVO), and synthetic diesel (GTL). All diesel types can be used in conventional internal combustion engines without any adjustments.

Although the combustion of GTL is associated with lower NO_x and PM emissions, the well-to-wheel CO_2 emissions are 5% higher due to more energy-intensive production than regular diesel (Panteia, 2019). CO_2 reducing policy measures could potentially drive up the GTL price in the future. Hence, GTL is left out of the scope of this research.

HVO is classified as biodiesel and considered a simple way to reduce emissions using combustion engines. HVO can be blended with plain diesel up to 30% without any engine modifications (Bohl et al., 2018). However, total emissions associated with biodiesel production are greater than for fossil fuel-produced diesel (ICCT, 2012; Jeswani et al., 2020). According to the LCA conducted by Jeswani et al. (2020), most biofuels have lower GHG emissions than fossil fuels when land use change is not taken into account in the analysis. However, in this case, GHG savings for most feedstocks are still not sufficient to satisfy the targets set by the RED. When land use change ís taken into account, the total emissions for biofuels are often higher than fossil fuel emissions (Jeswani et al., 2020). Total emissions from biofuels include direct emissions resulting from agriculture and processing, and indirect emissions from land use change, such as CO_2 emissions associated with deforestation.

Producing HVO from waste products would be associated with fewer emissions, but this is only scalable to a certain extent. Apart from emissions, driving HVO demand is associated with additional environmental and social risks, such as reduced biodiversity and implications for food security (ICCT, 2012). Even though HVO can reduce emissions in certain instances, the negative externalities raise questions about HVO's true sustainability. Hence, HVO is excluded from this research.

The use of batteries is also considered a promising and sustainable alternative to fossil fuel use, especially towards 2030 (European Commission, 2021). However, the larger volume and weight opposed to hydrogen is a downside of batteries (CCNR, 2020b). A 40-feet container could store 2 MWh of batteries or 758 kg hydrogen at 350 bar (TNO, 2019). Assuming a 50% tank-to-wake efficiency (HHV) for hydrogen-powered fuel cells and 100% for batteries, approximately 8 battery containers would be required for 1 hydrogen container. Hence, additional cargo space must be saved for battery containers. In addition, expensive electricity grid expansions are required for transporting electricity to the harbors, which may become superfluous when hydrogen becomes more dominant after 2030, as expected by the European Commission (2021). Finally, batteries for heavy-duty applications are still expensive at prices around 700 [€/kWh], which is a factor 7 compared to light-duty batteries (CCNR, 2020b). Current applications of batteries on ships in the Netherlands require customers to pay for a large part of the additional costs. For these reasons and to limit the scope, batteries are not considered in the remainder of this thesis.

The use of LNG is associated with emission reductions of 80%, 99%, and 20% compared to diesel combustion for NO_x, PM, and CO_2 emissions, respectively (IVR, 2020). Given the long lifetime of ships and engines, the use of LNG does not seem to align with the zero-emission goals in 2050. Moreover, using LNG requires various expensive modifications to a ship. Hence, LNG is left out of the scope of this research.

Alternative future fuels, such as methanol and ammonia, are also excluded because pure hydrogen is considered a better option for the IWT sector (MariGreen, 2018). For instance, the ammonia production process is not yet climate-neutral and neither is the engine technology commercially available (CCNR, 2020b). Therefore, the fuel is not ready to be immediately used for the IWT sector. For these reasons and to limit the scope of this study, these fuels have been excluded. The characteristics of hydrogen are described in Chapter 3.

2.1.5 Emissions

The primary emissions in the IWT sector are nitrogen oxide (NO_x), particulate matter (PM), and carbon dioxide (CO_2). PM emissions can be classified into $PM_{2.5}$ and PM_{10}, representing the maximum size of particulates in micrometers. In 2019, the sector emitted 25.9 kton NO_x, 0.8 kton PM, and 1914 kton CO_2 into the air (CBS, 2021a). These represent 11.1% (NO_x), 9.4% (PM), and 4.6% (CO_2) of the total emissions in the transport sector. In 2019, the emission intensity (emissions per euro added value) of water transport was 3.03 [gCO_2-equivalents/€]. In comparison, the emission intensity of road transport and the Dutch economy are only 0.47 and 0.32 [g/€], respectively (CBS, 2019). CE Delft (2018c) specifies environmental prices, which reflect the environmental damage caused by the emissions. The environmental prices for NO_x, PM_{10}, and CO_2 are estimated at 34.7, 44.6, and 0.68 [€/kg] in 2020, respectively. These prices result in total emissions costs of €878, 36, and 130 million in 2020 for NO_x, PM, and CO_2 emissions, respectively.

Since 1975, engine emissions [kg/kWh] of new ships have declined 0%, 44%, and 67% for CO_2, NO_x, and PM, respectively, due to stricter emissions standards and cleaner engines (EICB, 2015). CE Delft (2021) classified NO_x and PM emissions according to engine's construction year, as shown in Table 4. In the table, NO_x emissions for Stage-V engines have been adjusted to align them with the limits set in the Green Deal (2019). CO_2 emissions depend on the diesel consumption of the engines and can be determined by multiplying the diesel consumption and the CO_2 emissions per unit of fuel, the latter being 2.919 [g_{CO2}/kg_{diesel}] or 37 [g_{CO2}/kWh_{HHV}] (CE Delft, 2021). The diesel consumption values in Table 4 have been corrected for a lower efficiency of 33% (HHV) in 2020 (>300kW). The 33% efficiency is based on an average load level of 37% for ships (Sluiman et al., 2019; Heid et al., 2021). The efficiency development over time is based on CE Delft (2021). This correction is also performed for NO_x and PM emissions before 2003, when emission standards were absent in the sector.

Table 4: Engine emissions based on the engine construction year

	Emission standard	**NO_x [g/kWh]**	**PM [g/kWh]**	**Diesel consumption [g/kWh]**
1900-1974	n/a	12.6	0.67	274
1975-1979	n/a	12.4	0.67	268
1980-1984	n/a	12.6	0.67	274
1985-1989	n/a	12.2	0.67	262
1990-1994	n/a	11.8	0.44	256
1995-2002	n/a	11.0	0.33	239
2003-2007	CCR-I	9.2	0.29	233
2008-2018	CCR-II	7	0.19	233
2019-20xx	Stage-V <300kW	2.1	0.09	239
2020-20xx	Stage-V >300kW	1.8	0.0143	222

In 2019, the Green Deal on Maritime, Inland shipping, and Ports (henceforth, Green Deal) was published responding to the new Dutch government's coalition agreement in 2017. For inland shipping specifically, the Green Deal is in line with the Mannheim Declaration signed in 2018 by the member states of the Central Commission for Navigation on the Rhine (CCNR) (Green Deal, 2019). The Green Deal sets several goals and ambitions for emission reductions in the IWT sector. It is assumed that these goals need to be reached linearly.

- Goal by 2024: reducing carbon emissions by at least 20% and emissions of environmental pollutants by at least 10%, relative to 2015.
- Goal by 2030: reducing carbon emission by 40% – 50% relative to 2015, and 150 inland vessels that are equipped with a zero-emission drivetrain.
- Goal by 2035: reducing emissions of environmental pollutants of 35% - 50% relative to 2015.
- Goal by 2050: having a virtually zero-emission and climate-neutral inland fleet

This thesis considers the lower bounds whenever the target has been set as a range. NO_x and PM emissions are classified as environmental pollutants and are evaluated separately.

2.1.6 Policies

To assess the opportunities for hydrogen in the IWT sector, the most relevant policies that could hamper or facilitate the transition have been outlined. Firstly, technical policies are described regarding the hydrogen production, transport, bunkering and use. Secondly, the current and future emissions standards are described in the environmental policy section. Finally, economic policies are listed, which include taxes and subsidies on both capital expenditures and fuel. Note that current policies described are subject to future changes.

2.1.6.1 Technical policies - Infrastructure

Firstly, hydrogen needs to be produced, which requires a permit called the ‘omgevingsvergunning’. Hydrogen production is authorized when all safety guidelines are satisfied, and hydrogen production fits into area development plans (Ekinetix, 2020). Next, the hydrogen is ideally transported through pipelines. However, there is no legal basis yet for gas pipeline administrators to transport hydrogen (RLI, 2021). Alternatively, the hydrogen is transported by trucks, which is possible already. TNO (2019) summarized the criteria and certifications necessary for trucks and trailers to transport hydrogen according to EU regulations, such as the required MEGC (Multi-Element Gas Container) certification.

When hydrogen has been transported to the harbor, bunkering infrastructure is required. No sources have been found that describe the permit procedure for bunkering infrastructure specifically. Ekinetix (2020) describes the permit procedure for hydrogen refueling stations on roads. Here, the construction of hydrogen stations with storage capacities up to 5 ton require a permit called ‘Wabo-milieuvergunning’ and often a general permit for construction (Ekinetix, 2020). These permit procedures are often cumbersome as hydrogen bunkering stations are not yet included in any area development plans. When any technical adjustments are made during the process, the process must start over again (Ekinetix, 2020).

The technical design of these hydrogen stations is assessed based on PGS (Publicatiereeks gevaarlijke stoffen) publications that describe best practices, such as safety distances. Currently, PGS publications are limited to hydrogen refueling stations for road transport (PGS35) and LNG bunkering (PGS 33-2). Hydrogen bunkering stations are excluded from the PGS35 and PGS33-2 publications, which indicates a lack of regulation. In practice, the assessment for permits is based on guidelines for processing hydrogen at refueling stations for road transport, as far as the activities at refueling stations overlap with bunkering activities. Deviating activities are assessed based on the own insights of permit assessors (expert consultation).

In addition to specific regulations for hydrogen transport and infrastructure, a licensing system must be set up to license measuring equipment and qualify service engineers (RLI, 2021). It is expected that policies will develop in the coming years as the government has set ambitions for a larger use of hydrogen (expert consultation).

2.1.6.2 Environmental policies

New ships’ engines in the IWT sector built after 2003 and 2008 have to comply with CCR-I standards and CCR-II standards, respectively. In 2019, two-third of the inland vessel engines, predominantly smaller ships, did not comply with CCR-II emission standards. In the future, however, some ships will be forced to switch to cleaner engines. For instance, from 2025 onwards, ships that do not satisfy CCR-II standards cannot enter the Port of Rotterdam (Panteia, 2019). EICB (2015) predicted that many IWT operators have invested in CCR-II engines in the last few years because of these new regulations.

From 2019/2020 onwards, the new Stage-V standards set by the EU apply, which prescribe emission limits for new engines of Non-Road Mobile Machinery (NNRM), including inland vessels (Green Deal, 2019). These emission standards must contribute to reaching the emission targets set in the Green Deal, as described in section 2.1.5. The NO_x and PM emission limits for Stage-V engines are specified in Table 4. Stage-V limits are 74% and 95% lower than CCR-II limits for NO_x and PM emission, respectively, considering engine powers >300 kW. CO_2 emissions depend on the fuel used in these engines and are not restricted in the Green Deal.

Currently, Stage-V engines are 50% more expensive than CCR-II engines and cannot be produced on a large scale yet (Vermij & De Vries, 2019). In addition, certifying a Stage-V engine for inland vessels is still expensive for engine manufacturers. Due to these additional costs, many IWT operators decided to install a CCR-II engine in the years before 2020 (expert consultation).

2.1.6.3 Economic policies

To bridge the gap between total costs of ownership (TCO) of diesel- and hydrogen-powered drivetrains, economic policies could be necessary to incentivize IWT operators to switch to hydrogen. Economic instruments can be classified as price- or quantity-based economic instruments. When using price-based economic instruments (e.g. taxes), the economic incentive for IWT operators is determined artificially (Hepburn, 2006). However, when using quantity-based economic instruments (e.g. cap-and-trade systems), the economic incentive is determined by the imposed quantity restriction (Hepburn, 2006). Tighter quantity restrictions result in larger economic incentives.

Some economic policies are already in place in the Netherlands. However, to further reduce emissions and catalyze the transition towards cleaner fuels, interest groups within the sector argue for a European fund of €2-3 billion (Financieel Dagblad, 2021). The Netherlands contributed to about 33% of the total waterway freight transport in the EU in 2019 (CCR, 2019), which means a similar share of the €2-3 billion fund would be available to transition the Dutch fleet. Furthermore, an emission label that indicates a ship's emissions is currently being investigated. The emission label could help clean ships to get loans from banks more easily or receive discounts when entering harbors (Ministerie van Infrastructuur en Waterstaat, 2020).

The current subsidies and fiscal policies for capital and operational expenditures have been listed below. Some funds have been excluded because they are aimed at research or demonstration projects, or because registration deadlines for these funds have already passed (for instance, DKTI subsidy or the Innovatieregeling Duurzame Binnenvaart). At the moment, both diesel and hydrogen innovations are eligible for most subsidies (Panteia, 2019; EICB, 2021).

Economic policies - Capital

Subsidieregeling Verduurzaming Binnenvaartsschepen (SRVB): The SRVB supports IWT operators that are willing to replace a conventional engine. Until 2023, €12.7 million is available for the installation of cleaner engines. Until 2025, there is a budget of €65 million available for installing selective catalytic reduction (SCR) equipment. Forty, fifty, and sixty percent of the total investment is refunded for large, medium, and small enterprises, respectively. This refund is capped at €200.000 per vessel (RVO, 2021a).

Subsidieregeling Duurzame Scheepsbouw (SDS): This subsidy supports ship construction companies willing to build or retrofit a new ship. 25% of the investment is refunded and for each applicant capped at €1.25 million. For 2021, €4.6 million is available in total (RVO, 2021b).

There are also fiscal policies in place, which allow deducting part of the investment from a firm's taxable profits (Belastingdienst, 2020; Belastingdienst, 2021). Three examples of such policies are, the 'kleinschaligheidsinvesteringsaftrek' (KIA), 'energie-investeringsaftrek' (EIA), and the 'milieu-investeringsaftrek' (MIA). Both Stage-V engines and hydrogen-powered drivetrains are eligible for these fiscal policies (RVO, 2020a). Panteia (2019) states that the policies, in their current form, mainly subsidize conventional combustion engines.

These economic policies are subject to change and budgets are set to finance the first pilot projects. In the future, these budgets are likely to be expanded to support a larger number of shipping companies. As soon as the investment cost for hydrogen-powered drivetrains drop below the investment costs of diesel-powered drivetrains, these subsidies are likely to be phased out.

Economic policies - Fuel

Taxation of fuel used to be prohibited, according to the Act of Mannheim (TNO, 2019). However, the European Commission has recently proposed to revisit the tax exemptions for fossil fuels and investigates a minimum tax rate on fossil fuels used in the sector (European Commission, 2021). Currently, most economic policies circumvent the Act of Mannheim to place a higher burden on fossil fuels. For instance, fuel suppliers in the Dutch transport sector are obliged to supply an increasing share of renewable energy according to the Renewable Energy Directive II (RED-II). Their annual obligation is expressed in Renewable Energy Units (HBEs). One HBE represents 1 GJ of renewable energy. HBEs can be traded and sold to parties that struggle to decarbonize their supply. Hydrogen is not yet covered by the RED-II, and neither is the IWT sector. However, policymakers seek to introduce an annual obligation of renewable energy in the IWT sector from 2022 onwards (Staatscourant, 2020; Ministerie van Infrastructuur en Waterstaat, 2021). In addition, it is expected that hydrogen is included in the RED-II from 2022 onwards (Mulder, 2020). Here, blue hydrogen is not considered renewable energy and is excluded from this policy (Rijksoverheid, 2021). Current plans suggest that at least 5 PJ of renewable energy must be supplied to the Dutch

IWT sector in 2030 (Ministerie van Infrastructuur en Waterstaat, 2021). The renewable energy obligation corresponds to 20% of the total diesel consumption in the Dutch IWT sector (CBS, 2021f). However, introducing such a renewable energy obligation in the Netherlands apart from the EU RED-II guidelines, may incentivize IWT operators to bunker in neighbouring countries (i.e. Germany or Belgium)(CCNR, 2021d).

The price of one HBE is not publicly available but is estimated at 10-15 [€/GJ] (RVO, 2020b). Little predictions have been made about the development of the future HBE price in the literature. The HBE policy makes renewable fuels, such as hydrogen, more competitive in two ways. First, fossil fuel producers must purchase HBEs to meet their renewable energy obligation. It is assumed that the total costs of additional required HBEs are averaged across the total diesel consumption and charged on top of the diesel price. Second, hydrogen producers generate revenues by selling HBEs, which can be subtracted from the hydrogen production cost. Hence, the hydrogen price is lowered. In this thesis, the effect of the HBE policy on hydrogen prices is neglected because it assumed to be incorporated in the expected cost reductions for hydrogen, as described in section 3.2.2. Finally, a multiplier that would favour hydrogen over other renewable fuels, such as biodiesel, is being discussed among policymakers (Ministerie van Economische zaken en Klimaat, 2020). However, a multiplier for hydrogen is neglected in the calculations of this thesis because other renewable fuels are left out of the scope in this thesis.

Another EU system to reduce greenhouse gas (GHG) emissions is the Emission Trading Scheme (ETS). The ETS sets an absolute cap for GHG emissions that becomes stricter over time. Companies can receive allowances, which gives them the right to emit one tonne of CO_2-equivalents. The allowances can be traded against prices established by market mechanisms of supply and demand (CCNR, 2021d). Currently, the IWT sector is excluded from the Emission Trading Scheme (ETS). In the 'Fit for 55 Package' the European Commission proposes to extend the scope of the ETS to cover the Maritime sector, but only large ships with tonnages beyond 5000. Most ships operating in the IWT sector have tonnages below 5000 and therefore the IWT sector is largely excluded (European Commission, 2021). Furthermore, the 'Fit for 55 Package' proposed to include hydrogen production with electrolyzers in the ETS, making renewable hydrogen eligible for free allowances (European Commission, 2021). This would allow hydrogen producers to generate additional revenues by selling these allowances. In turn, this would lower the hydrogen price.

The ETS price was on average 25 and 55 [€/t] in 2020 and 2021, respectively (Ember, 2021). The impact assessment accompanying EU's 2030 Climate Target Plan projects CO_2 prices for the ETS sectors ranging from 32 to 65 [€/t] (European Commission, 2020). This would be sufficient to reduce economy-wide greenhouse gas emissions at least 55% by 2030. In the sustainable development scenario of IEA (2021) CO_2 prices for advanced economies are 63 [$/t] in 2025. After 2025, the CO_2 price rises towards 140 [$/t]] in 2040. The sustainable development scenario sets a path towards meeting objectives in the Paris Agreement. The CO_2 prices of the sustainable development scenario have been taken as a basis in this thesis.

Finally, SDE++ subsidies seek to refund the unprofitable part of renewable energy projects. SDE++ could drive down hydrogen prices. However, the SDE++ renumeration for hydrogen production has not been announced officially. For all renewable energy projects in the Netherlands, €5 billion is available. In this thesis, SDE++ subsidies are left out because they are assumed to be included in the expected hydrogen cost reductions towards 2050, as described in section 3.3.3. Besides, HBE revenues are likely to contribute to hydrogen production cost reductions to a larger extent, in case the HBE policy is introduced (Bos et al., 2020).

2.1.7 Hydrogen projects

In the Netherlands, 25 pilot projects in the IWT sector have been identified that apply hydrogen in various forms (EICB, 2020). Most projects seem to prefer the use of hydrogen in gaseous form because it is considered the only option that is technically and financially feasible at the moment (EICB, 2020). Liquid hydrogen is implemented less often because safety requirements related to hydrogen bunkering and storage are considered problematic (EICB, 2020). Liquid organic hydrogen carriers (LOHC) not implemented because they are LOHC not cost-competitive. Moreover, it is hard to collect and return residuals from LOHC (EICB, 2020).

The ship types involved in the pilot projects are quite diverse, such as container ships, wet cargo ships, bulk carriers, cabin vessels, push boats, water taxis, and boats for crew transfer. In 2020-2021, 6 ships were planned to be launched, mostly small-scale applications. In 2022, 11 ships are expected to be equipped with a hydrogen-powered drivetrain, and 16-65 ships over the period 2023–2025 (EICB, 2020).

2.2 Characteristics of hydrogen applications

There are numerous applications of hydrogen possible. The most promising hydrogen applications are selected as a scope of this research. First, a definition of a hydrogen application is provided. Next, 5 hydrogen carriers and 2 hydrogen converting technologies are described. Finally, the combinations between hydrogen carriers and hydrogen conversion technologies are evaluated. The most promising combinations are selected.

2.2.1 Definition of hydrogen

Hydrogen as a synthetic energy carrier has numerous benefits such as its high gravimetric energy density [MJ/kg], its abundance on earth in combined form, and the absence of greenhouse gas emissions during its oxidation (Singh et al., 2015). Moreover, CO_2 emissions are eliminated when produced from renewable resources, for instance (Dincer & Acar, 2015). The environmental impact of hydrogen can be indicated by different colors, such as grey, blue, and green hydrogen. Hydrogen produced from fossil fuels, where CO_2 is emitted into the air, is called grey hydrogen. Blue hydrogen is produced when a fraction of the emitted CO_2 is captured and stored. Green hydrogen is produced from renewable energy through electrolysis or photolysis, for instance (CE Delft, 2021). Green hydrogen is the final goal, but grey and blue hydrogen can function as steppingstones. Once hydrogen has been produced, it can be stored and distributed in gaseous form, liquid form, solid-state materials, or liquid organic hybrids (e.g., ammonia and methanol) (Singh et al., 2015). The energy content of hydrogen is 141.86 [MJ_{HHV}/kg], while diesel's energy content is only 45.6 [MJ_{HHV}/kg]. However, gaseous hydrogen has a lower volumetric energy density of 0.090 [kg/m^3] at 1 bar and 0°C, while diesel has a volumetric energy density of 0.846 [kg/l], which corresponds to 846 [kg/m^3]. Hence, hydrogen is often liquified or compressed to decrease its storage volume.

The various forms of hydrogen can be applied in an internal combustion engine or a fuel cell, which are the two leading conversion technologies for ships (MariGreen, 2018). This thesis investigates multiple combinations of hydrogen carriers and hydrogen conversion technologies. Such a combination is called a hydrogen application (e.g., gaseous hydrogen converted in a fuel cell). Hybrid forms with other energy carriers are also possible, such as the co-combustion of diesel and hydrogen in internal combustion engines.

2.2.2 Hydrogen carriers

Hydrogen carriers can be classified into physical-based carriers and material-based carriers (MariGreen, 2018). The physical-based types include compressed, and liquid hydrogen. Material-based types are more diverse and can include liquid organic hydrogen carriers and metal hydrides.

Compressed hydrogen
Compressed hydrogen (CH_2) is usually stored at pressures up to 700 bar at ambient temperature (MariGreen, 2018). Withdrawing the CH_2 from storage is relatively straightforward using a valve. Bunkering times for a hydrogen storage tank are 60 [g_{H2}/s], as specified by MariGreen (2018). CH_2 (700 bar) has a low energy density of 42 [kg/m^3] (IEA, 2019b).

Liquid hydrogen
Liquid hydrogen (LH_2) has a higher energy density (70.8 [kg/m^3]) than compressed hydrogen (IEA, 2019b). LH_2 must be stored below its boiling point (-253°C) at ambient to moderate pressures (MariGreen, 2018). The tanks must be insulated with a double wall to maintain this low temperature. However, heat exchange occurs to some extent, so the liquid hydrogen partially vaporizes. As a consequence, the pressure inside the tank increases over time up to a point where the maximum operating pressure is reached. At this point, the safety valves open to release some of the vaporized hydrogen. Hence, LH_2 is well-suited for applications with a constant fuel consumption to prevent hydrogen from being wasted.

Before LH_2 is consumed in an internal combustion engine or fuel cell, the LH_2 is vaporized. LH_2 requires relatively simple tanks for large amounts of hydrogen but needs the most complex release system (MariGreen, 2018). The Well-to-Wake (WtW) emissions from compressed and liquid hydrogen are comparable (Zemo, 2021).

Liquid organic hydrogen carrier

In a liquid organic hydrogen carrier (LOHC), no molecular hydrogen is present. The hydrogen is bonded to the carrier substance through the exothermic process of hydrogenation between 150 and 250°C. Before using the LOHC in a fuel cell or internal combustion engine, the LOHC must be dehydrogenated and converted to CH_2. Considerable effort is required to purify the hydrogen to reach the appropriate fuel quality for a fuel cell. The main advantage of LOHC is its high density compared to LH_2 and CH_2. Moreover, the existing diesel infrastructure can be reused for bunkering LOHC, although larger tanks are required and bunkering times need to be extended (MariGreen, 2018).

Metal hydrides

Hydrogen can be stored in metal hydrides through a chemical reaction between hydrogen and metallic molecules. Sodium borohydride ($NaBH_4$) is a metal hydride with a high gravimetric hydrogen storage capacity. This hydride is also safer to store at ambient conditions than CH_2 and LH_2. When the hydrogen has been separated again, the by-product $NaBO_2$ remains. It is costly and complex to recover $NaBH_4$ again from this by-product. Metal hydrides are not commercially produced yet on a large scale, and only little practical information is publicly available. Hence, metal hydrides are left out of the scope of this research.

Ammonia

Ammonia (NH_3) is a compound of nitrogen and hydrogen and has a higher volumetric energy density than hydrogen, which decreases the required storage space. Although the combustion of ammonia does not result in any CO_2 emissions, there are some nitrous oxide (N_2O) emissions, a more potent greenhouse gas. The production process of ammonia is considered not yet climate-neutral and neither is the engine technology commercially available (CCNR, 2020b). Furthermore, pure hydrogen is considered more cost-effective for the shipping sector in the long term (Hansson et al., 2020). For these reasons and to limit the scope of this study, ammonia has not been considered in the remainder of this thesis.

2.2.3 Hydrogen conversion technologies

Hydrogen can be converted into mechanical and electrical energy. An internal combustion engine (ICE) provides mechanical energy, whereas fuel cells produce electrical energy (MariGreen, 2018).

Internal Combustion Engine

Currently, most ships in the IWT sector are equipped with an ICE. Current ICEs can be adapted for hydrogen combustion for approximately 20% of the original engine price (MariGreen, 2018). NO_x emissions from hydrogen combustion are comparable to diesel combustion, but CO_2 and PM emissions are eliminated (CCNR, 2021a). Currently, hydrogen can be blended up to 65% in combustion engines, while in the future this expected to increase to 80%. ICEs have the advantage of being able to tolerate more hydrogen impurities than fuel cells (Yip et al., 2019). ICEs can be a direct drive or combined with a generator and electric motor (MariGreen, 2018). The latter is becoming more popular because diesel-electric drivetrains are easier to transition to zero-emission drivetrains, such as fuel cell systems (TNO, 2019; Panteia, 2019). Diesel-electric drivetrains are more expensive than conventional diesel-direct drivetrains, but on average, the fuel consumption is reduced by 2.6% (Panteia, 2019).

Fuel Cell

Fuel cells convert hydrogen to electricity and need to be combined with electric engines to produce the mechanical power needed for propulsion. As electric engines in ships require peak power for only a short time, the size of the fuel cell system can be minimized by storing the electricity in a buffer battery. The size of the battery and fuel cell system depend on a ship's load profile (MariGreen, 2018). Ships with homogeneous load profiles require only a small battery, whereas ships with strong power peaks require larger batteries. Whereas combustion engines' efficiency decreases when sailing at part-load, fuel cells show good part-load characteristics (MariGreen, 2018; Heid et al., 2021). Another benefit of hydrogen-powered fuel cell systems is the elimination of all NO_x, PM, and CO_2 emissions. Furthermore, fuel cells degrade rather than fail, increasing their reliability and availability (MariGreen, 2018). However, opposed to hydrogen that is combusted, hydrogen used in fuel cells should have a purity higher than 99.99 vol% (Dahlke-Wallet et al., 2020).

Fuel cell types relevant for maritime applications are the Proton Exchange Membrane Fuel Cell (PEMFC) and the Solid Oxide Fuel Cell (SOFC) (MariGreen, 2018). In this thesis, only low-temperature PEMFCs are considered because they are more reliable and characterized by fewer vibrations than high-temperature PEMFCs (MariGreen, 2018). PEMFCs have a tank-to-wheel efficiency of 50% (HHV) at average load of 37% (Heid et al., 2021). For simplicity reasons, tank-to-wheel are assumed similar to tank-to-wake efficiencies, which apply to ships. It is expected that PEMFCs will become 22% more efficient towards 2030 (TNO, 2019). Furthermore, PEMFCs tend to degrade 10% over their lifetime, which lowers the power supply (TNO, 2019).

The main benefit of SOFCs is their high tolerance towards impurities and other fuels, such as LNG and ammonia. However, these SOFCs are more expensive, have a lower power density, and a lower technology readiness level than PEMFCs (MariGreen, 2018). Although the use of pure hydrogen in SOFCs would be possible from a technical point of view, no SOFCs suited for pure hydrogen are available yet (Prat & Klebanoff, 2016). Hence, SOFCs are excluded for the remainder of this thesis.

2.2.4 Selection of technologies

In Table 5, the energy carriers and conversion technologies are evaluated based on the assessment of MariGreen (2018). The scoring ranges from fully disadvantageous to fully advantageous, indicated by [–] and [++], respectively. [n/a] indicates that the selection criterion is not relevant for comparison.

The table shows that CH_2 scores better on most selection criteria for all vessel types, except for range. Only cargo vessels that cover longer distances would preferably require a denser fuel to decrease the storage tank size (MariGreen, 2018). LH_2 is denser but has quite some downsides relative to CH_2, considering reliability, ease of bunkering, and costs. The main benefit of LOHC is the possibility of reusing existing infrastructure and short bunkering times. However, the use of LOHC is a costly and complex process. When assigning equal weight to each criterion, CH_2 can be considered the most promising energy carrier in most cases. The costs, often assigned a higher weight, are also most advantageous for CH_2.

Furthermore, ICEs display lower scores on emissions and vibrations but higher scores on costs and complexity of the applications. However, future cost reductions in the production of fuel cells and changing regulations could lead to an enhanced proposition for fuel cells.

Table 5: Assessment of energy carriers and energy conversion technologies

	CH_2	**LH_2**	**LOHC**	**ICE**	**ICE GENSET**	**LT-PEMFC**
Noise and vibrations	++	+	+	−−	−	++
Emissions	o	o	o	−−	−−	++
Range	−	+	+	n/a	n/a	n/a
Reliability	++	o	−	++	+	o
Ease of bunkering	+	o	++	n/a	n/a	n/a
Costs	+	o	−	++	+	−
Complexity of application	o	o	−	++	+	−

In Table 6, the assessment of hydrogen applications is presented. It stands out that PEMFCs only show promising results in combination with CH_2. PEMFC cannot provide the temperatures required for dehydrating the LOHC and evaporating LH_2. Generating additional heat only to dehydrate and evaporate is highly inefficient (MariGreen, 2018). Next, CH_2 is preferred in ICEs because no additional compression is needed to meet the required inlet pressure of converters (MariGreen, 2018). Combustion engines require higher inlet pressures than fuel cells and can benefit in particular from CH_2 (MariGreen, 2018).

Table 6: Hydrogen application assessment

	CH_2	**LH_2**	**LOHC**
ICE	++	+	+
ICE GENSET	++	+	+
LT-PEMFC	+	o	−

In conclusion, CH_2 has clear benefits over LH_2 and LOHC. ICEs score better on costs but worse on emissions, while LT-PEMFCs score better on emissions but worse on costs, two critical criteria in the energy transition. Given these considerations, only compressed gaseous hydrogen in an ICE and a LT-PEMFC are studied as hydrogen applications in the remainder of this thesis. Henceforth, LT-PEMFC will be referred as fuel cells. In addition, a diesel-direct combustion engine complying with Stage-V standards is studied as an alternative. Diesel-electric engines are becoming more popular (Panteia, 2019) but have a negligible direct effect on emission reductions. Hence, diesel-electric engines are excluded in this thesis.

2.3 Technical requirements for hydrogen use

Hydrogen must be produced and distributed to bunkering stations before it can be used aboard ships. In this section, the hydrogen production techniques, the future hydrogen supply, and the production locations are described. Next, the various distribution methods are outlined, followed by a description of the bunkering process. Finally, the ship requirements for hydrogen use are explained, which include a storage tank and hydrogen-powered drivetrain.

2.3.1 Production

Types of hydrogen
Currently, 80% of grey hydrogen in the Netherlands is produced through steam methane reforming (SMR), and the remaining 20% is produced as a by-product in the chemical industry (CE Delft, 2018b). Steam reforming is a method for producing syngas by an endothermic reaction of hydrocarbons (natural gas) and water (steam). In this process, the heat for the reaction must be supplied by an external source. After the syngas has been produced, the hydrogen is separated from the syngas (Simpson and Lutz, 2007). The SMR process emits about 9.5 $[\mathrm{kg}_{\mathrm{CO2}}/\mathrm{kg}_{\mathrm{H2}}]$ when using natural gas (IRENA, 2019). In the exemplary case of CE Delft (2018b) the exit pressure of hydrogen produced through SMR is 25 bar. Hydrogen produced through SMR is labeled as grey hydrogen.

In some SMR processes, a fraction of the emitted CO_2 is captured and stored. The hydrogen from these processes is labeled as blue hydrogen. Current SMR installations that apply carbon capture and storage (CCS) technology only manage to capture about half of CO_2 emissions, still emitting 4.75 $[\mathrm{kg}_{\mathrm{CO2}}/\mathrm{kg}_{\mathrm{H2}}]$ (IRENA, 2019). However, CCS technology can capture up to 90% of the CO_2 emission, corresponding to 0.95 kg $[\mathrm{kg}_{\mathrm{CO2}}/\mathrm{kg}_{\mathrm{H2}}]$ (CE Delft, 2018a; IRENA, 2019). It is assumed that this capture rate is reached in 2030. The captured CO_2 is transported to storage sites (e.g., empty gas fields) or production sites (e.g., greenhouses) where it is used.

Green hydrogen is produced using renewable resources and the production is associated with negligible amounts of CO_2 emissions. Green hydrogen is often produced through electrolysis, where water is split into hydrogen and oxygen by an electric current (Dincer & Acar, 2015). Hydrogen can be produced in alkaline electrolyzers or proton exchange membrane (PEM) electrolyzers (CE Delft, 2018b). Nowadays, production through alkaline electrolyzers is cheaper and used to produce large volumes of hydrogen. However, PEM electrolyzers can be operated more flexibly and perform better at partial load. PEM electrolyzers costs are expected to drop to levels slightly higher than alkaline electrolyzers costs (CE Delft, 2018b). The electricity used in electrolysis must be produced from renewable resources to label the hydrogen as green hydrogen. Furthermore, when considering the entire lifecycle of hydrogen production, emissions from the production of wind turbines must also be considered, such as done by Spath & Mann (2004). However, these emissions are left out of the scope of this thesis. In general, green hydrogen is the final goal but grey and blue hydrogen can function as steppingstones. Once hydrogen has been produced by either one of the above-mentioned processes, it must be compressed for storage or further distribution.

Production development

The current and future production sources of hydrogen are presented in Table 7. The table indicates that all hydrogen produced is labeled as grey at the moment. In 2030, the green, blue, and grey hydrogen shares are 19%, 35%, 46%, respectively. In 2050, all hydrogen is assumed green because green hydrogen production costs are expected to drop below the blue hydrogen production costs before 2050. The hydrogen demand in the entire Dutch transport sector is expected to rise from practically zero to 20 PJ in 2030 (Gasunie, 2019a) and further to 87 PJ in 2050 (CE Delft, 2018b). This implies that 7% and 20% of hydrogen in the Netherlands would be consumed in the transport sector in 2030 and 2050, respectively. It is assumed that grey hydrogen will only be used for existing hydrogen applications, such as fertilizer production. Hence, only blue and green hydrogen are considered for the IWT sector. Note that the predictions represented in Table 7 are subject to uncertainty and based on assumptions. For instance, the Port of Rotterdam predicts 18 Mton of green hydrogen is entering the port in 2050. This would correspond to much higher estimates for hydrogen demand in 2050.

Table 7: Current and expected future hydrogen production in the Netherlands[1]

	2019	**2030**	**2050**
Green hydrogen (PJ)	~ 0	54	178
Blue or imported green hydrogen (PJ)[2]	~ 0	100	194
Hydrogen from excess electricity(PJ)[3]	~ 0	n/a	72
Grey hydrogen (PJ)	175	130	~ 0
Total hydrogen	175	284	444

1) 2019: based on Gasunie (2018), CE Delft (2018b) and Gasunie (2019a), 2030: based on Gasunie (2019a), 2050: based on Gasunie (2018).

2) This is either imported (blue/green) or produced from natural gas with CCS (blue). In 2030, assumed blue. In 2050, assumed green.

3) Assumed green electricity and hence green hydrogen.

Production locations

Currently, there are 5 locations in the Netherlands that produce large amounts of hydrogen, as depicted in Figure 1 (TNO, 2020). These production facilities are often chemical plants located directly next to waterways (MariGreen, 2018).

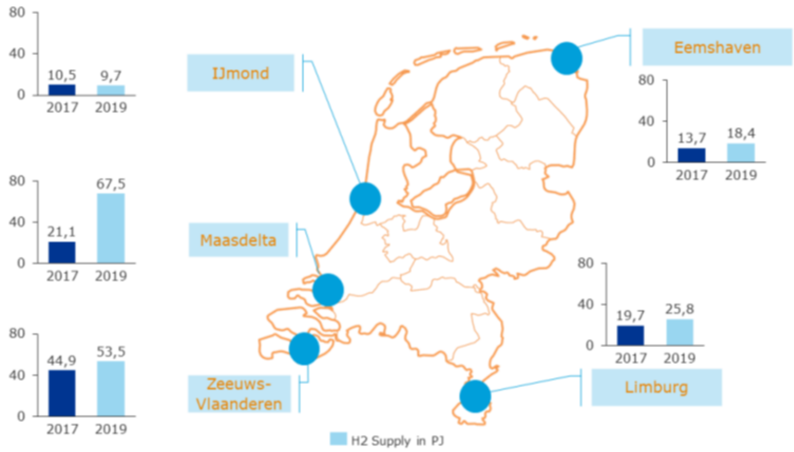


Figure 1: Hydrogen production locations in the Netherlands in 2019 (TNO, 2020)

Nowadays, almost all hydrogen is produced onshore but some hydrogen will be produced at sea in the future. As the energy transition progresses, more offshore wind energy is produced further asea. At some point, it may become more cost-effective to convert the electricity directly into hydrogen at sea and transport the hydrogen through pipelines to shore (TNO, 2020). In 2050, at least 37% of the green hydrogen production will occur offshore (North Sea Energy, 2020a).

The electrolysis process onshore can take place at centralized or decentralized locations. At centralized locations, it is easier to achieve economies of scale. However, decentralized strategic locations can facilitate the incorporation of variable wind and solar supply in the grid, which reduces investments in expanding the electricity grid (TNO, 2020). Ideally, the hydrogen is used directly at these production locations (TNO, 2020). For instance, a production location is planned in the Zuiderzeehaven in Kampen (Netherlands), which obliviates the need for further distribution (Hysolar, 2021).

2.3.2 Distribution

Distribution to ship

The hydrogen that is produced at a central location must be transported to its end user. Hydrogen is most commonly transported in gaseous or liquid form. Hydrogen is produced at low pressures (20–30 bar) and compressed before transport in gaseous form (Energy.gov, 2021). When using trucks for transport, hydrogen is stored in tubes at pressures between 200 and 500 bars. Alternatively, hydrogen can be transported through 20-48 inch pipelines at 30-80 bar (Jens et al., 2021). However, pressures can vary based on conditions like the temperature and the diameter of the pipes. Within the transport sector, hydrogen is currently transported in gaseous form using tube trailers (Deloitte, 2020). Yet, a strong shift towards 80% and 90% pipeline transport is expected in 2030 and in 2050, respectively (Deloitte, 2020).

When transporting in liquid form (LH_2), the gaseous hydrogen must be liquefied by cooling the hydrogen to a point below -253°. The liquefaction is relatively energy intensive. About 20–35% of hydrogen's energy content in relation to its lower calorific value is required for this, while only 10% is required for compression to 700 bar (MariGreen, 2018). The liquid hydrogen has a density of 70.8 [kg/m^3], which allows transporting about 3500 kg liquid hydrogen in a 50m^3 tank (Hydrogen Europe, 2017). Liquid hydrogen is mainly transported by truck, but trains and ships are potential alternatives (MariGreen, 2018). When using these modes of transport, emissions from the transport itself must be minimized. On-site production or central production combined with transportation through pipelines avoid these potential emissions and are therefore preferred (MariGreen, 2018).

Nowadays, hydrogen is supplied by trucks to smaller markets (e.g., automotive). The existing pipelines from the production sites are only connected to large existent customers, such as fertilizer producers (MariGreen, 2018). However, it is expected that the hydrogen infrastructure continues to expand due to the increasing use of hydrogen in passenger cars (MariGreen, 2018). Gasunie has offered to develop a dedicated hydrogen infrastructure by 2026, which connects the industrial clusters in the Netherlands and backbones of neighboring countries, as depicted in Figure 2 based on the European Backbone study (Jens et al., 2021). Towards 2050, the capacity of pipelines is increased, and more pipelines are added to the infrastructure (Gasunie & Tennet, 2019).

Figure 2: Planned hydrogen pipeline connections for 2026 in the Netherlands (Jens et al., 2021)

The backbone planned for 2026 overlaps with the main harbors in the Netherlands. For instance, seaports of Rotterdam, Terneuzen, and Amsterdam are covered by the backbone as well as the Nijmegen area, including large harbors in Cuijk, Gennep, and Oss. In Appendix B, the large harbors are mapped, and the backbone overlap is visualized.

Bunkering process

Nowadays, the prevalent bunkering method is ship-to-ship, where bunker vessels come alongside IWT vessels. This often happens while IWT vessels are being loaded or unloaded (MariGreen, 2018). On average, IWT ships bunker only once a week and have fuel tanks that can store volumes between 15 and 50m^3 (MariGreen, 2018). IWT operators often have individual arrangements with these bunker vessels. In this thesis, hydrogen is assumed to be transported by truck or pipeline, so only shore-to-ship and truck-to-ship bunkering apply.

Truck-to-ship bunkering is nowadays most common with LNG vessels and ferries (MariGreen, 2018). Shore-to-ship bunkering is most apparent when hydrogen is delivered through pipelines. In this method, a storage tank is often required in the harbor to store the hydrogen temporarily. At 25°C, a 40 ft. container could store 758 and 1082 kg hydrogen at 350 and 500 bar, respectively (TNO, 2019).

Fast bunkering is critical for push boats as they often drop off barges and are immediately combined with new barges (MariGreen, 2018). Bunkering times for ferries are non-critical because diesel trucks can drive onto the ferry and refuel while normal operations on the ferry continue (MariGreen, 2018). Cargo vessels usually bunker while the freight is being unloaded. Unloading/loading 104 containers takes about 8 hours (Konings, 2009).

Dispensers used for cars display filling rates of 0.65 [kg/minute] in 2020 and 2 [kg/minute] in 2050, which corresponds to a total bunkering time of 6-20 hours for a 1000kg hydrogen storage tank (Oldenbroek et al., 2017). In addition, the coupling of dispensers takes about 45 minutes (TNO, 2019). Such long bunkering times are problematic because most ships must wait for the bunkering to finish. Portable storage containers can be used to decrease bunkering times. Here, empty containers could be replaced by hydrogen-filled containers that are lifted onto the ship. While the ship is in motion, the hydrogen is pumped into the fixed tank unit that is connected to the drive train (MariGreen, 2018). This option is taken as a basis in this thesis.

2.3.3 Application

2.3.3.1 Onboard storage

The portable storage tank considered in this thesis is the high cube container developed by EMS (MariGreen, 2018). This 40 ft. container consists of 162 composite vessels and can store up to 1021 kg of hydrogen at 500 bar. The total weight of the entire container is about 27.500 kg. Such a container is perfectly suited for retrofitting container ships because the storage tank can easily be installed. When storing CH_2 on a ship, a vent mast is required to release hydrogen from the pressure relief valves. When placing this vent mast, the limited air draft at sailing routes must be considered. The specific requirements for onboard storage are listed by IMO (2013).

Figure 3: Portable storage container developed by EMS (MariGreen, 2018)

The required size of the storage tank depends on the average power demand, tank-to-wake efficiency, and average distance that must be covered using the hydrogen content in a single tank, as described in Appendix C.

2.3.3.2 Drivetrain

Diesel-powered combustion engine

New diesel-powered combustion engines must comply with the Stage-V emissions standards described in Table 4. These new diesel-powered combustion engines are often equipped with a Selective Catalytic Reduction (SCR) catalyst and a Diesel Particle Filter (DPF). SCR can reduce NO_x emissions up to 90% (STT Emtec, 2021b), while DPFs can reduce PM emissions by over 90% (STT Emtec, 2021a).

Hydrogen-powered combustion engine

The following changes in combustion engine components must be realized to make a conventional engine fit for hydrogen combustion (MariGreen, 2018):

- Injection System
- Turbocharger and intercooler
- Ignition system
- Lubrication system
- Cooling system
- Valvetrain
- Compression ratio
- Crankcase ventilation

The former three components are necessary for the proper functioning of the combustion engine, while the latter components are necessary to minimize emissions from hydrogen combustion. Hydrogen can be directly injected into the combustion chamber or mixed with air outside the combustion chamber before being injected. The latter option is technically less demanding and is more suitable for retrofitting conventional combustion engines. However, this option is associated with a higher risk of backfire and reduced achievable engine power (MariGreen, 2018). To obtain similar power output, hydrogen can potentially be blended with diesel up to 80%. Otherwise higher engine power needs to be installed, which is expensive and cumbersome. An 80% blending of hydrogen is assumed possible in 2050.

When combusting hydrogen, CO_2 and PM emissions are eliminated for the hydrogen blending share in the fuel mix. However, NO_x emissions are only slightly lower relative to diesel combustion (MariGreen, 2018). In 2001, complete combustion of hydrogen resulted in 9 [g/kWh] NO_x emissions (Energy.gov, 2001). According to Table 4, NO_x emissions from diesel-powered combustion engines were slightly higher than 9 [g/kWh]. Given these comparable emissions, an SCR catalyst needs to be installed to comply with new Stage-V emissions standards. However, this only applies when a new hydrogen combustion engine is installed.

Hydrogen-powered fuel cell

At the heart of the fuel cell system is the fuel cell stack. Other components are a fuel processor and air compressors, for instance. Fifty percent of the system costs can be allocated to the fuel cell stack, while the other 50% can be allocated to the remaining components (expert consultation). A fuel cell system must be combined with an electric engine. Fuel cell must be placed in a room that controls and signals potential hydrogen leakage (MariGreen, 2018). IMO (2013) specifies further requirements for safe machinery spaces. Using hydrogen in fuel cells allows to eliminate all emissions.

3 Methods

The method section describes why and how the hydrogen transition model has been constructed and which assumptions underlie the model. First, the relevance of creating energy systems models is justified. Second, the formulas and input values for the total cost of ownership calculations have been described. Afterwards, the setup and the underlying model assumptions are elaborated upon. Finally, the method for performing a sensitivity analysis is described.

3.1 Energy systems modeling

Energy system models can be created to gain insight into hydrogen transition dynamics and energy policy effectiveness (Pfenninger et al., 2014). An energy system can be defined as the process chain from the extraction of primary energy to the use of final energy (Pfenninger et al., 2014). An energy system model allows modeling the potential influence of selected factors on the adoption of hydrogen technologies and realization of predefined goals (McDowall, 2014). Energy systems models allow policymakers to state informed views on the direction that the energy transition should be steered towards to fulfill policy goals (Pfenninger et al., 2014). Possible future scenarios can be developed that incorporate policy instruments to realize these policy goals (Pfenninger et al., 2014).

Within the energy system, this thesis focuses on the use of final energy in the IWT sector. The extraction and distribution of primary energy are considered non-constraining for the final energy demand. Many energy system modeling studies research the transition in the broader economic system, which results in a simplistic representation of sectoral technology and cost dynamics (McDowall, 2014). Hence, this thesis focuses explicitly on the IWT sector and models the decision-making process for IWT operators. The model assumes that economic criteria are decisive in the decision-making process because IWT operators ascribe higher value to economic criteria than environmental and social criteria (Hansson et al., 2020). Fuel costs are considered the most important economic criterion, followed by investment cost.

In the model, cost reductions are incorporated that are determined exogenously and insensitive to the future deployment of technologies in the IWT sector, as recommended by Anandarajah et al. (2013) and McDowall (2014). Future cost estimates are always uncertain, and hence energy system models are not used to predict the future but to understand how decision-making dynamics are influenced by different circumstances (Hansson et al., 2020).

To provide a brief overview about the model's setup in this thesis, a simplified flowchart in Fig. 4 has been constructed. It shows that existing ships install a hydrogen-powered drivetrain in the replacement year whenever this is cheaper than installing a new diesel-powered combustion engine. In this case, the total cost of ownership (TCO) is calculated over a fixed period. The replacement year could be brought forward when the TCO of a new drivetrain is lower than the TCO of the installed engine in a certain year before the replacement year. In this case the TCO is calculated over the installed engine's remaining lifetime. Ships that are commissioned in the period 2021-2050 install a drivetrain system with the lowest TCO. Ships that are scrapped in the near future replace their engine when this is financially beneficial. After the decision-making process has been simulated, the effects on emissions and the hydrogen demand are calculated. Finally, the effect of policy measures on the hydrogen demand and emissions is evaluated by repeating stage 1 and stage 2 with adjusted settings. Note that the flowchart is a simplification of the model. The dynamics in the model are further elaborated upon in the remainder of this chapter.

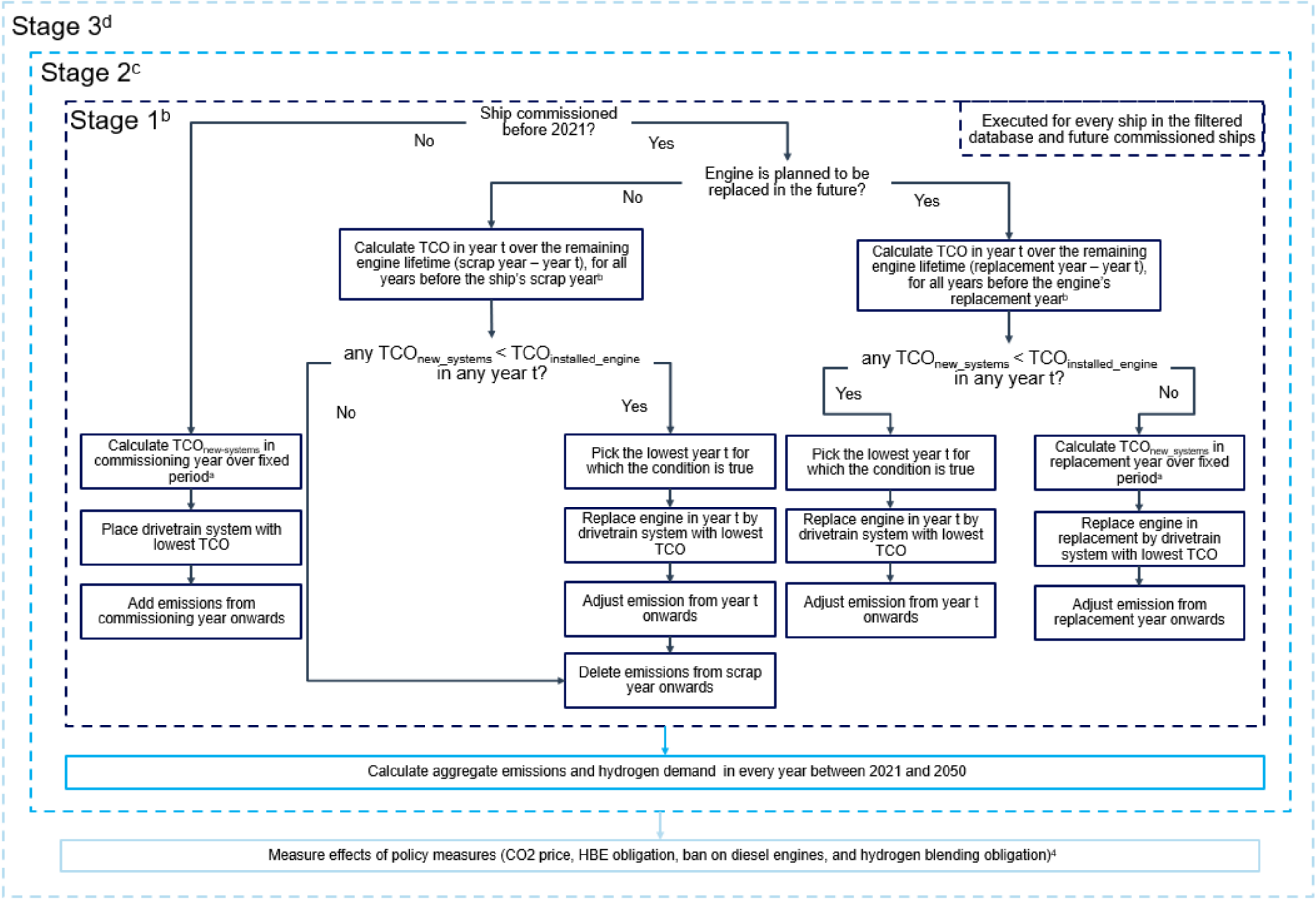


Figure 4: Simplified flowchart of the transition model

[a] Discussed in detail in section 3.2

[b] Discussed in detail in section 3.3.1

[c] Discussed in detail in section 3.3.2

[d] Discussed in detail in section 3.3.3

3.2 Total cost of ownership (TCO)

3.2.1 Formulas TCO

This thesis models the decision-making process of IWT operators from an economic perspective. IWT operators install a new drivetrain based on the total costs of ownership [€] (TCO). TCO comprise the capital costs [€] plus the cost of operation, which include operational maintenance cost [€] and costs of fuel [€] (see Eq.3.1). Since the lifetime of different system components varies, the TCO must be calculated over a fixed period (K). This allows for TCO comparison between different systems. In addition, TCO calculations over a longer period allows to take into account future hydrogen cost reductions when comparing diesel- and hydrogen powered drivetrains. The start of this fixed period is called t=0 and refers to the (potential) replacement year of the engine. The TCO are calculated for three drivetrain systems for every ship in the Dutch fleet, where:

s = drivetrain system (Diesel-ICE, H2-ICE and H2-FC)
i = component of drivetrain system (s) (Table 8)
j = ship
t = year, where t=0 refers to the year when decision-making takes place

$$TCO_{\mathrm{sj}} = \sum_{t=0}^{K} CC_{\mathrm{sjt}} + OMC_{\mathrm{sjt}} + CF_{\mathrm{sjt}} \tag{3.1}$$

Where:

TCO = Total Cost of Ownership [€]
CC = Capital Cost [€] (Eq. 3.2)
OMC = Operational Maintenance Cost [€] (Eq. 3.4)
CF = Cost of Fuel [€] (Eq. 3.5)

Capital Cost

The CC depend on multiple parameters (Eq. 3.2). First, the investment cost [€/component specific capacity] (IC) of the different system (s) components (i). The investment costs could reduce over time, and so the investment is based on the investment cost in the first year of the TCO calculation (t=0). Second, the required quantity [specific component capacity] (Q) of a certain system component (si) depends on the ship characteristics (j) and the (potential) replacement year (t=0). In addition, the installation cost [€] (I) are added, which depend on the system (s) that is installed and the (potential) replacement year of the engine.

The capital recovery factor [%] (CRF) is the ratio of a constant annuity from the present value of the total depreciation costs over a certain period. Hence, the CRF allows to obtain annual depreciation costs that consider the weighted average cost of capital (WACC), which is explained below. The CRF that is used to calculate the annuity for system components is based on the component lifetime. The CRF that is used to calculate the annuity for the installation costs is based on the drivetrain lifetime.

$$CC_{\mathrm{sjt}} = CRF_{\mathrm{s(t=0)}} \times I_{\mathrm{s(t=0)}} + \sum_{si}^{N} CRF_{\mathrm{si(t=0)}} \times Q_{\mathrm{sij(t=0)}} \times IC_{\mathrm{si(t=0)}} \tag{3.2}$$

Where:

CC = Capital Cost [€]
CRF = Capital Recovery Factor [%] (Eq. 3.3)
Q = Quantity [specific component capacity] (Eq. 3.6 and 3.7)
IC = Investment Cost [€/specific component capacity] (Table 8)
I = Installation Cost [€] (Table 9)
N = Number of system components

The CRF is calculated according to Eq. 3.3 and considers the economic lifetime (LT) of system components (si) and a discount rate, which is set to the weighted average cost of capital [%] (WACC). In the WACC, both the cost of debt and the cost of equity are weighted.

For instance, an investment of €1000 is depreciated over 10 years with a discount rate of 10%. The CRF is 0.163, which means that every year a constant annuity of €163 is depreciated. The net present value of 10 annuities equals the initial investment of €1000.

An exception is made in these calculations for the installation costs, which are depreciated over the economic lifetime of a system. The economic lifetime of a system is set equal to the drivetrain lifetime.

$$CRF_{\mathrm{si(t=0)}} = WACC_{\mathrm{s(t=0)}} \times \frac{(1 + WACC_{\mathrm{s(t=0)}})^{\mathrm{LT}_{\mathrm{si(t=0)}}}}{(1 + WACC_{\mathrm{s(t=0)}})^{\mathrm{LT}_{\mathrm{si(t=0)}}} - 1} \tag{3.3}$$

Where:

CRF = Capital Recovery Factor [%]
$WACC$ = Weighted Average Cost of Capital [%] (Table 9)
LT = Economic Lifetime [years] (Table 8)

Operational Maintenance Cost

The OMC for a system is expressed as an annual percentage (OM) of Q and IC. The net present value of all components' future maintenance cost is calculated using a discount rate (r) that is set equal to the inflation rate.

$$OMC_{\mathrm{sjt}} = \sum_{si}^{N} OM_{\mathrm{sit}} \times Q_{\mathrm{sij(t=0)}} \times IC_{\mathrm{si(t=0)}} \times \frac{1}{(1+r)^{\mathrm{t}}} \tag{3.4}$$

Where:

OM = Operational Maintenance (Table 8)
Q = Quantity [specific component capacity] (Eq. 3.6 and 3.7)
IC = Investment Cost [€/specific component capacity] (Table 8)
r = Discount rate [%] (Table 9)
N = Number of system components

Cost of Fuel

The Cost of Fuel (CF) depends on the fuel price [€/kWh] (FP), which is affected by the type of fuel required in the system (s) and cost reductions over the years (t). Furthermore, the fuel cost depend on the ship's fuel consumption [kWh] (FCO), which is affected by the ship's power requirement (j) and the system's drivetrain efficiency in the installation year (t=0). The net present value of future fuel cost is calculated over the fixed period (K), using a discount rate (r) set equal to the inflation rate. In the future, levies on fossil fuels are potentially added to the cost of fuel, which is explained in section 3.3.3.

$$CF_{\mathrm{sjt}} = FP_{\mathrm{st}} \times FCO_{\mathrm{sj(t=0)}} \times \frac{1}{(1+r)^{t}} \tag{3.5}$$

Where:

CF = Cost of Fuel [€]
FP = Fuel Price [€/kWh] (Fig. 5)
FCO = Fuel Consumption [kWh/year] (Eq. 3.9)
r = Discount rate [%] (Table 9)
K = Fixed period [years] (Table 9)

3.2.2 Input values TCO

3.2.2.1 Capital and maintenance values

The input variables IC, OM, and LT for the system components (si) in the replacement year (t) have been listed in Table 8 for 2020 and 2050. It is assumed that cost reductions between 2020 and 2050 occur linearly.

Table 8: Investment cost (IC), Operational maintenance (OM), Economic lifetime (LT) and Efficiency (η) of system (s) components (i) in 2020 and 2050

			2020				2050			
s***	i	Component	IC	OM	LT	η	IC	OM	LT	η
0	0	**Diesel Stage-V combustion engine**	500 [€/kW]	10%	50.000 [hours]*	33%	500 [€/kW]	10%	50.000 [hours]*	33%
1	0	**H_2 Stage-V combustion engine**	425 [€/kW]	10%	50.000 [hours]*	35%	425 [€/kW]	10%	50.000 [hours]*	35%
1	1	**H_2 storage tank**	540 [€/kg]	1%	30 [years]	-	270 [€/kg]	1%	30 [years]	-
2	0	**Fuel cell system (excl. stack)**	840 [€/kW]	5%	70.000 [hours]*	50%	420 [€/kW]	5%	70.000 [hours]*	61%
2	1	**Fuel cell stack**	840 [€/kW]	5%	25.000 [hours]*	**	420 [€/kW]	5%	40.000 [hours]*	**
2	2	**Electric engine**	59 [€/kW]	5%	30 [years]	**	59 [€/kW]	5%	30 [years]	**
2	3	**H_2 storage tank**	540 [€/kg]	1%	30 [years]	-	270 [€/kg]	1%	30 [years]	-

* Economic lifetime in years calculated for each ship based on effective operational hours, as specified in Table 3.
** Incorporated in the Tank-To-Wake (TTW) efficiency of the fuel cell system.
*** s=0,1,2 corresponds to drivetrain system Diesel-ICE, H2-ICE, and H2-FC, respectively.

Diesel Stage-V combustion engine

According to CCNR (2020b), the investment costs for a Stage-V engine running on conventional diesel are 500 [€/kW]. These are assumed to remain constant towards 2050 and include the investment in Selective Catalytic Reduction (SCR) catalyst of 100 [€/kW] to reduce NO_x emissions and a Diesel Particulate Filter (DPF) of 100 [€/kW] to reduce PM emissions (CCNR, 2020b; TNO, 2019). The maintenance cost are estimated at 10% in 2020 and 2050, which includes AdBlue® consumption necessary for the chemical reaction in the SCR catalyst (CCNR, 2020b). Combustion engines are characterized by a lot of moving parts, which require relatively much maintenance. The lifetime of a combustion engine depends on its rounds per minute (RPM). The average RPM of 1700 in the database is taken as a basis. Combustion engines (>1250 RPM) can operate for 50.000 hours until revision (EICB, 2015). However, given future developments the revision of a combustion engine is assumed to be non-profitable, so 50.000 hours is used as a basis for the entire engine lifetime. Finally, the efficiency (HHV) of diesel-powered combustion engines at average load (37%) is approximately 33% (Heid et al., 2021).

Hydrogen Stage-V combustion engine

According to MariGreen (2018), the minimal necessary modifications to make a conventional combustion engine fit for hydrogen combustion require an investment of about 20% of regular diesel engine cost. A regular diesel engine is about 270 [€/kW], which means a hydrogen combustion engines will cost 325 [€/kW] (MariGreen, 2018). However, an SCR catalyst of 100 [€/kW] must be included to minimize NOx emissions and make the engine Stage-V compliant. Therefore, a total investment of about 425 [€/kW] is assumed, which remains constant towards 2050. The efficiency (HHV) of hydrogen combustion engines is 35% at average load, which assumes diesel is still combusted to a certain extent (Heid et al., 2021). The maintenance cost and economic lifetime are similar to diesel Stage-V combustion engines.

Fuel cell system

At the heart of the fuel cell system is the fuel cell stack. Other components are a fuel processor and air compressors, for instance. Fuel cell systems for ships are significantly more expensive than for cars due to higher durability requirements. Current and targeted fuel cell system lifetimes in cars are 5000 and 8000 hours for 2020 and 2050, respectively (Whiston et al., 2019), while lifetimes are already 70.000 hours for fuel cell systems in ships (expert consultation). To extend the lifetime of a fuel cells, high quality and more expensive materials are required. The fuel cell system cost for ships is 1675 [€/kW] in 2020 (IEA, 2019a). Reports of CCNR (2020b), TNO (2019) MariGreen (2018) and fuel cell manufacturers mention fuel cell system costs in the same order of magnitude. Manufacturers claim that the sale price is even lower than the production costs, which are currently about 2500 [€/kW] (expert consultation).

Furthermore, high costs are associated with research and development (R&D) and certification of fuel cells to meet high quality and safety standards required for the operation of fuel cells under tough and wet conditions (expert consultation). Manufacturers claim that the design of fuel cells for the IWT sector is significantly different from fuel cells used in the automotive sector and therefore separate production lines are required. As the total fuel cell sales are lower than in the automotive industry, the R&D and certification costs must be allocated among a smaller number of users (expert consultation). The extended lifetime, lower production volumes and higher quality standards explain the price difference between fuel cells in cars and ships.

In this research, fuel cell system costs are assumed to be 1675 [€/kW] in 2019 and drop to 840 [€/kW] in the long term, which is assumed to be 2050 (IEA, 2019a; CCNR, 2020b; expert consultation). However, some other experts claim higher learning rates of 30% can be expected for fuel cells comparable to battery and solar cell technology. In addition, these experts claim that fuel cells produced for cars and trucks can also be used in ships, which would bring similar economies of scale. Van Biert et al. (2021) claim that low-temperature fuel cells for heavy-duty applications fall from 1750 [€/kW], on average in 2020, to 600 and 80 [€/kW] in 2030 and 2050, respectively. To evaluate the effect of lower fuel cell prices, these alternative prices for fuel cell systems are also modeled and assessed.

Fifty percent of the fuel cell system costs can be allocated to the fuel cell stack. The remaining 50% of the system costs belong to the other components (expert consultation). The maintenance percentage for a fuel cell system in fuel cell electric vehicles (FCEV) is 5% in both 2020 and 2050 (Oldenbroek et al., 2017). The maintenance cost for fuel cells in ships is assumed similar to the maintenance cost of FCEV (expert consultation). The economic lifetime of fuel cell stacks is currently 25.000 hours according to CCNR (2020b) and manufacturers. This increases to 40.000 hours towards 2030 and remains constant afterwards (expert consultation). Beyond 40.000 hours the additional investment in high-quality materials is not expected to offset the additional lifetime (expert consultation). The economic lifetime of the remaining components in the fuel cell system is 70.000 hours (expert consultation). It is assumed that the lifetime of the remaining components (e.g. fuel processor and air compressors) has already been optimized and therefore additional investments in high-quality materials do not offset the additional lifetime gains.

The tank-to-wheel efficiency in FCEV is 50% (HHV) at average load of 37% (Heid et al., 2021). Tank-to-wheel efficiency is assumed equal to the tank-to-wake efficiency as both ships and cars operate in part-load most of the time. The tank-to-wake efficiency is assumed to increase 22% towards 2030 (TNO, 2019) and remains constant towards 2050. Efficiency improvements can be accomplished through the reuse of waste hate, for instance (expert consultation).

Electric engine

The cost of an electric propulsion engine for ships is 59 [€/kW] in 2019, which remains constant towards 2050 (IEA, 2019a). The maintenance percentage of the electric engine is similar to the maintenance percentage of the fuel cell system (Oldenbroek et al., 2017). The economic lifetime of an exemplary electric engine is 30 years (STADT, 2019), which is assumed to remain constant towards 2050. The efficiency of the electric engine is already included in the tank-to-wake efficiency specified for the fuel cell system.

H_2 storage tank

Currently, 40 ft portable storage containers with a maximum pressure of 300 bar can store 740kg. These containers are sold for €400.000, which corresponds to 540 [€/kg] (expert consultation). A reduction in storage cost of 50% is expected towards 2050 (IEA, 2019; Adams, 2020; Oldenbroek et al., 2017). Oldenbroek et al. (2017) assume a lifetime of 30 years and 1% maintenance for high-pressure storage. This is also taken as a basis for portable containers used on ships.

The portable storage containers for ships are often rented, so future cost reductions are considered when calculating the investment costs at the start (t=0) of the fixed period (K). This is done by taking the average investment cost of a storage tank over the fixed period. For instance, when calculating the TCO for 2030, the average investment cost of 450 [€/kg] in 2030 and 270 [€/kg] in 2050 is taken, which equals (450 + 270) 360 [€/kg].

Weighted average cost of capital (WACC)

The cost of capital study performed by Castedello and Schöniger (2018) suggests a 6% WACC for the transport sector, which is assumed for investments in diesel combustion engines (Table 9). However, a higher WACC is often used for hydrogen investments due to higher technology risks. Therefore, the WACC for hydrogen is set to 8%, similar to the studies of IEA (2019b) and FCH (2019). It is assumed that the WACC for hydrogen investments reduces to 6% towards 2050, because the technology risk diminishes over time.

Discount rate

A discount rate of 1.5% is used, equal to the average inflation rate over the last 5 years in the Netherlands (CBS, 2021c).

Installation cost

Installation costs include labor and procedural costs related to the certification, testing and installation of the drivetrain and storage tank. In addition, any costs for modifications to the ship that are required are included, such as new wiring and piping.

The installation cost for a diesel-powered combustion engine is €20.000, while for installing a hydrogen-powered combustion engine this is €50.000 (CCNR, 2020b). In the case of a hydrogen-powered combustion engine, the certification and testing costs are higher to comply with safety standards. In addition, a hydrogen storage tank must be installed and connected to the combustion engine. The cost for installing a fuel cell system are €100.000 in 2020 (expert consultation). Here, an electric drive and fuel cell system must be installed, which is associated with high costs. Towards 2050, the installation costs for hydrogen-powered drivetrains are expected to equal installation costs for diesel-powered drivetrains due to experience gained and smoother certification and testing procedures (expert consultation).

Table 9: WACC, discount rate (r) and Installation cost (I) used for TCO calculations

	2020	**2050**
$\text{WACC}_{\text{diesel}}$	6%	6%
WACC_{H2}	8%	6%
r	1.5%	1.5%
$\text{I}_{\text{Diesel-ICE}}$	€20.000	€20.000
$\text{I}_{\text{H2-ICE}}$	€50.000	€20.000
$\text{I}_{\text{H2-FC}}$	€100.000	€20.000

3.2.2.2 Fuel values

Diesel price

The diesel price has been fluctuating over the last decade. Therefore, the diesel price in the Dutch IWT sector in 2021 is assumed to equal the average price between 2010 and 2020. This average price is 1.16 [€/l], including excise duties and excluding value-added taxes (VAT) (Efofenedex, 2020). IWT operators often have contracts with fuel suppliers and purchase large amounts of diesel. For instance, members sector associations can jointly purchase diesel for a price that is 15% lower than the price listed at Efofenedex (2020). This lower price is used in this thesis. The diesel price is correlated to the crude oil price (EIA, 2021a). Hence, the future diesel price can be predicted based on the expected crude oil price development. The crude oil price is assumed to decrease by 10% towards 2025 and an additional 7% towards 2040 in a sustainable development scenario (IEA, 2021). It is expected that this trend continues until 2050 with an additional 2% crude oil price reduction.

Green hydrogen price

BloombergNEF (2020) estimates current and future costs of hydrogen that are used as a basis in this thesis. In 2020, 2030 and 2050, the green hydrogen production cost from large-scale alkaline electrolysis in Western Europe are reported to be 3.6, 2 and 1.2 [$/kg], respectively. Afterwards, hydrogen can be stored in salt caverns at 0.23 [$/kg]. In the future, hydrogen can also be stored in depleted gas fields against comparable cost (expert consultation). It is assumed that 50% of the hydrogen passes through storage, so average storage costs are estimated at 0.12 [$/kg]. Next, the hydrogen is transported to the harbor. In 2020, all hydrogen is still transported by truck. In 2030 and 2050, 80 and 90% is transported through pipelines, respectively (Deloitte, 2020). The transport cost of small volumes by truck for 100 km is estimated at 1.73 [$/kg], which includes movement, compression and associated storage. Transport through transmission pipelines for 100 km is estimated at 0.1 [$/kg]. It is expected that the costs of truck and pipeline transport remain relatively constant towards the future. When the hydrogen has arrived in the harbor, the hydrogen is temporarily stored in pressurized containers at 300 bar before being lifted onto ships. The costs of pressurized container storage are 0.19 and 0.17 [$/kg] in 2020 and 2050, respectively. All together the delivered hydrogen costs are estimated at 5.64, 2.74, 1.75 [$/kg] in 2020, 2030 and 2050, respectively (Table 10). A conversion rate of 0.84 [$/€] is assumed.

Table 10: Delivered green hydrogen cost development breakdown for 2020, 2030, and 2050

	2020	**2030**	**2050**
Production through electrolysis [$/kg]	3.6	2	1.2
Storage in salt caverns/depleted gas fields [$/kg]	0.12	0.12	0.12
Compression and 100 km transport [$/kg]	1.73	0.43	0.26
Container storage in harbor [$/kg]	0.19	0.19	0.17
Total [$/kg]	**5.64**	**2.74**	**1.75**

Blue hydrogen price

In 2020, blue hydrogen production costs from natural gas were estimated at 1.4-2.5 [$/kg], assuming natural gas prices ranging between 1.1-10.3 [$/MBtu] (BloombergNEF, 2020). Natural gas prices in Europe are relatively high compared to the US. Therefore, an above-average natural gas price is assumed for the Netherlands. As the natural gas price is a large determinant for blue hydrogen production costs, above-average blue hydrogen production costs are assumed. These are 2.3, 2.3 and 2 [$/kg] in 2020, 2030 and 2050, respectively. Storage, compression, and transport costs are similar to the values used for delivered green hydrogen costs (Table 11).

Table 11: Delivered blue hydrogen cost development breakdown for 2020, 2030, and 2050

	2020	**2030**	**2050**
Production from natural gas with CCS [$/kg]	2.3	2.3	2
Storage in salt caverns/depleted gas fields [$/kg]	0.12	0.12	0.12
Compression and 100 km transport [$/kg]	1.73	0.43	0.26
Container storage in harbor [$/kg]	0.19	0.19	0.17
Total [$/kg]	**4.34**	**3.04**	**2.55**

Final fuel prices

The price development for diesel and hydrogen has been depicted in Figure 5. The fuel prices have been corrected for energy densities of 10.7 [$\mathrm{kWh_{HHV}/l_{Diesel}}$] and 39.4 [$\mathrm{kWh_{HHV}/kg_{H2}}$]. After 2050, the prices are assumed to remain constant at 2050 levels because the energy transition must be largely completed by then. Note that in the future excise duties may be imposed on hydrogen when the fuel becomes more dominant. For now, these potential excise duties have been excluded.

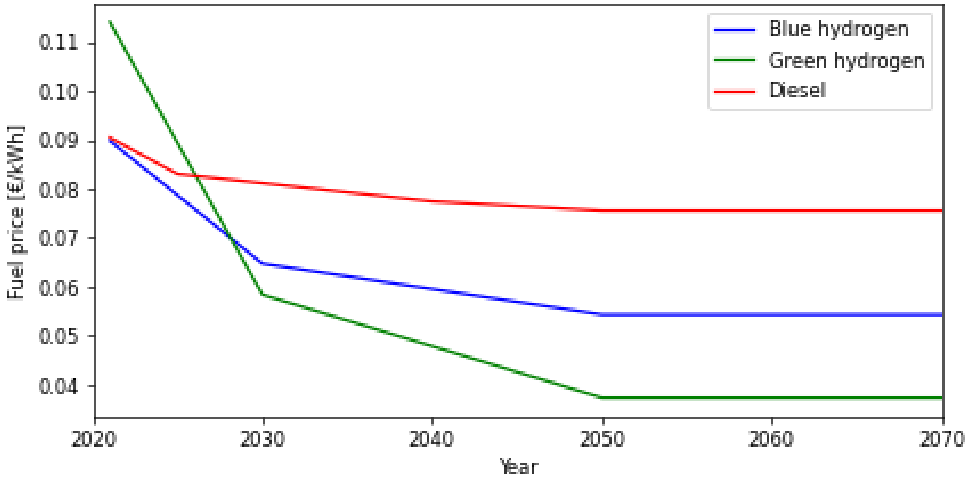


Figure 5: Diesel (incl. excise duties), green hydrogen, and blue hydrogen expected price development excluding VAT towards 2070

The lowest hydrogen costs are taken as a starting point in TCO calculations (Figure 6). Hence, before 2029 most IWT operators switch to blue hydrogen, while they shift to green hydrogen after 2029. However, some IWT operators are willing to pay a premium for green hydrogen before 2029, which is considered in the emission calculations described in section 3.3.2.

The weighted fuel price depends on the mix between hydrogen and diesel used in the drivetrain system. The Share of Diesel (SoD) for every drivetrain system has been listed in Table 12. In hydrogen-powered combustion engines, hydrogen is blended with diesel up to 35 and 65% of the total energy content, for heavy-load and light-load, respectively. This is currently achieved for tractors in the Netherlands without any performance degradation (Blomsma, 2020). It is assumed this would also be technically feasible for hydrogen-powered combustion engines in ships. In ships the upper 25% of the power demand is only required 9% of the time, which is characterized as heavy-load (Sluiman et al., 2019). The remaining time is assumed medium-load for loaded ships and upstream trips, and light-load for empty ships and downstream trips. This results in an 55% average hydrogen blending percentage. In the future, hydrogen can be blended up to 80% without performance degradation.

Table 12: Share of Diesel (SoD) for different drivetrain systems

	2020	**2050**
$SoD_{\text{Diesel-ICE}}$	100%	100%
$SoD_{\text{H2-ICE}}$	45%	20%
$SoD_{\text{H2-FC}}$	0%	0%

Based on the fuel mix for different drivetrain systems the weighted fuel price has been depicted in Figure 6.

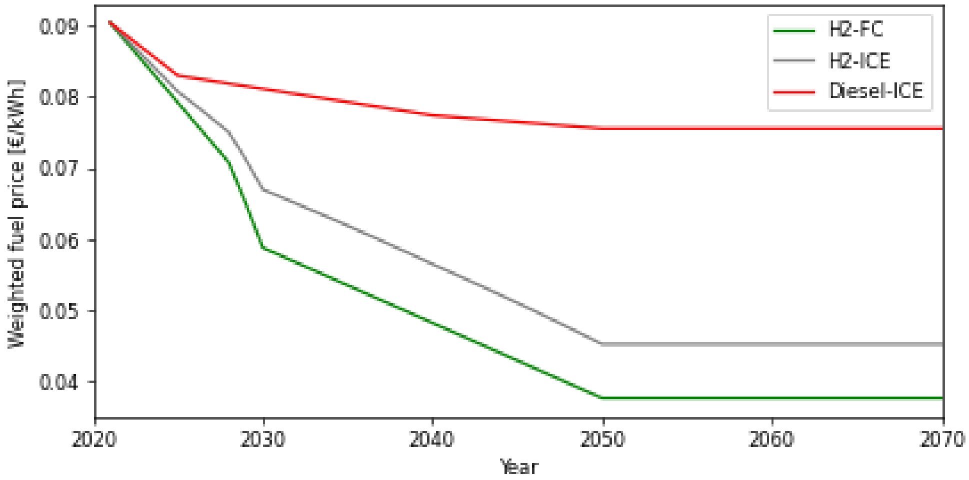


Figure 6: Weighted fuel price development towards 2070 for different drivetrain systems

3.2.2.3 Quantity values

The required quantities (Q) of system components depend on individual ship characteristics (j) in the IVR database. For certain ships, the data in the database is incomplete and must be estimated. The assumptions underlying these estimates have been explained in Appendix C. Furthermore, the database does not contain all relevant ship characteristics. Hence, some ship characteristics have been added based on assumptions described in Appendix C. Using these ship characteristics the required quantities can be determined. The following ship characteristics are relevant for TCO calculations:

- Total engine power [kW] (TEP)
- Effective operational hours [hours/year] (EOH)
- Average load [%] (AL)
- Average trip distance [hours] (ATD)

Quantity drivetrain

First, the required power capacity is determined for the drivetrain components of diesel-powered combustion engines (s=0,i=0), hydrogen-powered combustion engines (s=1, i=0), and hydrogen-powered fuel cells (s=2, i=0,1). The required power capacity equals a ship's total engine power (Eq. 3.6). Fuel cells display 10% degradation over the lifetime, so additional power needs to be installed. Degradation for combustion engines is assumed zero.

$$Q_{\mathrm{sij(t=0)}} = TEP_{\mathrm{j}} \times (1 + D_{\mathrm{si}}) \tag{3.6}$$

For:

s,i = (0,0), (1,0), (2,0), (2,1), (2,2), see Table 8

Where:

Q = Quantity [kW]
TEP = Total Engine Power [kW] (Appendix C)
D = Degradation rate [%] (10% for fuel cells, 0% for combustion engines)

Quantity hydrogen storage

The required storage tank capacity [kg] is determined according to Eq. 3.7 (see next page). The storage capacity depends on the ship's total engine power [kW], average load [%], average trip distance [hours], hydrogen consumption [kg/kWh$_{\mathrm{HHV}}$], and margins [%] for safety (M$_1$) and peak demand (M$_2$). The margins are set to 20% for peak demand (M$_1$ and 20% for safety (M$_2$. The latter considers unforeseen circumstances during the trip, such as bad weather (TNO, 2019). The hydrogen consumption (HCO) is calculated according to Eq. 3.8. It depends on the hydrogen energy density, which is 39.4 [kWh$_{\mathrm{HHV}}$/kgH2] and the drivetrain efficiency [%](η). Finally, the storage capacity depends on the Share of Diesel (SoD), where a 45% Share of Diesel indicates that the hydrogen storage tank only needs to cover for 55% of the energy requirement.

$$Q_{\mathrm{sij(t=0)}} = TEP_{\mathrm{j}} \times AL_{\mathrm{j}} \times ATD_{\mathrm{j}} \times HCO_{\mathrm{s(t=0)}} \times (1 - SoD_{\mathrm{s(t=0)}}) \times (1 + M_1 + M_2) \tag{3.7}$$

For:

s,i = (1,1), (2,3)

Where:

Q = Quantity [kg]
TEP = Total Engine Power [kW] (Appendix C)
AL = Average Load [%] (Appendix C)
ATD = Average Trip Distance [hours] (Appendix C)
HCO = Hydrogen Consumption [$\mathrm{kWh_{HHV}/kgH_2}$] (Eq. 3.8)
SoD = Share of Diesel [%] (Table 12)
M = Margins [%] (specified above)

$$HCO_{\mathrm{st}} = \frac{1}{HED} \times \frac{1}{\eta_{\mathrm{st}}} \tag{3.8}$$

Where:

HCO = Hydrogen Consumption [$\mathrm{kWh_{HHV}/kgH_2}$]
HED = Hydrogen Energy Density [$\mathrm{kWh_{HHV}/kgH_2}$] (=39.4)
η = Efficiency [%] (Table 8)

Quantity fuel

The systems' fuel consumption [kWh/year] for every ship is necessary to determine to cost of fuel. The fuel consumption depends on the ship's total engine power [kW], average load [%], effective operational hours [hours/year] and drivetrain efficiency (Eq. 3.9).

$$FCO_{\mathrm{sj(t=0)}} = TEP_{\mathrm{j}} \times AL_{\mathrm{j}} \times EOH_j \times \frac{1}{\eta_{\mathrm{s(t=0)}}} \tag{3.9}$$

Where:

FCO = Fuel Consumption [kWh/year] (Eq. 3.9)
TEP = Total Engine Power [kW] (Appendix C)
AL = Average Load [%] (Appendix C)
EOH = Effective Operational Hours [hours/year] (Appendix C)
η = Drivetrain system efficiency [%] (Table 8)

3.3 Transition model

The transition model is based on the filtered IVR database that includes cargo ships, push boats, and passenger ships. The model consists of three stages. The first stage simulates the engine replacements of the existing fleet, the commissioning of new ships, and the scrapping of old ships. At the second stage, the simulation effects on emissions and hydrogen demand are calculated. At the third stage, the effects of adding and changing policy parameters are evaluated. The scenario without any new policy interventions is called the base scenario. Scenarios where new policy interventions are turned on are called alternative scenarios.

It is important to note that only a limited number of ships are allowed install a hydrogen-powered drivetrain in the model before 2025. Due to a lack of bunkering infrastructure and regulations, most ships do not shift to hydrogen, even though this may seem beneficial from an economic perspective. EICB (2020) expects 65 ships are equipped with hydrogen in 2025. Those ships are often part of pilot projects. The model assumes that from 2025 onwards, bunkering infrastructure is ready and regulations are in place.

3.3.1 Stage 1

Replacing engines of existing fleet

In the ship's engine replacement year (Appendix C), the trade-off is being made between installing a diesel-powered Stage-V combustion engine and a hydrogen-powered drivetrain (either ICE or FC). The option with the lowest total cost of ownership (TCO) is picked. Passenger ships ascribe a higher value to fuel cell properties, such as the reduced noise and emissions. Therefore, when the diesel-powered combustion engine TCO are only up to 10% higher than the hydrogen-powered fuel cell TCO, the latter is installed in passenger ships. There are two reasons for IWT operators to replace their ship's engine earlier than the original replacement year. The original replacement year refers to the year when the engine lifetime has passed twice (Appendix C). The two reasons for earlier engine replacement are listed below.

1. IWT operators decide on earlier engine replacement when the TCO of a hydrogen-powered drivetrain in a certain year outweigh the TCO of the current diesel engine. Here, the TCO are calculated over the remaining lifetime of the current engine. An engine price of 270 [€/kW] is assumed for old engines that are not equipped with any emission reduction technologies, such as SCR catalysts and DPF (MariGreen, 2018). The current engine can also be adjusted for hydrogen combustion. The investment for these adjustments is 50 [€/kW].

   Example: The engine of ship j must be replaced in 2040. In 2027, the TCO of a new hydrogen-powered fuel cell over the remaining lifetime (13 years) is €500.000. The current engine TCO over the remaining lifetime is €490.000. In this case an earlier engine replacement is not financially beneficial. However, in 2028, the TCO of a hydrogen-powered fuel cell over the remaining lifetime (12 years) is €450.000, while this is 460.000 [€] for the current engine. In this case, the engine is replaced in 2028 because of economic benefits.

To determine whether an earlier replacement is economically beneficial, some adjustments must be made to the original TCO formulas specified in section 3.2. These adjustments are listed below.

- The engine replacement year is adjusted to the potential replacement year, which can be any year between 2021 and the engine's original replacement year. For any year before the engine's original replacement year, the TCO of all drivetrains are compared.
- The fixed period is adjusted to the remaining lifetime
- The diesel engine efficiency is adjusted based on the engine's construction year. The efficiency (33%) decreases by the same rate as the diesel consumption increases in Table 4. For instance, the efficiency of a combustion engine constructed in 2004 is 32%.
- The capital cost for diesel combustion engines are eliminated because the remaining depreciation expenses occur independent of an earlier replacement by a hydrogen-powered drivetrain.
- The investment cost for a conventional diesel engine is assumed 270 [€/kW]. Those cost are used to determine operational maintenance cost.
- The investment cost for a hydrogen-powered combustion engine is assumed to be 50 [€/kW], which is necessary to make adjustments the current diesel engine. Whenever an IWT operators decides to make their current engine fit for hydrogen combustion, the storage tank investment is subtracted from future capital costs in TCO calculations.

2. IWT operators decide on earlier engine replacement when a ship, that is equipped with an old engine, often enters the Port of Rotterdam. From 2025 onwards, ships that do not satisfy CCR-II standards are not allowed to enter the Port of Rotterdam (Panteia, 2019). TNO (2021) assumes that 15% of all cargo and push boat trips goes to the Port of Rotterdam and 95% of these ships already satisfy the CCR-II standards. Hence, it is assumed that 5% of the remaining ships will replace their engine before 2025. The model picks 38 ships for early engine replacement, which corresponds to 5% times 15% of the total freight fleet (cargo vessels and push boats). The engines of these ships must be constructed before 2009, the year in which CCR-II standards were introduced. The replacement year of these ships is brought forward to any year between 2021 and 2025 based on random selection.

Commissioning of new ships

There have been large fluctuations in the number of commissioned ships over the past decade. Therefore, the average number of commissioned ships over the past 10 years (2010–2020) has been taken as a base level for 2021. It is also hypothesized that the new ship size increases every year, which can be associated with a decreasing number of commissioned ships, ceteris paribus. To confirm this hypothesis, the new ship's average tonnage increase and the total annual tonnage increase in the Netherlands are compared using the IVR database and CBS (2021e).

Based on the IVR database, the average tonnage per commissioned ship in the period 1990–2005 (1205 tons) has been compared with the average tonnage per commissioned ship in 2005–2020 (1767 tons). This indicates an average annual increase of 3.1%. According to CBS (2021e), 346.33 million tons were transported in 2010 and 357.07 million tons in 2019. Data for 2020 is also available but is left out to avoid the effects of the covid-19 crisis. Based on the numbers from 2010 and 2019, the annual increase in total transported weight is 0.34%. This is lower than the 3.1% annual increase in average tonnage per commissioned ship. Hence, it can be concluded that the number of ships will decrease in the future by 2.76% (3.1 – 0.34) annually.

It is assumed that future ships have similar characteristics to ships that were commissioned in the last decade. The ship type is determined by randomly selecting a ship type from the list of all commissioned ships between 2010 and 2020. Based on the ship type, the ship length is randomly selected from a list of active ships of the same ship type. The ship length is corrected for an expected annual increase in ship length of 3.1%. This is similar to the average increase in tonnage, as mentioned above. Based on the ship length, the engine power and effective operational hours can be calculated, as described in Appendix C.

The engine placement decision is made according to the TCO comparison described in section 3.2. However, the installation costs are neglected because the ship is built from scratch.

Scrapping of old ships

When the engine lifetime has been passed 4 times, the ship is assumed to be scrapped (expert consultation). Passing the engine lifetime 4 times means that the first engine has been revised and replaced, and the second engine has been revised. When the calculated scrap year lies before 2021, the ship is assumed to be scrapped already and not incorporated in any calculations.

3.3.2 Stage 2

Emissions

For every year between 2020 and 2050, the aggregate emissions of the entire fleet are determined. In years before the engine's replacement, the emissions of individual ships are determined based on ship's building year, as described in section 2.1.5. When the engine has been replaced, the ship's emissions are lowered.

When a new diesel-powered combustion engine is installed, the emissions are lowered to Stage-V standards. For engine powers greater than 300kW, these are 1.8 and 0.01 [g/kWh] for NO_x and PM emissions, respectively. For engine powers smaller than 300kW, these are 2.1 and 0.11 [g/kWh] for NO_x and PM emissions, respectively. CO_2 emissions are assumed to be 120 and 112 [g/kWh] for new diesel-powered combustion engines <300kW and >300kW, respectively.

When a new hydrogen-powered combustion engine is installed, NO_x emissions are lowered to Stage-V standards. CO_2 and PM emissions are fully eliminated for hydrogen share in the fuel mix, but are only lowered to a limited extent for the diesel share in the fuel mix. When the current engine is made fit for hydrogen combustion, the NO_x emissions remain similar to the old engine's emissions because no SCR catalyst is installed. In addition, the emissions for the diesel share in the fuel mix are not lowered because the engine does not comply with Stage-V standards.

When a fuel cell is installed, all emissions are assumed to be fully eliminated. Emissions of commissioned ships are only incorporated after the commissioning year. Emissions of scrapped ships are only considered before the scrap year.

The emissions are modeled and do not completely align with actual emissions. As the Dutch emissions targets are set in reference to 2015, a hypothetical starting point for the emissions in 2015 is required to determine the emission reductions. The total reduction in real emissions between 2015 and 2021 is determined based on CBS (2021e). Next, the hypothetical starting point for NO_x, PM, and CO_2 emissions in 2015 can be calculated using the formula below, where the modeled emissions in 2020 refer to a situation where no engines have been replaced yet.

$$HE_{2015} = \frac{ME_{2020}}{1 - \frac{RE_{2015} - RE_{2020}}{RE_{2015}}} \tag{3.10}$$

Where:

HE = Hypothetical Emissions [kg]
ME = Modeled Emissions [kg] (model output)
RE = Real Emissions [kg] (CBS, 2021a)

This results in the hypothetical starting point in 2015, which allows to calculate future emission reductions according to the model. The hypothetical starting point is calculated for NO_x, PM, and CO_2 emissions.

As described in section 2.3.1, not all hydrogen in the future will be green hydrogen. Hence, the emissions from the blue hydrogen production are considered. Those emissions are currently estimated at 4.75 [kg_{CO2}/kg_{H2}] and decrease to 0.95 kg [kg_{CO2}/kg_{H2}] in 2030. In the years before 2029, most hydrogen-powered ships are assumed to consume blue hydrogen because of economic benefits. However, 35% of the ships will favor green hydrogen before 2029 despite higher costs. This aligns with the estimate of Gasunie (2019a) about the hydrogen mix in 2030, as described in section 2.3.1. Finally, additional NO_x emission reductions are incorporated in the model by installing selective catalytic reduction (SCR) catalysts in ships. In total, €65 million subsidies are available until 2025 for the installation of SCR catalysts. The SCR catalysts costs are 100 [€/kWh] (TNO, 2021). For small enterprises, 60% of the costs can be refunded, capped at €200.000. It is assumed that all companies in the Dutch IWT sector are considered small enterprises. The SCR catalysts are installed until the full budget is spent. According to experts, most ships that install an SCR catalyst have CCR-II engines installed as these engines are probably not going to be replaced in the near future. Hence, SCR catalysts are installed in ships built after 2009 or in ships that installed a new engine after 2009. It is assumed that IWT operators will not install SCR catalysts without subsidies. SCR catalysts reduce NO_x emissions up to 90% (STT Emtec, 2021b). In the model, NO_x emissions are set to Stage-V standards when an SCR catalyst is installed.

Hydrogen demand

The total hydrogen demand in the IWT sector is determined by aggregating the hydrogen demand of all ships (Z). The hydrogen demand for an individual ship depends on its fuel consumption and the hydrogen share in the fuel mix. The total hydrogen demand is calculated according to Equation 3.11.

$$HD_{\mathrm{t}} = \sum_{j}^{Z} FCO_{\mathrm{jt}} \times (1 - SoD_{\mathrm{jt}}) \times \frac{1}{3.6 \times 10^{9}} \tag{3.11}$$

Where:

HD = Hydrogen Demand [PJ/year]
FCO = Fuel Consumption [kWh/year] (Eq. 3.9)
SoD = Share of Diesel [%] (Table 12)

3.3.3 Stage 3

Stage 3 starts with a base scenario that forms a starting point for evaluating the effects of policy measures. Next, the effects of CO_2 taxes, an HBE obligation, bans on diesel engines, and a hydrogen blending obligation on the emission reductions are evaluated separately. Finally, two alternative scenarios are proposed based on the evaluated effectiveness of policy measures.

3.3.3.1 Base scenario

The base scenario represents a simulation of the aggregate IWT operator decision-making process considering all projected technical and economic developments. In the base scenario, all future policy measures have been disabled in the model. For the base scenario, the fleet development (stage 1) and resulting emission reductions and hydrogen demand (Stage 2) are evaluated using a conservative fuel cell price development. Here, fuel cell prices drop to 840 [€/kW] in 2050. However, the base scenario is also evaluated using an optimistic fuel cell price development, where fuel cell prices drop to 600 and 80 [€/kW] in 2030 and 2050, respectively. The effects of policy measures are evaluated based on the base scenario that assumes a conservative fuel cell price development.

3.3.3.2 CO_2 taxes

The CO_2 price can be turned on in the model, which adds CO_2 taxes to the diesel cost. The CO_2 price does not apply in the IWT sector at the moment, so CO_2 prices can be active (y=1) or inactive (y=0) depending on the introduction year (t) of the CO_2 tax. The CO_2 taxes (CT) depend on the ship's CO_2 emissions (CE) in a certain year and the CO_2 price (CP). It is assumed that CO_2 emitted through the production of blue hydrogen is not taxed. To incorporate CO_2 taxes into the TCO, the CO_2 taxes must be discounted to present value using a discount rate. The formula for calculating CO_2 taxes is described in equation 3.12.

$$CT_{\mathrm{sjt}} = CP_{\mathrm{t}} \times CE_{\mathrm{sj(t=0)}} \times \frac{1}{(1+r)^t} \times y_t \tag{3.12}$$

Where:

CT = CO_2 Taxes [€]
CP = CO_2 Price [€/t] (Fig. 7)
CE = CO2 Emissions [t] (Eq. 3.13)
r = Discount rate [%] (Table 9)
y = Introduction of CO2 taxes [0 or 1], where 0 = not active and 1 = active

CO_2 price

The ETS price was on average 25 and 50[€/t] in 2020 and 2021, respectively (Ember, 2021). The impact assessment accompanying EU's 2030 Climate Target Plan projects CO_2 prices for ETS sectors ranging from 32 to 65 [€/t] (European Commission, 2020). This would be sufficient to reduce economy-wide greenhouse gas emissions at least 55% by 2030. In the sustainable development scenario of IEA (2021), CO_2 prices for advanced economies are 63 [\$/t] in 2025. After 2025, the CO_2 price rises to 140 [\$/t] in 2040. The sustainable development scenario sets a path towards meeting the objectives outlined in the Paris Agreement. The CO_2 prices in the sustainable development scenario have been taken as a basis in this thesis. The trend between 2025 and 2040 is extrapolated towards 2050. The CO_2 price is assumed to remain constant towards 2070 because climate targets have been achieved, according to the Paris Agreement. The CO_2 price development has been depicted in Fig. 7, using a conversion rate of 0.84 [€/\$]

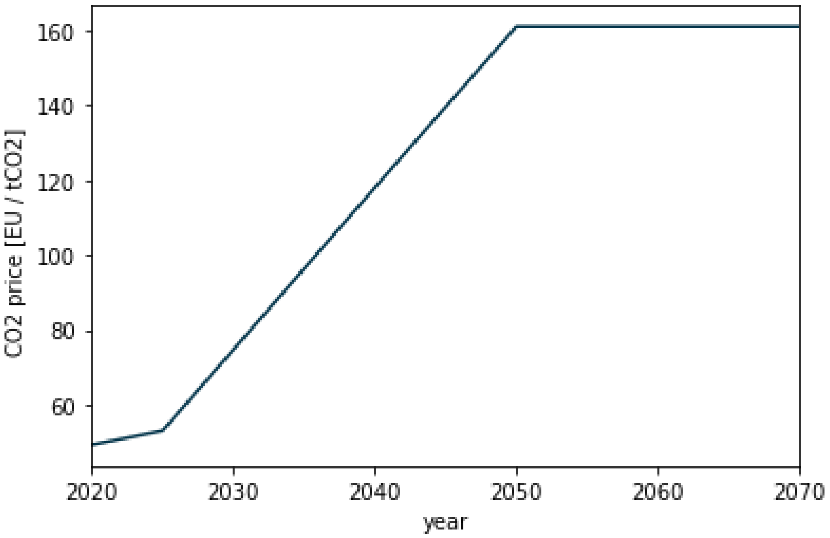


Figure 7: Expected CO_2 price development towards 2070

Quantity CO_2 emissions

The ship's CO_2 emissions must be calculated to determine the CO_2 taxes. The CO_2 emissions (CE) depend on the ship's fuel consumption (FCO), share of diesel (SoD), and CO_2 emissions per kWh, the latter being 37 [g/kWh_{HHV}]. The CO_2 emissions must be converted from grams to tons.

$$CE_{\mathrm{sj(t=0)}} = FCO_{\mathrm{sj(t=0)}} \times SoD_{\mathrm{s(t=0)}} \times \frac{37}{10^6} \tag{3.13}$$

Where:

CE = CO_2 Emissions [t]
FCO = Fuel Consumption [kWh/year] (Eq. 3.9)
SoD = Share of Diesel [%] (Table 12)

Model testing

By default, the CO_2 price starts at 50 [€/t] and rises to 160 [€/t] in 2050 (Figure 7). The starting price can be adjusted, as well as the CO_2 scenario. The CO_2 scenario is equal to 1 by default, where the CO_2 price rises to 160 euro per ton in 2050. A CO_2 scenario of 1.2 suggests a CO_2 price in 2050 of 192 [€/t]. The effect of different CO_2 prices is evaluated by the changes in emission reductions in 2050.

CO_2 tax revenues could be saved in an innovation fund and used to further bridge the gap between TCO of diesel and TCO of hydrogen-powered drivetrains in the form of subsidies. Fuel cell systems are slightly favored over hydrogen combustion engines in the model when providing these subsidies because they are associated with additional NO_x reductions. Note that the CO_2 tax revenues are only collected when introducing a CO_2 tax apart from the ETS. Within the ETS, CO_2 allowances are traded within and across industries and do not result in public tax revenues. In that case, it is assumed that the government contributes to the innovation fund.

3.3.3.3 HBE obligation

When the IWT sector and hydrogen are included in the RED-II, the HBE costs of fuel suppliers for buying certificates are passed on to IWT operators. The total HBE costs for fuel suppliers depend on the HBE price (HBEP) and the total number of certificates that must be purchased. The latter corresponds to the sector's renewable energy obligation (REO) minus the sector's renewable energy consumption (REC), both measured in gigajoules. The total HBE costs are divided by the sectoral diesel consumption (DCO) to obtain a HBE premium that can be charged on top of the diesel price. The HBE costs for a single ship are determined by multiplying this HBE premium by the ship's diesel consumption (eq. 3.14). Minor efficiency differences between hydrogen and diesel combustion have been neglected here. The annual HBE costs must be depreciated to the present value in order to include them in the TCO. Finally, the IWT sector is not yet covered by the RED-II, so the HBE obligation can be active (x=1) or inactive (x=0) depending on the introduction year. Note that in reality the HBE policy would also lower the hydrogen price. However, this has been neglected in this thesis as explained in section 2.1.6.

$$HBEC_{\mathrm{sjt}} = \frac{HBEP_{\mathrm{t}} \times (REO_t - REC_t)}{DCO_t} \times FCO_{\mathrm{sj(t=0)}} \times SoD_{\mathrm{sj(t=0)}} \times \frac{1}{(1+r)^t} \times x_t \tag{3.14}$$

Where:

$HBEC$ = HBE Cost [€]
$HBEP$ = HBE Price [€/GJ] (Fig. 8)
REO = Renewable Energy Obligation in IWT sector [GJ/year]
REC = Renewable Energy Consumption in IWT sector [GJ/year] (Eq. 3.15)
FCO = Fuel Consumption of ship [kWh/year] (Eq. 3.9)
SoD = Share of Diesel [%] (Table 12)
DCO = Diesel Consumption in IWT sector [kWh/year] (Eq. 3.16)
r = Discount rate [%] (Table 9)
x = Introduction of RED-II [0 or 1], where 0 = not active and 1 = active

HBE price

The HBE-G price has been fluctuating around 13 [€/GJ] in 2020 (PBL, 2021). HBE-G includes some biofuels and advanced renewable fuels. An HBE price of 13 [€/GJ] is taken as a base level for 2021. However, no studies are available that estimate HBE price development towards 2050. The future HBE price depends on the annual obligation of renewable energy supply for all covered sectors in the Netherlands. It is assumed that the annual obligations are set in a way that ensures zero emissions in 2050, similarly to the emission cap in the ETS. In that case, the increase in renewable energy uptake is assumed to correlate with the decrease in GHG emissions. Therefore, this thesis assumes a similar trend for HBE price development as for CO_2 price development (Fig. 8).

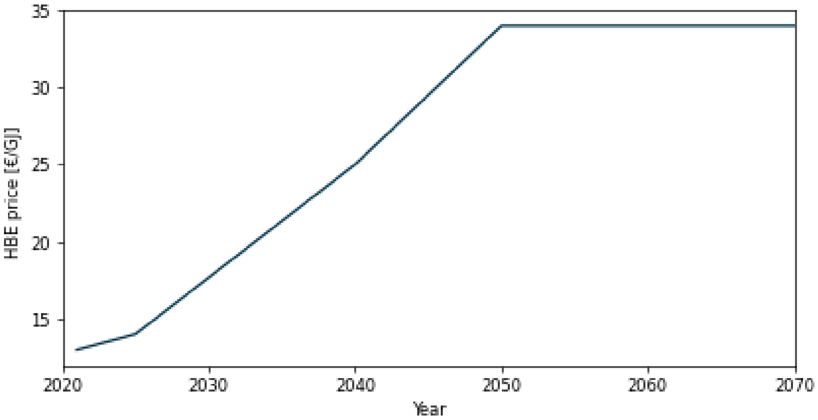


Figure 8: Expected HBE price development towards 2070

HBE premium

To obtain the HBE premium that is charged on top of the diesel price, the renewable energy obligation (REO), sectoral renewable energy consumption (REC), the sectoral diesel consumption (DCO), and the share of diesel (SoD) for each ship must be determined.

The REC corresponds to the aggregate hydrogen consumption of all ships (Z) in the sector, which is determined endogenously according to equation 3.15. Here, the engine's installation year is used when determining the share of diesel (SoD) in hydrogen-powered combustion engines. Blue hydrogen is not considered as renewable energy under the RED-II. Therefore, the REC is multiplied by the share of green hydrogen ($SoGH_2$). Before 2029, 35% is willing to pay a premium for green hydrogen. After 2029, green hydrogen is cheaper than blue hydrogen and all IWT operators will use green hydrogen. Finally, the REC is converted to gigajoules. The DCO corresponds to the aggregate diesel consumption (Eq. 3.16). It is assumed there are no alternatives to diesel and hydrogen in the fuel mix.

The REO is expected to be introduced from 2022 onwards and rises linearly to 20% of the total sector fuel consumption in 2030, as described in section 2.1.6. It is assumed the REO in 2050 will be in line with the zero-emission goals and therefore equals the total sector fuel consumption (i.e. REC + DCO $\times 3.6^3$).

$$REC_t = \sum_{j}^{Z} FCO_{\mathrm{jt}} \times (1 - SoD_{\mathrm{jt}}) \times SoGH_2 \times 3.6^3 \tag{3.15}$$

$$DCO_{\mathrm{t}} = \sum_{j}^{Z} FCO_{\mathrm{jt}} \times SoD_{\mathrm{jt}} \tag{3.16}$$

Where:

REC = Renewable Energy Consumption in sector [GJ/year]
DCO = Diesel Consumption in sector [kWh/year]
FCO = Fuel Consumption [kWh/year] (Eq. 3.9)
SoD = Share of Diesel [%] (Table 12)
$SoGH_2$ = Share of Green Hydrogen (35% before 2029, 100% after 2029)
Z = Total number of ships

Model testing

The parameters that influence the effect of an HBE introduction are the HBE obligation level and the HBE price. The effect of multiple HBE prices is evaluated against 4 HBE obligations levels in 2030 and 2050. Those 4 levels corresponds to 25, 50, 75 and 100% of the HBE obligation level (REO) specified above.

The HBE premium depends on the number of ships that shift to hydrogen. Therefore the engine replacement decisions of all IWT operators co-determine the HBE premium. A large number of ships shifting to hydrogen lowers the number of HBEs that must be purchased by fuel suppliers. As a consequence, the HBE premium for diesel-powered ships is lowered. The HBE premium in the model is based on the decisions of previous ships that have ran through the model. For instance, when ship A decides to switch to a hydrogen-powered fuel cell in 2030, the HBE premium for ship B is slightly lowered in all future years because the renewable fuel consumption in the sector has increased.

In case the HBE obligation in 2050 equals the total fuel consumption (i.e. all fuel must be renewable), the HBE premium [€/GJ] equals the HBE price [€/GJ].

3.3.3.4 Ban on (diesel) combustion engines

A ban on the placement of new diesel-powered combustion engines can be turned on in a specific year. From that year onwards, the IWT operator always chooses a hydrogen-powered drivetrain over a new diesel-powered combustion engine in the original replacement year. The effect of introducing the ban in different years on the emission reductions in 2050 is evaluated.

In addition, a ban could be placed on the revision of all combustion engines. This would decrease the lifetime of engines and contribute to further emission reductions. In this case, the replacement year is set to the engine revision year (Appendix C) for ships that must replace their engine in the future and have not revised their engine in the past. The engine is then replaced by a new hydrogen-powered fuel cell in the updated replacement year.

3.3.3.5 Hydrogen blending obligation

A blending obligation for carbon-free fuels in the shipping industry is suggested by governmental advisory bodies (RLI, 2021). In the model, a hydrogen blending obligation could be turned on in a specific year, where a certain percentage must be blended with diesel. This, however, forces IWT operators to install a hydrogen storage tank and make their engine fit for hydrogen combustion. As a result of a hydrogen blending obligation, CO_2 and PM emissions are reduced by the blending percentage. NO_x emissions for hydrogen-powered combustion engines are comparable to diesel-powered combustion engines. The ships' emissions, potential CO_2 taxes, and fuel costs are adjusted proportionally to the blending percentage. The effect of the introduction of a 55% hydrogen blending obligation in 2030 has been evaluated. The percentage has been based on the hydrogen share in the fuel mix that is currently possible for hydrogen-powered combustion engines (Table 12). The year has been picked arbitrarily to illustrate the effect. In general, it holds that a larger percentage leads to more significant emission reductions. The year determines when the emission drop occurs and the magnitude of the emission drop. The earlier a hydrogen blending obligation is introduced, the larger the emission drop in that year due to a larger number of ships equipped with diesel-powered engines in early years.

In addition to the effect of a hydrogen blending obligation, the total investment costs necessary for engine adjustments and on-board hydrogen storage are calculated for the remaining diesel-powered fleet. Once capital investments in engine adjustments and a storage tank have been made, IWT operators may decide to blend a larger percentage due to economic benefits. However, this would require a larger storage tank. This scenario has not been modeled.

3.3.3.6 Alternative scenarios

Based on the effects of policy measures, two alternative scenarios are constructed that are designed to meet the emission targets after 2030. The emission targets for 2024 are difficult to realize because the model restricts the number of ships that can be equipped with a hydrogen-powered drivetrain before 2025. It is assumed that the infrastructure and regulations are not in place yet to facilitate large-scale adoption of hydrogen in the sector before 2025. The alternative scenarios are evaluated for conservative and optimistic fuel cell price developments.

3.4 Sensitivity analysis

Sensitivity dataset

Two alternative datasets have been generated as a reference in order to determine the influence of filtering decisions (Appendix C) made in the dataset that is used. The base scenario is simulated using the alternative datasets to identify potential differences in outcomes. The alternative datasets are:

- IVR database including cargo ships and push boats (freight transport only)
- PROMINENT database (freight transport only)

The IVR database is not always up to date and some data for ships is missing (Stichting Projecten Binnenvaart, 2016). Therefore, in the PROMINENT project, they corrected and added values in the database. The PROMINENT database is an improved version of the 2014 IVR database. This database includes all ships involved in freight transport.

Sensitivity input variables

A sensitivity analysis is also performed to determine the influences of input variables on the calculated emission reductions. As sensitivity analyses require large amounts of computing power, 200 items are randomly sampled from the dataset. A two-sided one sample t-test showed that there are no significant statistical differences between the dataset and sample mean regarding the engine power, ship length, and ship building year. In addition, a two-sided one proportion z-test has been performed and indicates no significant statistical differences between the proportion of ship types present in the dataset and sample. Hence, it can be concluded that the 200 items are a representative sample from the dataset. The statistical tests are described further in Appendix E.

The sensitivity analysis is performed according to the Sobol method (Sobol, 2001). The Sobol method is a variance-based sensitivity analysis used to decompose the output (i.e. emissions) variance into fractions that can be attributed to input variables. Variance-based analyses can deal with nonlinear responses and can measure the effect of interactions between input variables (Saltelli & Annoni, 2010). To perform the sensitivity analysis several steps need to be taken.

First, the problem needs to be defined that specifies the input variables and their boundary values. The boundary values have been set to 0% and 200% of the default value in order to provide similar slack for all variables. In some cases, lower bounds of zero have been converted to small numbers to prevent division-by-zero-errors. The input variables and their boundary values are presented in Table 13. For most variables a scenario is used to adjust input value percentually, which is necessary for variables that change over time in the model. For instance, a scenario of 2 implies a doubling of the input default value.

Table 13: Input variables and corresponding boundary and default values for sensitivity analysis

Input variable	**Boundary values**	**Default value**
ICE efficiency	[0.01, 0.68]	0.34
FC efficiency scenario	[0.01, 2]	1
Installation costs H_2 ICE scenario	[0.01, 2]	1
Installation cost H_2 FC scenario	[0.01, 2]	1
FC price scenario	[0.01, 2]	1
H_2 storage price scenario	[0.01, 2]	1
Electric engine price scenario	[0.01, 2]	1
Diesel ICE price scenario	[0.01, 2]	1
H_2 ICE price scenario	[0.01, 2]	1
Diesel price scenario	[0.01, 2]	1
Hydrogen price scenario	[0.01, 2]	1
ICE maintenance percentage	[0.01, 0.2]	0.1
FC maintenance percentage	[0.01. 0.1]	0.05
Diesel WACC	[0.01, 0.12]	0.059
Hydrogen WACC	[0.01, 2]	1
Inflation	[0.001, 0.03]	0.015
Fixed period	[1, 40]	20

Second, samples are created using Saltelli's (2002) sampling technique, which is designed for Sobol's sensitivity analysis. The sample size for Sobol's sensitivity analysis is N(2K+2), where N is the minimum number of model evaluations needed for estimating the effect of one individual variable and K is the number of input variables (Nguyen & Reiter, 2015). N takes a value of 16, 32, 64, and so on. If the confidence interval of the most dominant parameter is greater than 10%, the N needs to be increased (Zhang et al., 2015).

Third, the model's output is evaluated for each of the samples, which generates sensitivity indices. Three types of sensitivity indices are generated:

1. First-order indices indicate the individual contribution of a single input variable to the output variance averaged over the contribution of other input variables.
2. Second-order indices indicate the contribution to the output variance caused by the interaction of two input variables.
3. Total-order indices indicate the total contribution of single input variables to the output variance. The total contribution includes first-order effects and all second-order interactions.

The first-, second-, and total-order indices must be positive values (Zhang et al., 2015). Furthermore, the total-order sensitivity index must be greater than the first-order sensitivity index of a single variable. When these conditions are not satisfied, the sample size should be increased. Finally, sensitivity index values greater than 0.05 are considered significant (Zhang et al., 2015).

4 Results

4.1 TCO for average ship

The TCO for every ship in the IVR database has been simulated for every year between 2020 and 2050. The breakdown of the average TCO for diesel-powered combustion engines, hydrogen-powered combustion engines, and hydrogen-powered fuel cells are shown in Figures 9, 10, and 11. Note that these TCO are calculated under the assumptions described in section 3.2 and therefore do not assume that engines can be made fit for hydrogen combustion, for instance. Furthermore, these are TCO for an average ship, so the TCO may be lower or higher for some ships. Lower average TCO for a hydrogen-powered drivetrain does not necessarily indicate that the majority of ships shift a hydrogen-powered drivetrain. For instance, the TCO for a hydrogen-powered fuel cell could be €1 million lower than the TCO for a diesel-powered combustion engine for one ship, while for two other ships the TCO are €0.2 million higher. This results in a relatively lower average hydrogen-powered fuel cell TCO, while only one-third of the ships actually installs such a drivetrain. Hence, the average TCO mainly illustrate the trends in TCO development over time. The formula for calculating the TCO for an average ship is described in equation 4.1.

$$ATCO_{\mathrm{st}} = \frac{\sum_{j}^{Z} TCO_{\mathrm{sjt}}}{Z} \tag{4.1}$$

Where:

$ATCO$ = Average Total Cost of Ownership [€]
TCO = Total Cost of Ownership [€] (Eq. 3.1)
Z = Total number of ships

Figure 9 shows the average TCO development of diesel-powered combustion engines. It stands out that these TCO for an average ship remain relatively constant at approximately €3 million towards 2050. The fuel cost are the largest cost component and drop slightly towards 2050 as a consequence of decreasing diesel prices (Fig. 5). Note that CO_2 taxes and HBE cost are zero because these are turned off by default in the model.

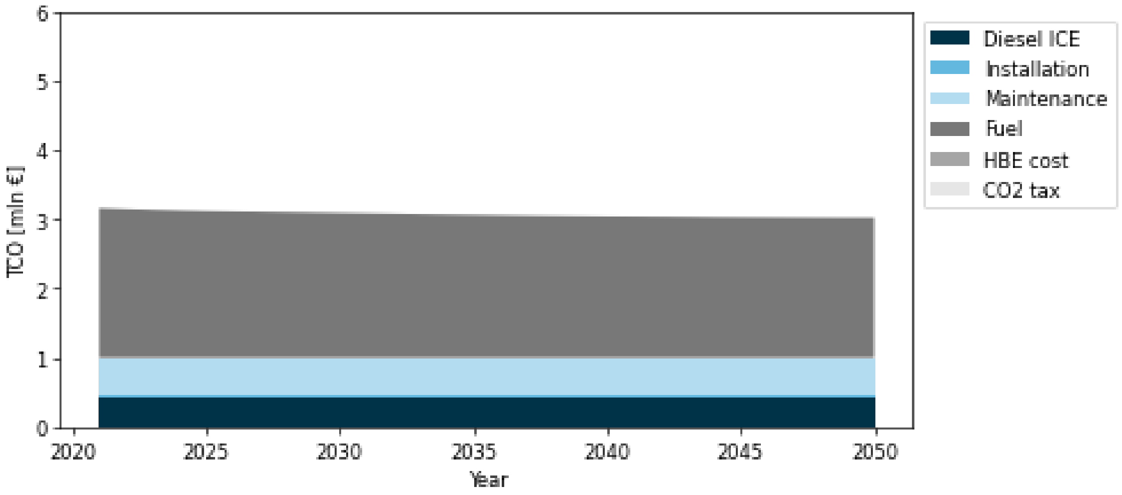


Figure 9: TCO diesel-powered combustion engine for average ship towards 2050

Figure 10 shows the average TCO development of hydrogen-powered combustion engines, which drop to €2.8 million in 2050, on average. In 2030, a steep drop occurs in storage tank costs because the average distance to be covered with the energy content in a single tank decreases due to improved infrastructure, as described in Appendix C. Furthermore, the TCO drop as a consequence of decreasing storage tank and fuel prices. As hydrogen comprises the major part in the fuel mix for hydrogen-powered combustion engines, the total fuel costs are lower than for diesel-powered combustion engines.

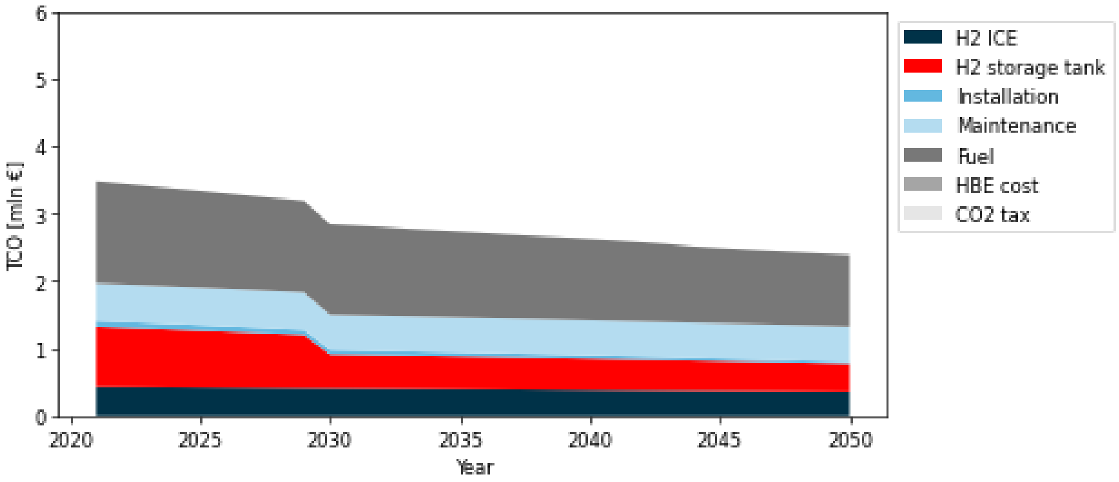


Figure 10: TCO hydrogen-powered combustion engine for average ship towards 2050

Figure 11 illustrates the average TCO development of hydrogen-powered fuel cells, which decrease to €2.5 million in 2050. It stands out that, despite a larger hydrogen share in the fuel mix, fuel costs and storage tank costs are lower for hydrogen-powered fuel cells than for hydrogen-powered combustion engines due to the higher efficiency of fuel cells. The maintenance costs are slightly higher than for hydrogen-powered combustion engines as a consequence of higher capital costs for hydrogen-powered fuel cells. The largest cost reductions are achieved due to drops in fuel cell and storage tank prices, which directly reduces capital cost and indirectly reduces maintenance cost.

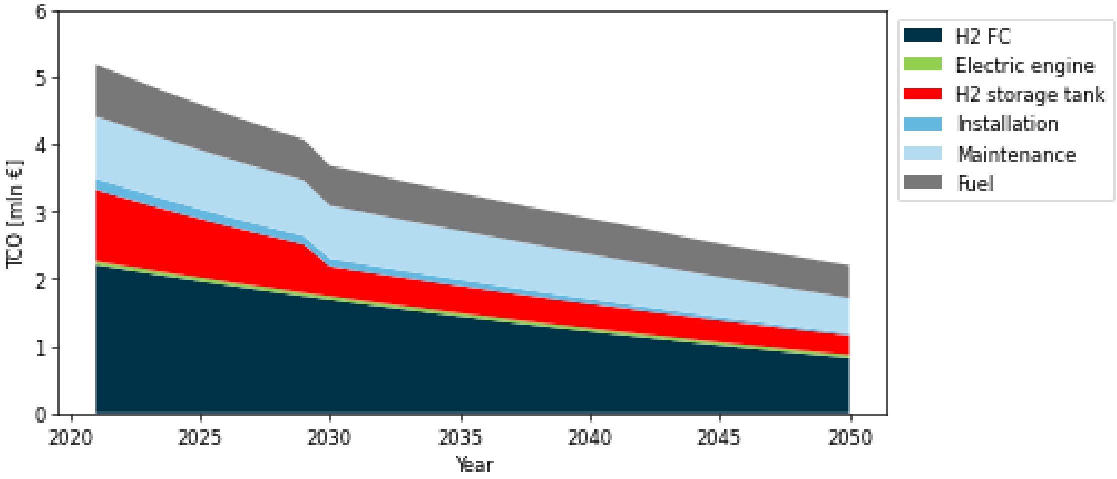


Figure 11: TCO hydrogen-powered fuel cell for average ship towards 2050

4.2 Base scenario

The base scenario represents a simulation of the aggregate IWT operator decision-making process considering all projected technical and economic developments. The introduction of CO_2 taxes, an HBE obligation, bans, and a hydrogen blending obligations have been disabled in the model, as specified in Table 14.

Table 14: Settings base scenario

Variable	Value
CO_2 price	Inactive
HBE obligation	Inactive
Ban on placement diesel engines	Inactive
Ban on revision of combustion engines	Inactive
Hydrogen blending obligation	Inactive

4.2.1 Fleet development

The fleet development in the base scenario has been displayed in Figure 12. The figure shows a declining number of commissioned ships due to the expected increasing future vessel size. In 2021, 32 ships are commissioned, while only 5 ships are commissioned in 2050. The number of annually scrapped ships fluctuates around 29 ships, on average. The number of new engines peaks in 2044 because IWT operators decide to replace their engine earlier due to economic benefits. Disregarding

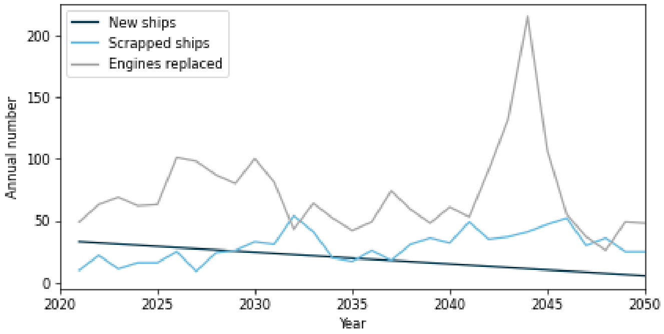


Figure 12: Fleet development towards 2050 in base scenario

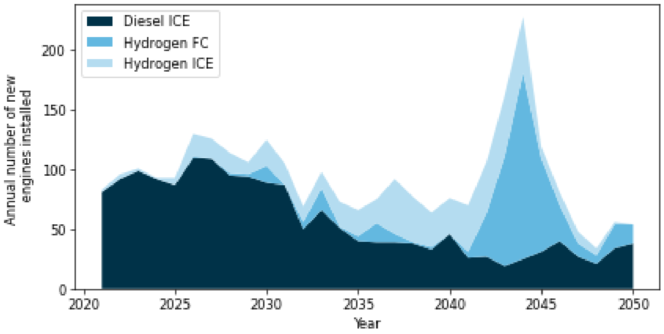


Figure 13: New engines types placed towards 2050 in base scenario

the earlier replacements, most engines are installed in the period 2020-2031. As most engines need to be replaced after 60-70 years, the engines of ships commissioned during the peak in 1955-1965 (Appendix C) must be replaced between 2020 and 2030. Additionally, 38 ships decide to replace their engine before 2025 due to emission constraints introduced in the Port of Rotterdam in 2025.

Figure 13 shows all new engine types that are installed, including replaced engines and engines installed in new ships. Towards 2043, an increasing number of IWT operators shifts to a hydrogen-powered drivetrain. In the period 2043-2045, it turns out that about 300 IWT operators decide to replace their ship's engine earlier by a hydrogen-powered fuel cell. After 2045, the number of ships that shift to a hydrogen-powered fuel cell drops because ships with the most favourable characteristics (e.g. high engine powers) have already shifted. These favourable characteristics are explained later in this section.

Some ships decide to make their existing diesel engines fit for hydrogen combustion due to economic benefits. Figure 14 shows a first peak of 375 converted engines in 2025, which is the first opportunity according to the model's constraints. It is assumed that before 2025 the infrastructure and regulation do not facilitate large-scale adoption of hydrogen. Ships that make their diesel engines fit for hydrogen typically have favourable characteristics like high engine powers and a large number of annual operating hours. This enables fuel cost savings to offset the additional investments. In addition, ships that frequently bunker require a smaller storage tank, which reduces the initial investment. After 2025, the ships with these most favourable characteristics have shifted. In 2030, the average distance that ships must run on a single storage tank drops, as explained in Appendix C. The improved infrastructure enables ships to bunker after a single trip instead of a round trip, which decreases the need for a large hydrogen storage tank and lowers cost. This explains the increased number of ships that make their engine fit for hydrogen combustion in 2030. After 2030, the number of IWT operators that make their ship fit for hydrogen combustion decreases because many IWT operators have already adjusted or replaced their engines, or earlier replacement by a hydrogen-powered fuel cell becomes more economically beneficial.

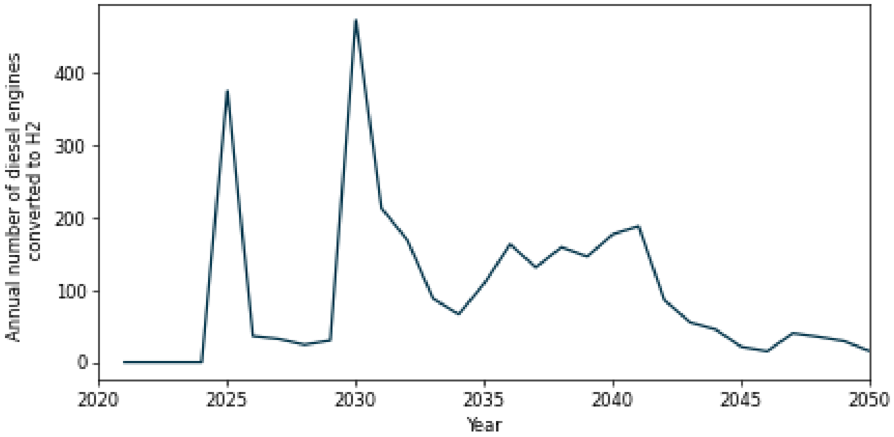


Figure 14: Diesel-powered engines made fit for hydrogen combustion towards 2050 in base scenario

The aggregate numbers for the base scenario in the period 2020–2050 have been listed in Table 15. Most IWT operators have switched to hydrogen-powered combustion engine in the base scenario, followed by diesel-powered combustion engines and hydrogen-powered fuel cells, respectively. The majority of existing vessels that install a hydrogen-powered drivetrain shift earlier due to economic benefits.

Table 15: Aggregate numbers of fleet development in the base scenario

	Diesel - ICE	**Hydrogen - ICE**	**Hydrogen - FC**	**Total**
New ships	407	163	92	662
Scrapped ships	n/a	n/a	n/a	875
Engines replaced	1318	407	433	2158
Adjusted engines*	n/a	2920	n/a	2920
Total	1725	3490	525	

* These represent diesel-powered combustion engines that have been made fit for hydrogen combustion

In general, ships that bunker often prefer a hydrogen-powered combustion engine over a hydrogen-powered fuel cell. Frequent bunkering allows to decrease the size and cost of a storage tank. The storage tank is often larger for ships equipped with a combustion engine due to lower efficiencies.

Considering the scrapping and commissioning of ships over the entire period 2020-2050, the fleet consists of 5027 active ships in 2050. This indicates that about 80% of the entire fleet has shifted towards a hydrogen-powered drivetrain in the base scenario. Although Table 15 provides insight into the fleet development, note that some double counting may have occurred due to the following dynamics:

- New and existing ships that installed a diesel-powered combustion engine may have shifted towards a hydrogen-powered drivetrain later.

- Existing ships that have made their diesel-powered combustion engine fit for hydrogen combustion may have shifted towards a hydrogen-powered drivetrain later.
- Scrapped ships may have replaced or adjusted their engine before their scrap year.

According to Figure 15, the ships that replace their conventional diesel-powered combustion engine with a hydrogen-powered fuel cell are often push boats (see classification in Appendix C, Table 19). Push boats are characterized by a high number of annual operational hours up to 7258 hours. This results in a high fuel consumption and thus higher fuel savings that can offset additional investments required for a more expensive hydrogen-powered fuel cell. These fuel savings are higher for hydrogen-powered fuel cells than hydrogen-powered combustion engine as fuel cells can fully run on hydrogen an can achieve higher efficiencies. Furthermore, push boats display frequent bunkering behavior, which decreases the required size of hydrogen storage tank. Passenger ships are willing to pay a premium for a hydrogen-powered fuel cell and are therefore more likely to install this drivetrain. The remaining ships that are shifting towards a hydrogen-powered drivetrain are characterized by high engine powers and a high number of annual operating hours. Note that Figure 15 only includes ships that replace their engine, and therefore excludes ships that only make their engine fit for hydrogen combustion.

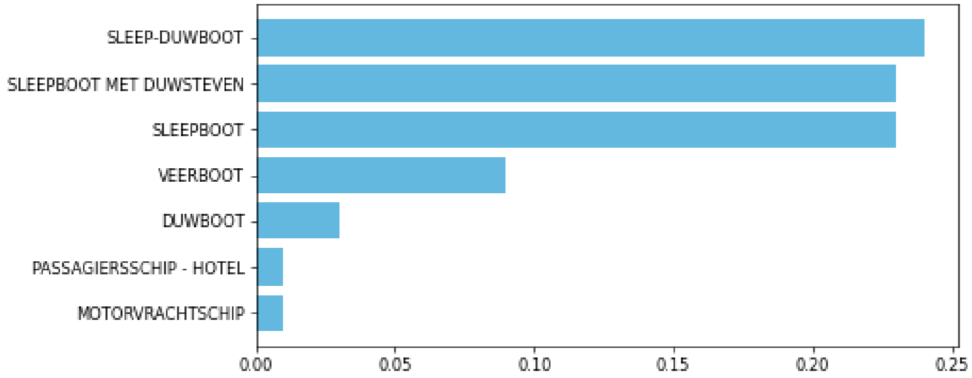


Figure 15: Share of ship types that replace diesel-powered combustion engines by a hydrogen-powered drivetrain in the base scenario (see ship classification in Appendix C, Table 19)

4.2.2 Emission reductions

As a consequence of the fleet changes, the fleet's total emissions are reduced, according to Figure 16. However, the emission reductions in the base scenario are not sufficient to meet most of the Green Deal targets, as specified in Table 16.

Table 16: Emission reductions in the base scenario

	NO_x target	**NO_x achieved**	**PM target**	**PM achieved**	**CO_2 target**	**CO_2 achieved**
2024	10%	30%	10%	29%	20%	7%
2030	n/a	n/a	n/a	n/a	40%	33%
2035	35%	46%	35%	67%	n/a	n/a
2050	100%	66%	100%	87%	100%	63%

Figure 16 shows a steep NO_x emission reduction towards 2025 caused by the installation of SCR catalysts in CCR-II engines, which is financed by the SRVB subsidy of €65 million (section 2.1.6). This reduces NO_x emissions for these ships to Stage-V standards. According to the model results, 1466 ships install SCR catalysts using this subsidy. Furthermore, the NO_x and PM emissions drop because a large number of ships shifts to a cleaner diesel-powered combustion engine that must satisfy Stage-V standards. In the same period, there is a slight increase in CO_2 emissions due to an increasing number of total ships active in the Dutch fleet. The number of ships that is commissioned is larger than the number of ships that is scrapped (Fig. 12). Moreover, new ships are often larger and equipped with larger engines, which brings along higher emissions. In fact, an average new ship is equipped with an engine of 1016 kW, while an scrapped ship is equipped with an engine of only 394 kW. In addition, the increased ship length is related to a higher number of annual operating hours (Table 3).

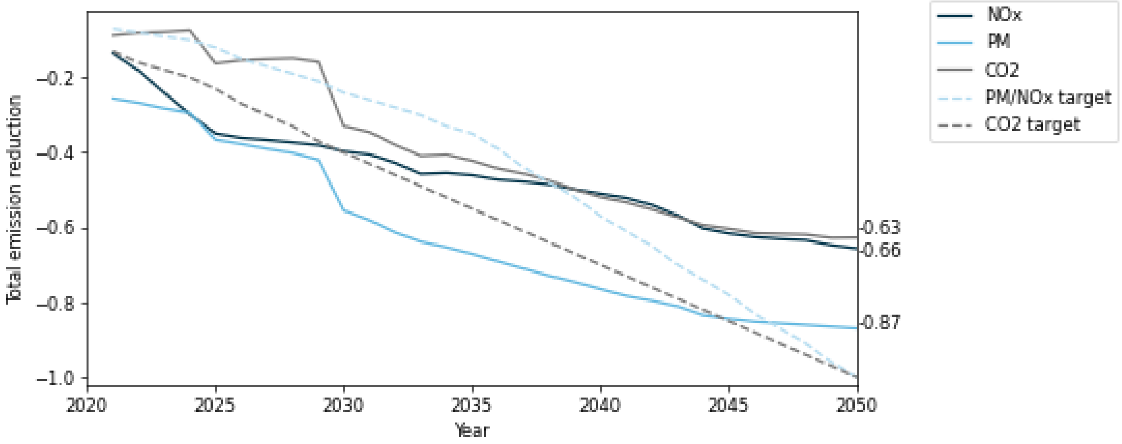


Figure 16: Emission reduction development towards 2050 in the base scenario

In 2025, 375 ships make their diesel engine fit for hydrogen combustion, which causes a steep drop in PM and CO_2 emissions. NO_x emissions are similar for hydrogen and diesel combustion. However, NO_x emissions are lowered in 2025 due to the installation of SCR, as explained above. Towards 2030, the PM and NO_x emissions are slightly lowered due to ships shifting to cleaner diesel Stage-V engines. Again, CO_2 emissions are slightly increasing due to the increasing size of the fleet. In 2030, it is expected that the bunkering infrastructure has improved and hence switching to a hydrogen-powered drivetrain becomes cheaper due to lower required storage capacity. Many IWT operators decide to make their engine fit for hydrogen combustion in 2030, which explains the large drop in CO_2 and PM emissions. After 2030, the emissions gradually decrease as more IWT operators decide to install a hydrogen-powered drivetrain. In 2043, a large number of hydrogen-powered fuel cells are installed, but emissions are only reduced to a limited extent. This indicates that IWT operators who have made their engines fit for hydrogen combustion in the past, now decide to install a hydrogen-powered fuel cell. In such cases, the CO_2 and PM emissions have been reduced significantly in the past, while the NO_x emissions remained high in case these ships did not install an SCR catalyst.

The emission reduction cannot be directly linked to the number of new engine types installed because the emission reduction depends on the ship's engine power, annual operating hours, and the old engine's building year. For instance, replacing older engines of large vessels result in larger emission reductions.

4.2.3 Hydrogen demand

The hydrogen demand rises to 14.8 PJ in 2050 in the base scenario (Figure 17). Large increases in hydrogen demand can be detected in years where many ships shift to hydrogen. However, note that some ships can have a larger fuel consumption than others. In addition, ships shifting to a hydrogen-powered combustion engine generally have a larger hydrogen consumption than ships shifting to a hydrogen-powered fuel cell due to lower efficiencies. Especially when the hydrogen share in the fuel mix for hydrogen-powered combustion engines becomes larger and fuel cell efficiency increases towards the future. From 2043, Figure 17 shows that the hydrogen demand stagnates, while new hydrogen-powered fuel cells are still installed according to Figure 13. This indicates that ships that have made their engine fit for hydrogen combustion in the past, now switch to a hydrogen-powered fuel cell or are being scrapped. In 2049, 17 ships are being scrapped that have made their engine fit for hydrogen combustion in the past, which contributes to the small drop in hydrogen demand.

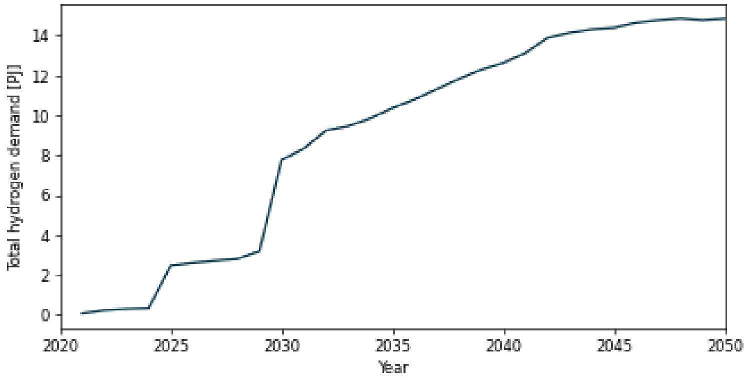


Figure 17: Hydrogen demand development towards 2050 in the base scenario

4.2.4 Base scenario assuming optimistic fuel cell price developments

Figure 18 shows that an optimistic price scenario for fuel cells incentivizes IWT operators to install a hydrogen-powered fuel cell earlier. Here, the fuel cell price drops to 600 and 80 [€/kW] in 2030 and 2050, respectively. In early years, many IWT operators still decide to make their engine fit for hydrogen combustion. However, many ships install a hydrogen-powered fuel cell in later years. The first peak occurs in 2036, which are the ships with favorable characteristics. Then, the second peak occurs from 2042, when more mainstream ships shift to a hydrogen-powered fuel cell.
In Figure 19 the emission reductions over time have been illustrated. The figure shows that all emission are eliminated in 2048 in this scenario. This means that all ships have installed a hydrogen-powered fuel cell, including ships that have shifted to a diesel-powered combustion engine in the past. Although emission targets for 2050 are achieved in this scenario, intermediate targets for CO_2 emissions are not yet achieved.

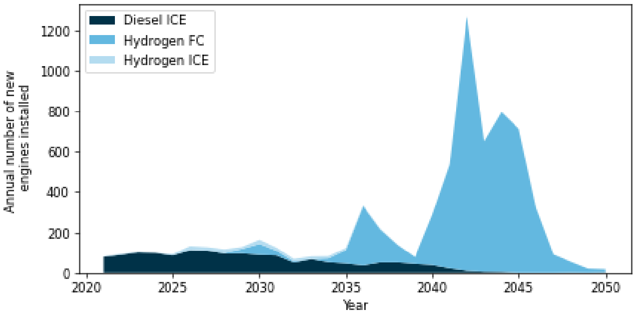


Figure 18: New engine types installed towards 2050 in the base scenario assuming an optimistic fuel cell price development

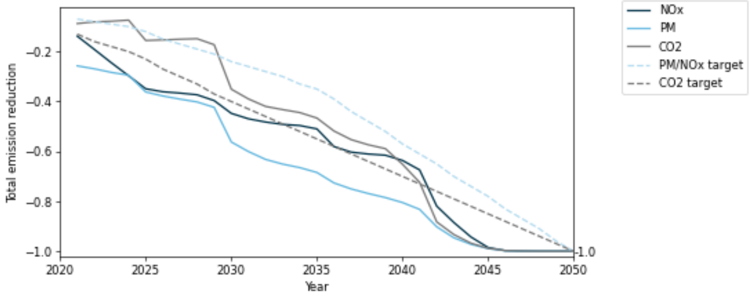


Figure 19: Emission reduction towards 2050 in the base scenario assuming an optimistic fuel cell price development

4.3 Policy effects

The effect of a CO_2 price, an HBE obligation, a ban on the installation or revision of (diesel) combustion engines, and a hydrogen blending obligation are evaluated separately using the conservative fuel cell price development.

4.3.1 CO2 price

The introduction of CO_2 taxes has been evaluated and depicted in Figure 20. The CO_2 price is charged on top of the diesel price, which motivates IWT operators to make their engines fit for hydrogen combustion or choose to replace their existing engines (earlier) by a hydrogen-powered drivetrain.

CO_2 prices that gradually rise to 40 [€/t] in 2050 do not have significant effects on NO_x and PM emission reductions (Fig. 20). This indicates that IWT operators who installed a new diesel-powered combustion engine in the base scenario, now switch to a hydrogen-powered drivetrain. In this case, NO_x and PM emissions have dropped to Stage-V standards already in the base scenario, whereas CO_2 emissions remained relatively constant. When the CO_2 price rises beyond 40 [€/t] in 2050, ships that have made their engine fit for hydrogen combustion in the base scenario, now install a hydrogen-powered fuel cell. This is displayed in Figure 20 by a stronger reduction in NO_x than CO_2 emissions. For CO_2 prices beyond 80 [€/t], the trend for all emissions is similar. This indicates that many IWT operators who did not replace or adjust their engine in the base scenario, now replace their old diesel-powered combustion engine by a hydrogen-powered fuel cell. Finally, a CO_2 price of 240 [€/t] in 2050 would encourage all ships to install a hydrogen-powered fuel cell because all emissions would be eliminated.

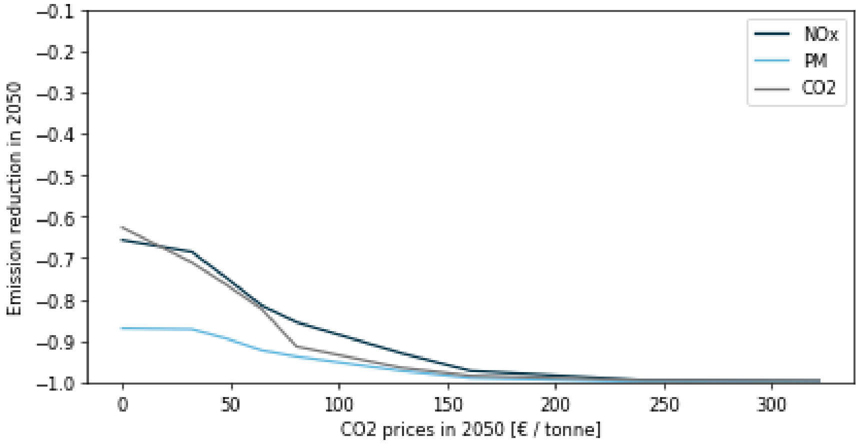


Figure 20: Effect of CO_2 price on emission reduction in 2050

CO_2 tax revenues

The CO_2 tax can be turned on in the model. In that case, by default, the CO_2 price starts at 50 [€/t] in 2021 and rises to 160 [€/t] in 2050. Given these settings, the annual total CO_2 tax revenues are depicted in Figure 21. The CO_2 tax revenues remain relatively constant around €70 million annually, which relates to an increasing CO_2 price and decreasing CO_2 emissions. After 2044, the CO_2 tax revenues drop due to an increasing number of ships that shift to a hydrogen-powered drivetrain. Note that no CO_2 revenues are generated when the IWT sector is included in the ETS, as explained in section 3.3.2.

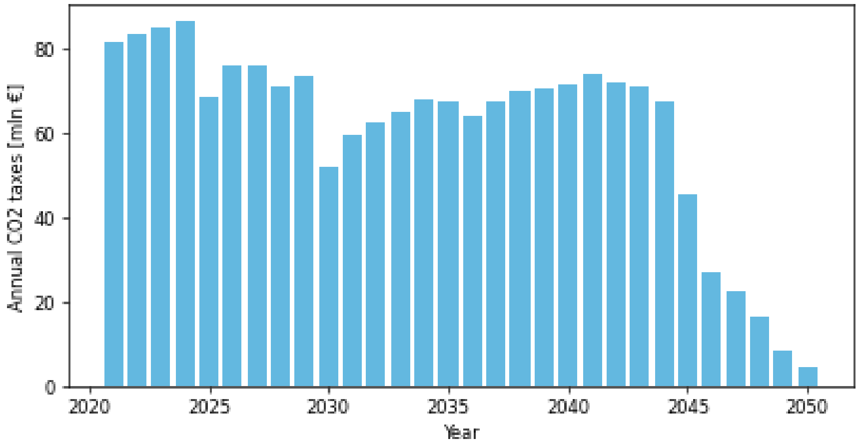


Figure 21: CO_2 tax revenues towards 2050 with a CO_2 price rising to €160 per ton in 2050

Innovation fund

An innovation fund is filled with government budget or CO_2 tax revenues from the sector. Subsidies from this fund would help strengthen the business case for hydrogen-powered drivetrains. Moreover, IWT operators would find it more interesting to replace their engine earlier than the original replacement year. In this case, subsidies are provided for the capital investment in hydrogen-powered fuel cells including the storage tank. The subsidies cover 40% of the capital investment, are capped at €500.000, and are only provided to IWT operators that would not prefer a hydrogen-powered fuel cell otherwise. These numbers have been picked arbitrarily to show the effect of subsidies. However, the provision of subsidies can be optimized to achieve the highest effectiveness on the shortest term.

The described conditions for providing subsidies results in annual total subsides as depicted in Figure 22. It shows that in early years, relatively low amounts of total subsidies are provided because the subsidy is often not sufficient to bridge the gap between TCO of hydrogen-powered fuel cell and a new diesel-powered or hydrogen-powered combustion engine. In later years, the gap decreases and more IWT operators receive the subsidy. However, the years 2025 and 2030 are exceptions. 2025 is the first year in which large scale installation of hydrogen-powered drivetrains is assumed possible. In 2030, there is a drop in total cost for storage aboard because the infrastructure has improved which allows more frequent bunkering. In those years, the TCO gap is suddenly small enough to be covered by the subsidies.

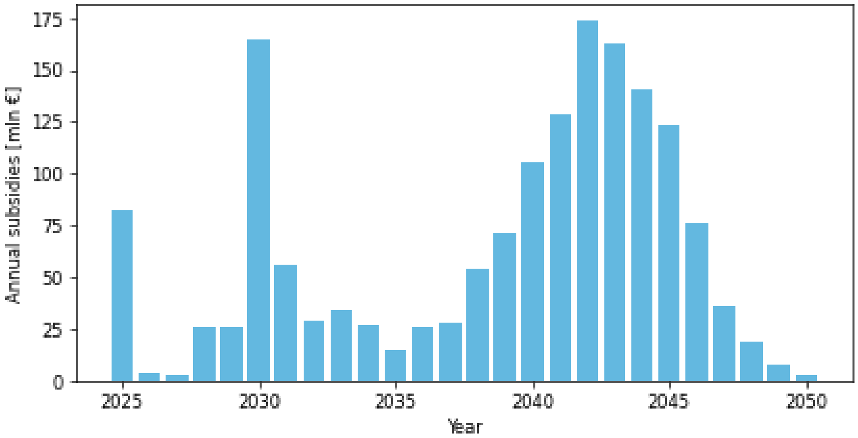


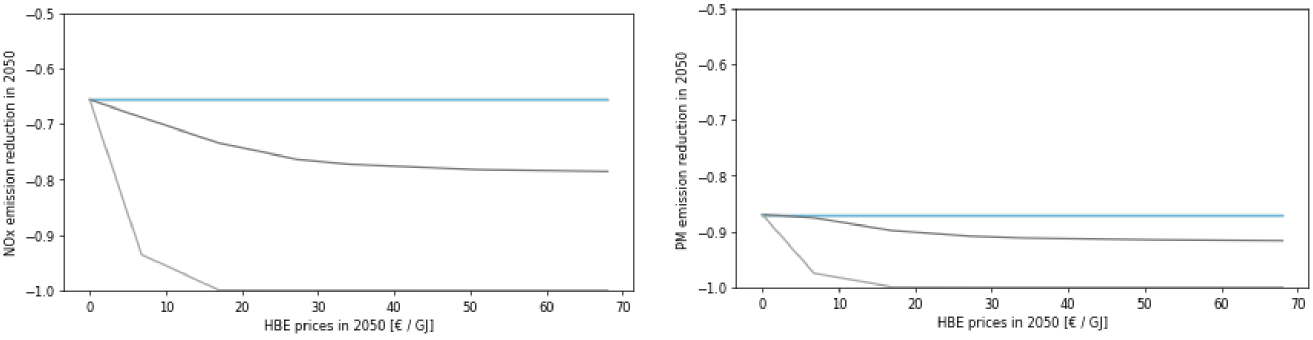
Figure 22: Annual total subsidies provided on hydrogen-powered fuel cell capital investment using a 40% funding rate that is capped at €500.000

The subsidies in conjunction with a CO_2 price that rises to 160 [€/t] in 2050, result in a full elimination of all emissions in 2050. This would not be achieved with a stand-alone CO_2 price because CO_2 emissions only reduce up to 95% in that case (Figure 20. Furthermore, ships shift earlier to a hydrogen-powered fuel cell due to the subsidies provided. Hence, emissions drop in earlier years, which contributes to reaching intermediate emission targets.

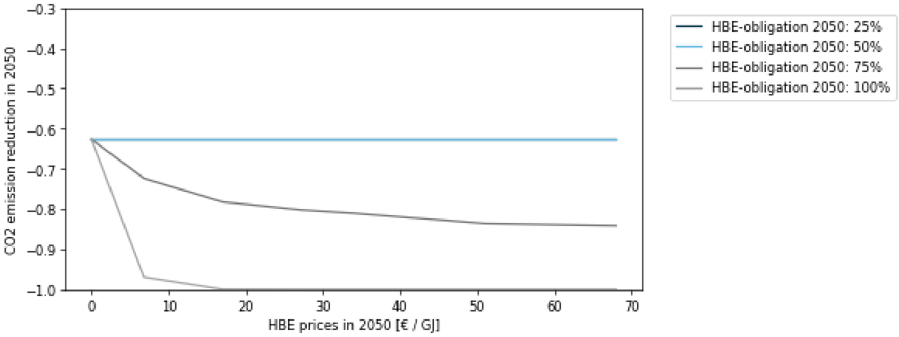
4.3.2 HBE obligation

The effects of an HBE obligation on the NO_x, PM, and CO_2 emissions have been depicted in Figure 23. The effect is determined by the share of renewable energy that must be supplied to the sector (HBE obligation level) and the HBE price. The HBE premium that is charged on top of the diesel price is determined endogenously, as explained in section 3.3.1. In years where the sector's renewable energy consumption is higher than the HBE obligation level, the HBE premium is zero. The figures show that an HBE price of 17 [€/GJ] is sufficient to eliminate all emissions by 2050 when the HBE obligation level equals 100% in 2050. In this scenario, an HBE price beyond 17 [€/GJ] in 2050 would result in higher emission reductions in earlier years. In other scenarios, the HBE premium remains low in many years due to a smaller or no gap between the HBE obligation and the sector's renewable energy consumption. Hence, fewer IWT operators decide to install a hydrogen-powered drivetrain before 2050. In case the HBE obligation level is set to 25 or 50% the HBE regime has no effect.

In reality, when the HBE obligation levels are set in accordance with intermediate emission targets, the HBE regime contributes to reaching CO_2 and PM targets virtually. Although not all emission reductions may be achieved within the sector itself, the emissions are reduced in other sectors that are cheaper to decarbonize. NO_x emission reductions may fall short when many IWT operators decide to install a hydrogen-powered combustion engines, which display comparable NO_x emissions to diesel-powered combustion engines.



(NO_x) (PM)



(CO_2)

Figure 23: The effects of HBE obligation and HBE price levels on NO_x, PM, and CO_2 emission reduction in 2050

4.3.3 Ban on (diesel) combustion engines

Ban on new diesel engines

Figure 24 shows the effect of a ban on new diesel engines in different years on the emission reductions in 2050. It turns out this ban has almost no effect on NO_x and PM emissions. Ships that would shift to a new diesel-powered combustion engine in the base scenario now shift to a hydrogen-powered combustion engine, which is the next best alternative in most cases. New hydrogen-powered and diesel-powered combustion engines have comparable NO_x emissions that comply with Stage-V standards. In addition, PM emissions are already negligible for new diesel-powered combustion engines (see Table 4), which explains why shifting to a hydrogen-powered combustion engines does not results in large additional PM emission reductions.

The CO_2 emissions drop steadily when the ban on new diesel-powered combustion engines is introduced earlier. The drop in CO_2 emissions depends on (1) the number of new diesel-powered combustion engines installed in the base scenario from the introduction year onwards, (2) the hydrogen share in the fuel mix of hydrogen-powered combustion engines, and (3) the number of ships preferring a hydrogen-powered fuel cell over a hydrogen-powered combustion engine. A ban on new diesel engines is more effective when combustion engines are completely banned. In that case, IWT operators are forced to install a hydrogen-powered fuel cell when (re)placing their engine.

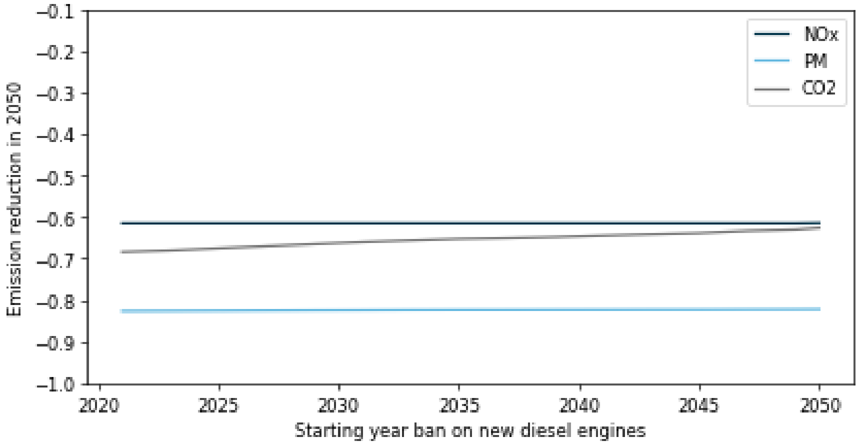


Figure 24: Effect of ban on new diesel engines on emission reduction in 2050

Ban on revision and placement of combustion engines

The long engine lifetimes allow ships to use their current engines beyond 2050. Hence, a ban on the revision of current engines would result in a forced earlier replacement. In addition, in order to gain additional emission reductions in 2050, the ban on diesel engines can be extended to all combustion engines. Figure 25 shows the joined effect of a ban on the revision and placement of combustion engines in different years on the emission reductions in 2050. This policy measure would force IWT operators to replace their engine earlier by a hydrogen-powered fuel cell. The figure illustrates that the earlier the ban is introduced, the more emissions are reduced in 2050. The ban triggers the following dynamics in the model:

1. Some IWT operators that installed a new hydrogen- or diesel-powered combustion engine in the base scenario, now install a hydrogen-powered fuel cell in the revision year.
2. Some IWT operators that made their engine fit for hydrogen combustion, now install a new hydrogen-powered combustion engine in the revision year.
3. Some IWT operators that did not replace or adjust their engine in the base scenario, now install a new hydrogen-powered fuel cell in the revision year.

The first dynamic results in lower NO_x and CO_2 emissions, while the PM emissions remain similar. The PM emission are already low for new hydrogen- and diesel-powered engines that comply with Stage-V standards (Table 4). The second and third dynamic reduce all emissions, but PM and CO_2 emissions are only reduced for the share of diesel used in the fuel mix in case the engine has been made fit for hydrogen combustion in the past. Although IWT operators are obliged to install a hydrogen-powered fuel cell when replacing their ships' engine, yet a large number of ships is still equipped with a diesel-powered combustion engine. This is due to the long engine lifetimes, as specified in Table 4. In total, 1771 ship engines are not replaced or revised in the period 2020-2050. Although some ships replace their engine due to economic benefits, for most ships the economic incentives are not sufficient.

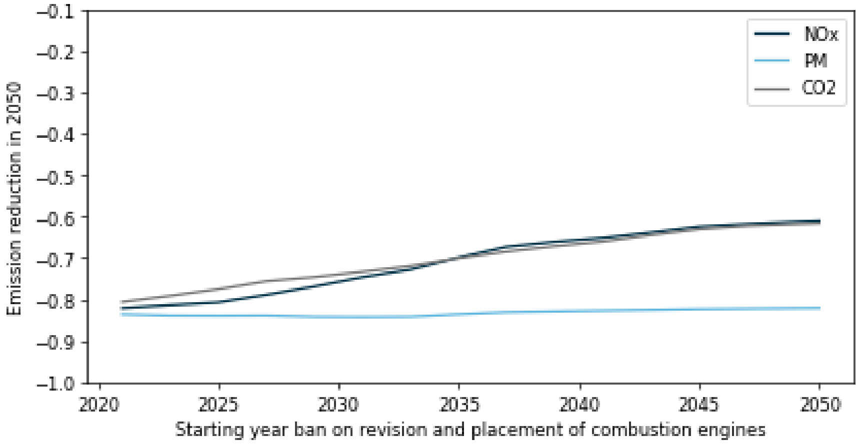


Figure 25: Effect of ban on the revision and placement of combustion engines on emission reduction in 2050

4.3.4 Hydrogen blending obligation

The effect of the introduction of a 55% hydrogen blending obligation in 2030 has been depicted in Figure 26. The percentage has been based on the hydrogen share that is currently possible in hydrogen-powered combustion engines (Table 12). The year has been picked arbitrarily to illustrate the effect. In general, it holds that a larger percentage leads to more significant emission reductions. The year determines the moment and magnitude of the emission drop. The earlier the hydrogen blending obligation is introduced, the larger the emission drop due to a larger number of ships that are not equipped with a hydrogen-powered drivetrain yet. This policy forces IWT operators to make their diesel engines fit for hydrogen combustion. As a result, in 2030, there is a steep drop in PM and CO_2 emissions. NO_x emissions from diesel and hydrogen-powered combustion engine are comparable, which explains the absence of a significant NO_x emission drop. NO_x emissions can only be reduced when SCR catalysts are installed. Finally, a small increase in NO_x and CO_2 emission can be detected in 2034 because the 20 commissioned ships are much larger than the 20 scrapped ships in that year. PM emissions are negligible for new hydrogen-powered combustion engines according to Stage-V standards and therefore remain relatively constant in that year.

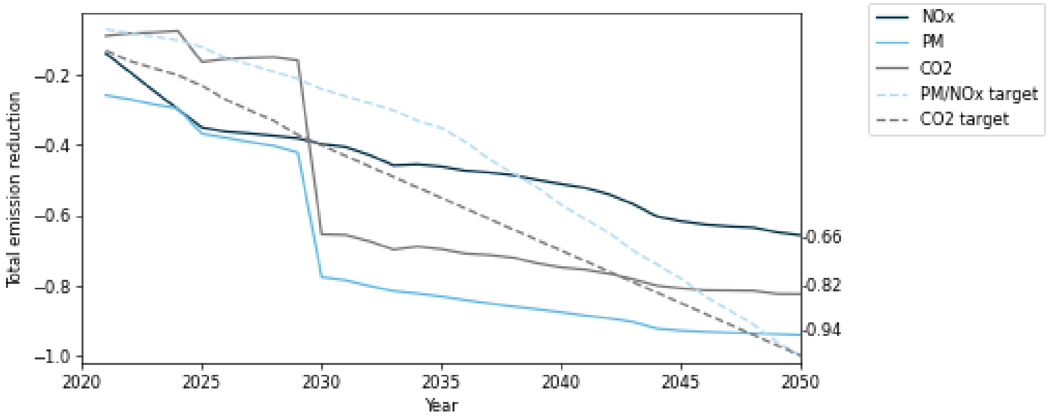


Figure 26: Effect of hydrogen blending obligation on emission reduction towards 2050

When introducing a 55% hydrogen blending obligation, the remaining diesel fleet needs to be equipped with a hydrogen storage tank and some engine adjustments are necessary. The total investment required to transition the remaining diesel fleet is presented in Figure 27. The total fleet investment reduces from €1.8 billion in 2021 to €0.2 billion in 2050 as more ships have shifted to hydrogen in the meantime. It seems reasonable to refund a certain percentage of the investment through subsidies. Note that the total fleet investment would be lower when other policies are introduced in conjunction with the hydrogen blending obligation.

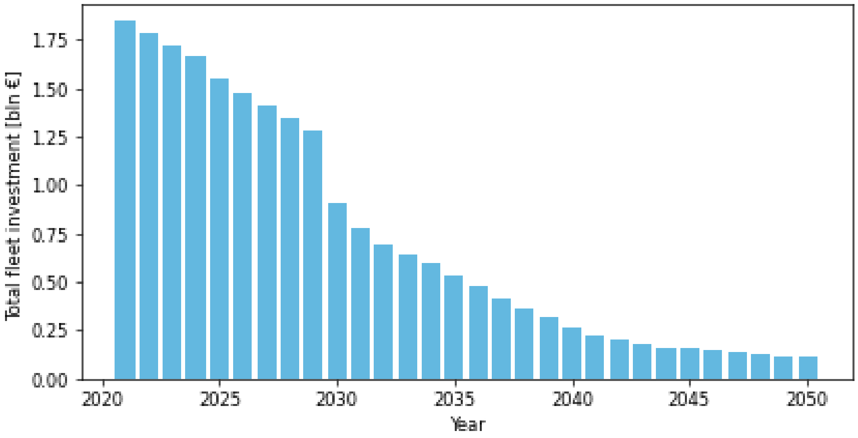


Figure 27: Total investment for making the remaining diesel fleet fit for 55% hydrogen combustion towards 2050

4.4 Alternative scenarios

Two alternative scenarios are proposed based on the effects of policy measures. Alternative scenario 1 includes the introduction of an HBE obligation and a hydrogen blending obligation. Alternative scenario 2 includes a CO_2 price and subsidies on fuel cell system investments. The alternative scenarios have been evaluated assuming both conservative and optimistic fuel cell price developments. Ultimately, the alternative scenarios are designed to meet the emission targets in 2030 and 2050.

Alternative scenario 1

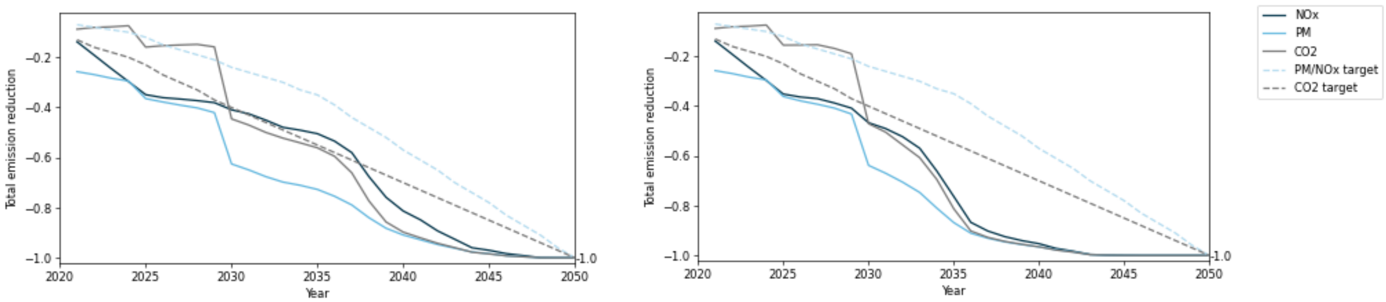
This alternative scenario includes an introduction of an HBE obligation. The results (Figure 23) indicate this is an effective measure for reducing emissions. Plans are being made by policymakers to introduce this policy measure in 2022. Furthermore, the first alternative scenario includes a hydrogen blending obligation of 20% in 2030. The introduction of a hydrogen blending obligation does not lead to significant additional reductions in 2050, but would be required to reach intermediate CO_2 emission targets in 2030. The effect of a hydrogen blending obligations can be considered similar to a CO_2 emission cap that limits the amount of emitted CO_2 emissions for each ship. However, a CO_2 emission cap would also allow ships to switch to biodiesel, for instance. A blending obligations is also advised by governmental advisory bodies, as mentioned in section 3.3.1. The most significant model settings for alternative scenario 1 have been presented in Table 17.

Table 17: Settings alternative scenario 1

Variable	**Value**
CO_2 price	Inactive
Innovation fund	Inactive
Ban on placement diesel engines	Inactive
Ban on revision of combustion engines	Inactive
HBE obligation	Active
HBE obligation in 2050	100%
HBE price in 2050	€34 per GJ
Hydrogen blending obligation	Active
Hydrogen blending obligation year	2030
Hydrogen blending percentage	20%

Due to policy measures in the first alternative scenario, more ships have installed hydrogen-powered fuel cells. Although most ships shift to a hydrogen-powered fuel cell after 2037, many ships have made their engines fit for hydrogen in earlier years. Before 2030, 398 IWT operators have made these adjustments to their ship's engine, while the remaining ships were forced in 2030 by the hydrogen blending obligation. The total fleet investment for making the ships fit for hydrogen combustion is €0.8 billion. All of these converted engines have been replaced by a hydrogen-powered fuel cell later due to economic benefits. In 2050, all ships are equipped with a hydrogen-powered fuel cell and emissions drop to zero (Figure 28). The total hydrogen demand equals 16.4 PJ in 2050.

When assuming an optimistic fuel cell price development, the emission drop takes place in 2035 already and emissions are fully eliminated by 2045.



(1) (2)

Figure 28: Emission reductions towards 2050 in alternative scenario 1 assuming (1) conservative and (2) optimistic fuel cell price developments

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Alternative scenario 2

In the second alternative scenario, a CO_2 price and a subsidy on fuel cell investments have been introduced, which seem effective in reducing emissions according to the results. Plans are developed to include the shipping industry in the ETS, but the IWT sector is yet excluded. Subsidies are currently provided to a limited extent, but these funds could be expanded. A CO_2 price is able to reduce emissions significantly and subsidies are necessary to meet the emission targets. The CO_2 price is set in accordance with the sustainable development scenario and rises to 160 [€/t] in 2050. Before 2030, the subsidies refund 40% of the capital investment for a hydrogen-powered fuel cell because a large gap must still be bridged by most IWT operators in order to favour a hydrogen-powered fuel cell. After 2030, only 10% is refunded because hydrogen-powered fuel cells become more cost-competitive. For similar reasons, the subsidies are capped at €750.000 per ship in 2025, which gradually drops to €200.000 in 2050. The subsidies are only provided whenever the hydrogen-powered fuel cell TCO are higher than the diesel-powered combustion engine TCO. The most important settings for this scenario have been presented in Table 18.

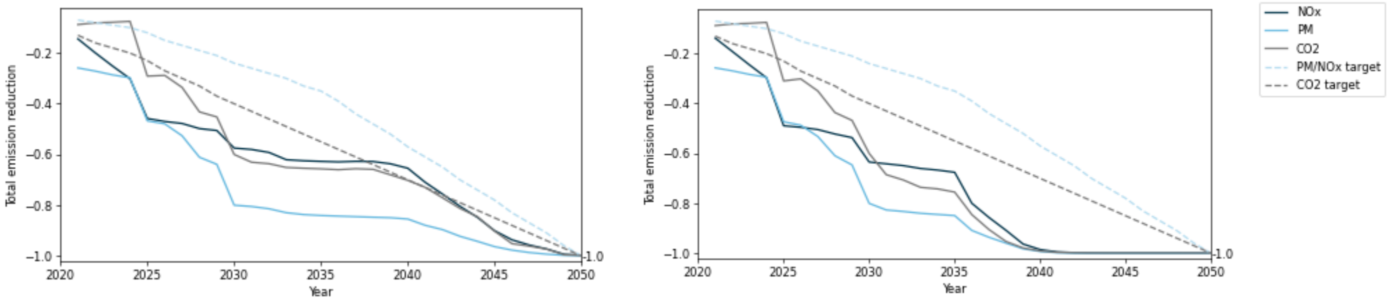
The introduction of a CO_2 price and a subsidy on fuel cell investments results in 100% emission reduction in 2050 (Fig. 29). Thanks to the subsidies and the CO_2 price, many ships shift to a hydrogen-powered fuel cell in 2025, which causes a large drop in emissions. Thanks to the CO_2 price, many shift decide to make their engine fit for hydrogen combustion before 2030. In total, CO_2 tax revenues comprise €1.6 billion, while only €700 million of subsidies is spent on transitioning the fleet. The subsidy provisioning system could even be optimized further. For instance, in this alternative scenario, 40% of the total investment is refunded for every ship before 2030, while for some ships, a smaller amount would suffice. In addition, an annual budget could be set, which

Table 18: Settings alternative scenario 2

Variable	**Value**
CO_2 price	Active
CO_2 price 2050	€160 per ton
Innovation fund	Active
Subsidy cap 2025	€750.000 per ship
Subsidy cap 2050	€200.000 per ship
Funding rate before 2030	40% of capital investment
Funding rate after 2030	10% of capital investment
Ban on placement diesel engines	Inactive
Ban on revision of combustion engines	Inactive
HBE obligation	Inactive
Hydrogen blending obligation	Inactive

would incentivize IWT operators to delay the engine replacement to years when there is still budget left. In later years, the fuel cell system costs are lower, and hence, the subsidies provided are lower too. In 2050, all ships are equipped with a hydrogen-powered fuel cell. In total, 3745 IWT operators decide to make their engine fit for hydrogen before they install a hydrogen-powered fuel cell. In 2050, the total hydrogen demand equals 16.4 PJ.

When assuming an optimistic fuel cell price development, the emissions drop faster and the fleet is already climate-neutral in 2040. Subsidies contribute to closing the TCO gap between hydrogen-powered fuel cells and diesel-powered combustion engines, especially in early years.



(1) (2)

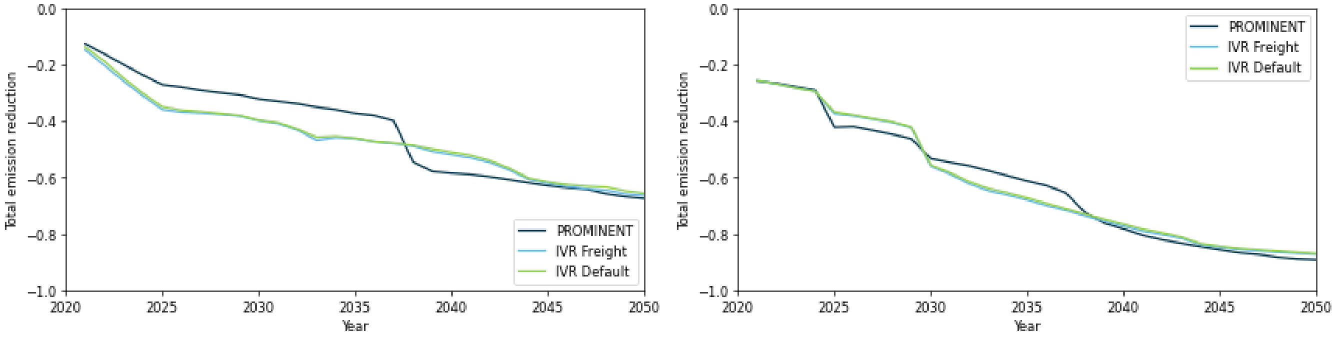
Figure 29: Emission reductions towards 2050 in alternative scenario 2 for (1) conservative and (2) optimistic fuel cell price developments

4.5 Sensitivity analysis

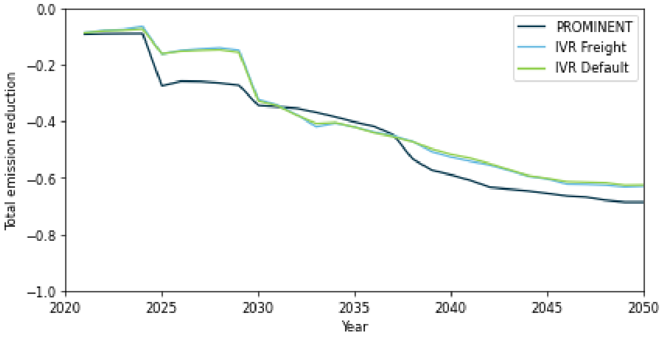
4.5.1 Sensitivity dataset

Two alternative datasets have been simulated in the transition model to gain insight into the effect of input data on the projected emission reductions. The NO_x, PM, CO_2 emission reductions for different input data using the base scenario settings have been depicted in Figure 30. The IVR Default is the dataset used in this research. The IVR Freight is the IVR Default dataset filtered on cargo ships and push boats. The PROMINENT dataset contains cargo ships and push boats only and is an improved version of the 2014 IVR Freight dataset.

Figure 30 shows slightly higher emission reductions in 2050 when the PROMINENT dataset is used as input data. In addition, some emission drops occur at another point in time. However, the differences in emission reductions using the PROMINENT and IVR database are only minor, which indicates that running the model using an updated version of the IVR database would affect the results to a limited extent. The deviations between the emission reduction developments are hard to explain as the changes made in the PROMINENT database are not documented specifically. Finally, only minor deviations can be detected between the IVR Freight and the IVR Default dataset. This indicates that leaving out passenger ships from the analysis would hardly change the results.



(NO_x) (PM)



(CO_2)

Figure 30: NO_x, PM, and CO_2 emission reduction development for multiple datasets

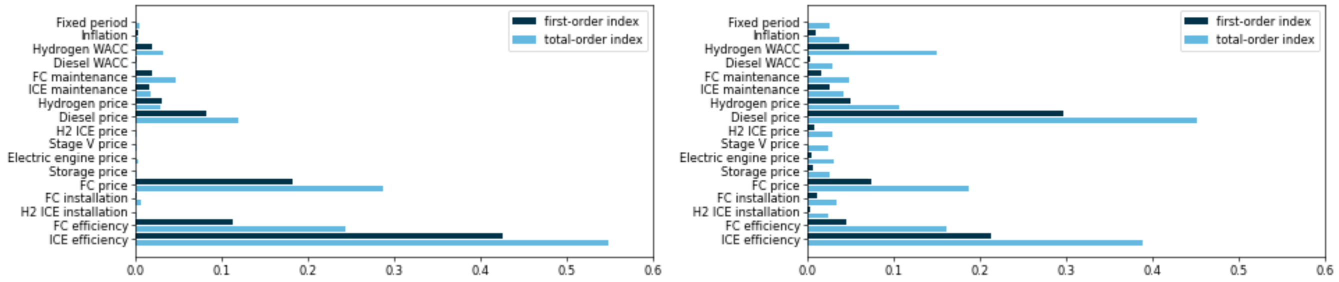
4.5.2 Sensitivity parameters

The results of the sensitivity analysis on input variables provide a simple overview of the most influential factors in the transition model. Though, the analysis explains the dynamics underlying the results only to a limited extent. Especially for total-order indices, it is hard to identify the origin of the effect. The theory about the interpretation of the results is recapped briefly here. The sensitivity analysis generates three sensitivity indices that are:

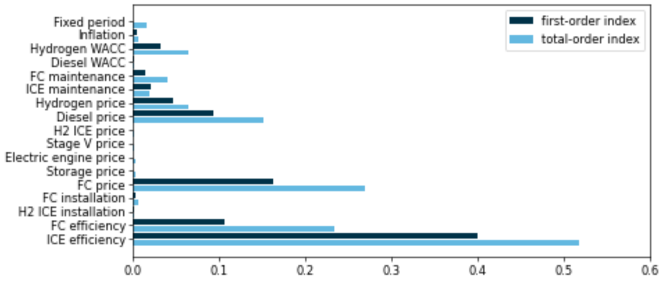
1. First-order indices indicate the individual contribution of a single input variable to the output variance averaged over the contribution of other input variables.
2. Second-order indices indicate the contribution to the output variance caused by the interaction of two input variables.
3. Total-order indices indicate the total contribution of single input variables to the output variance. The total contribution includes first-order effects and all second-order interactions.

Sensitivity index values greater than 0.05 are considered significant. Furthermore, the total-order index must be greater than the first-order index, and confidence levels must be lower than 0.1. More detailed output, including confidence levels and second-order indices, can be found in Appendix F.

Figure 31 shows the output of the sensitivity analysis for NO_x, PM and CO_2 emissions. The drivetrain efficiency turns out to have significant effects on the emissions. Higher efficiencies would significantly reduce fuel consumption, which reduces the fuel and storage tank cost proportionally. Fuel cost and the investment costs comprise a large part of the TCO. For instance, low efficiencies for combustion engines would put hydrogen-powered fuel cells in a better position, which would result in lower emissions. Relatively, a larger increase in fuel cell efficiency is required to achieve a similar effect because fuel costs comprise a smaller part of the hydrogen-powered fuel cell TCO. Hence, the influence of fuel cell efficiency is smaller than the influence of combustion engine efficiency. According to Appendix F, some second-order effects can be identified between the combustion engine efficiency, and the fuel cell efficiency and the diesel price. These are all influential input variables that are mutually reinforcing. For instance, a high fuel cell efficiency would reinforce a low combustion engine efficiency and be very beneficial for the business case of hydrogen-powered fuel cells.



(NO_x) (PM)



(CO_2)

Figure 31: Effect of input variables on NO_x, PM, and CO_2 emission reductions in 2050

The sensitivity analysis shows a significant effect of fuel cell prices. A reduction in fuel cell prices reduces the capital investment and would indirectly reduce maintenance cost. The capital investment comprises a large part of the hydrogen-powered fuel cell TCO. When hydrogen-powered fuel cells become competitive with other drivetrains, the greatest emission reductions can be achieved.

The diesel price has a significant effect on all emissions. Diesel costs comprise a large part of the TCO for a diesel-powered drivetrain. High diesel costs would put hydrogen-powered drivetrains in a better position and stimulate IWT operators to replace their engine before 2050. Diesel prices have a larger effect than hydrogen prices because the sensitivity analysis allows diesel prices to rise more in an absolute sense. A doubling of the diesel price would be more influential than a doubling of the hydrogen price because the hydrogen price is lower in general.

The remaining input variables do not display any significant (>0.05) first-order effects. However, significant total-order effects on the PM and CO_2 emissions can be detected for the hydrogen price and hydrogen WACC. The hydrogen price can interact with the fuel cell efficiency, for instance. The effect of a hydrogen price is reinforced by a low fuel cell efficiency. The hydrogen cost contribute substantially to the TCO of hydrogen-powered drivetrains, especially for hydrogen-powered combustion engines. Installing a hydrogen-powered combustion engine particularly decreases PM and CO_2 emissions. Finally, the hydrogen WACC can interact with the fuel cell price, for instance. High fuel cell prices reinforce the influence of the WACC for hydrogen-related investments. As mentioned before, the fuel cell price largely influences the TCO, and so does the hydrogen WACC.

5 Discussion

This research aims to identify policy measures that facilitate the hydrogen transition and help achieve emission targets in the Dutch IWT sector. Although the results indicate a potential for hydrogen, various factors, such as technology and policy development, determine whether hydrogen will be adopted in the IWT sector. This chapter discusses the results, complexities, limitations, and other considerations involved in this thesis.

First and foremost, it should be noted that the techno-economic simulation of the hydrogen transition in this research is based on various literature-based assumptions, such as the cost development for hydrogen and fuel cells. The sensitivity analysis indicates that the most influential input variables are drivetrain efficiency, fuel cell prices and diesel prices.

There is a wide range of estimates present in the literature, either more optimistic or more conservative than the numbers used in this thesis. For instance, PWC (2021) estimate green hydrogen production costs at 1.88 [€/kg] on average for the Netherlands in 2050, which is more conservative than the 1.01 [€/kg] used in this research based on BloombergNEF (2020). These different estimates are caused by the underlying assumptions used in the studies, such as the levelized costs of electricity from offshore wind. Furthermore, the assumptions about fuel cell price development vary across studies. Van Biert et al. (2021) predict fuel cell prices for heavy-duty applications drop to 80 [€/kW] in 2050, while IEA (2019a) claims fuel cell prices for ships only drop to 840 [€/kW]. When an optimistic fuel cell price development is assumed, the results suggest that emission targets in 2050 can be met without any policy interventions. However, some intermediate targets are not achieved, especially regarding CO_2 emissions.

In addition to the uncertainty in the parametrization of the model, the input dataset may also influence the results. The IVR database is not entirely up to date because the database depends on IWT operators' information supply. Therefore certain ships may not be active anymore or have installed another engine type. However, simulating the model using alternative (updated) datasets does not influence the outcomes significantly, as indicated in section 4.5.1.

The transition model mainly considers the economic trade-off between hydrogen- and diesel-powered drivetrains, whereas other factors, such as safety regulations, insurance policies, and bunkering infrastructure, are prerequisites for a successful transition. It is assumed that in 2025, regulations and sufficient bunkering infrastructure are in place. In addition, rational decision-making is assumed among IWT operators who consider total costs of ownership as their leading guide in the decision-making process. However, the quantitative transition model in this thesis is unable to recognize and model all tacit assumptions that guide stakeholder decisions in practice. Hence, quantitative models should ideally be complemented with qualitative transition scenarios, as suggested by McDowall (2014).

In most cases, the capital investment for hydrogen-powered drivetrains is greater than for diesel-powered engines. Given the rational decision-making approach, the model assumes that IWT operators have sufficient faith in future fuel cost reductions which can offset the larger capital investment. However, in reality, IWT operators are often risk-averse because they represent micro-sized (family) enterprises that operate or own only one vessel. A wrong investment decision could have severe consequences for these small enterprises. To limit the risk of switching to a hydrogen-powered drivetrain, IWT operators could decide to install new diesel-powered combustion engines and make the engine fit for hydrogen combustion whenever they are more confident about the business case for hydrogen. However, as long as the government continues to support alternatives such as biodiesel (HVO) in the long term, shippers will refrain from shifting to a hydrogen-powered drivetrain. Biodiesel requires no additional investments and hence presents a lower risk to IWT operators. Yet, the true sustainability of biodiesel is highly questioned in the literature when considering the entire value chain.

The transition model is designed to accurately represent the decision-making dynamics in the IWT sector. However, the true complexity can never be modeled, especially given the time schedule for this thesis. Hence, some ship characteristics and decision-making dynamics have been generalized. For instance, the average distance of a trip has been estimated for every ship based on the exemplary routes of four ship types (Appendix C). In addition, the potential missed revenues associated with reduced cargo space on hydrogen-powered ships have been neglected, although TNO (2019) claims these missed revenues are only 1-2% of the total operational expenditures, including fuel costs. Finally, the possibility that IWT operators favor a hydrogen-powered drivetrain over a diesel-powered drivetrain despite higher costs is largely excluded. A recent study shows that 20% of the shipping companies is prepared to pay a 3-10% premium for green logistics (Reifenberg & Wengler, 2021). In the transition model, only passenger ships are prepared to pay a 10% premium for a hydrogen-powered fuel cell due to the full elimination of emissions and noise reduction. In reality, other ships may be prepared to pay a similar premium.

5.1 Base scenario

This thesis indicates that hydrogen is a promising alternative for diesel that helps achieve significant emission reductions. However, in the base scenario, where hydrogen is offered as an alternative option, insufficient emission reductions regarding CO_2 (63%), NO_x (66%), and PM (87%) are achieved to meet the zero-emission targets for 2050 agreed on in the Green Deal. As total cost of ownership for hydrogen-powered drivetrains are often higher than for diesel-powered combustion engines, the latter is often installed in the (re)placement year of the engine. Total costs of ownership are considered the most important decision-making criterion for IWT operators. Regarding these total costs of ownership, policy interventions can potentially improve the competitive position of hydrogen-powered drivetrains and accomplish additional emission reductions.

5.2 Policy interventions

CO_2 tax

First of all, the introduction of CO_2 taxes has been modeled. The IWT sector is currently not covered by the ETS, which means IWT operators are not required to pay CO_2 taxes. However, the entire European IWT sector is potentially included when emission reductions prove unsatisfactory. Alternatively, the Dutch government could decide to introduce CO_2 taxes on a national level. A tax measure is relatively easy to implement and administer on a national level compared to a European level (CCNR, 2021d). However, introducing CO_2 taxes on a national level could inhibit the effect of such a policy. For instance, diesel-powered ships could decide to bunker in neighboring countries, or international companies could decide to ship their cargo through other countries.

The results suggest that CO_2 prices that gradually rise to 40 [€/t] in 2050 do not have significant effects on NO_x and PM emission reductions (Fig. 20). When the CO_2 price rises beyond 40 [€/t] in 2050, ships that have made their engine fit for hydrogen combustion in the base scenario, now install a hydrogen-powered fuel cell. For CO_2 prices beyond 80 [€/t], all emissions are decreased to a similar extent. This indicates that many IWT operators who did not replace or adjust their engine in the base scenario, now replace their old diesel-powered combustion engine by a hydrogen-powered fuel cell. Finally, a CO_2 price of 240 [€/t] in 2050 would encourage all ships to install a hydrogen-powered fuel cell and fully eliminate all emissions.

In the sustainable development scenario of the International Energy Agency (CO_2 prices rise to 160 [€/t] in 2050), CO_2 emissions (95%) would be significantly reduced. However, experts claim that a stand-alone tax does not provide the right financial incentivize to invest in hydrogen-powered drivetrains as the sector often perceives such a tax as a fine (CCNR, 2021d). The acceptance would be higher when the revenues are saved in a dedicated fund designated for investments in greening techniques in the IWT sector (CCNR, 2021d). As a result of introducing a CO_2 price, the fund would be filled with annual CO_2 tax revenues of approximately €70 million towards 2050. When this fund is used to further bridge the gap between hydrogen-powered drivetrains and diesel-powered drivetrain TCO, emissions are fully eliminated in 2050.

A CO_2 price set according to the ETS, ensures that the IWT sector is charged with the same CO_2 price as other sectors. However, the marginal abatement costs differ among sectors. The marginal abatement costs are relatively high in the IWT sector due to high investment cost for hydrogen-powered drivetrains and high remaining depreciation costs for old engines. This must be considered when introducing the CO_2 price in the IWT sector (CCNR, 2021d). When the CO_2 price is low, IWT operators tend the deduct additional costs from their margin. High additional costs are often passed on to the shipper (CCNR, 2021d). IWT operators are reluctant to pass on additional costs to shippers as they might shift to other modes of transport (i.e., rail or road), which could have disastrous consequences (CCNR, 2021d).

In general, a CO_2 tax is considered a fair mechanism because large polluters are taxed most. As the CO_2 tax directly relates to the emissions, IWT operators are incentivized to switch to a hydrogen-powered drivetrain that is associated with lower emissions (CCNR, 2021d). The CO_2 tax can be charged on top of the diesel price. In that case the CO_2 tax directly relates to the ship's fuel consumption (CCNR, 2021d).

Opposed the price-based national CO_2 tax, the ETS is a quantity-based economic instrument. This ensures that CO_2 and PM emission goals in the IWT sector are achieved virtually and the marginal abatement costs are minimized across the EU. Whereas the effectiveness of a price-based national CO_2 taxes depends on many uncertain cost developments (e.g. hydrogen price), the ETS ensures that emissions are reduced regardless of cost developments. However, note that NO_x emission reductions can fall short when many IWT operators decide to switch to a hydrogen-powered combustion engine. NO_x emissions from hydrogen-powered combustion engines are comparable to diesel-powered combustion engines, so reduced CO_2 do not result in reduced NO_x emissions.

HBE obligation

Second, an HBE obligation could be introduced, which can be considered as an quantity-based economic instrument. The results suggest that high obligation levels in 2050 can reduce emissions significantly. Currently, policymakers seek to introduce the HBE obligation in the IWT sector in 2022 where the HBE obligation level is set to 5 PJ in 2030. When introducing an HBE obligation, policymakers must consider unfair competition with other countries and modes of transport, as described above.

In reality, when the HBE obligation levels are set in accordance with (intermediate) emission targets, the HBE regime ensures that these targets for CO_2 and PM emissions are met virtually. When the HBE obligation level is not met in the IWT sector, fuel suppliers purchase HBE certificates from other sectors that are cheaper to decarbonize and charge the cost on to the IWT sector. A market mechanism of supply and demand for these HBE certificates determines the HBE price. However, a fixed price development is assumed in this thesis due to the inability to model such market mechanism within the scope of this thesis.

It is expected that the HBE price rises to 34 [€· GJ] in 2050 and the HBE obligation levels for 2030 and 2050 are set to 20% and 100%. The 20% in 2030 aligns with the current plans of 5 PJ HBE obligation in 2030. The 100% HBE obligation algines witht the zero-emission goals in 2050. Using these assumptions, introducing an HBE obligation in the IWT sector eliminates all emissions in 2050. However, intermediate CO_2 emissions targets are not met under this policy.

Ban on (diesel) combustion engines

Third, a ban on new diesel engines or the revision of conventional diesel engines could be introduced. According to the results, a ban on the installation of new diesel engines mainly reduces CO_2 emissions while NO_x and PM emission remain constant. IWT operators that installed a new diesel-powered combustion engine in the base scenario, now install a hydrogen-powered combustion engine, which is often the next best alternative.

In order to gain additional emission reductions in 2050, the ban on diesel engines can be extended to all combustion engines. In addition, the long engine lifetimes allow ships to use their current engines beyond 2050. Hence, a ban on the revision of current engines would result in a forced earlier replacement. This extension of the ban mainly results in larger NO_x and CO_2 emissions. Nevertheless, many engines are still not replaced or revised before 2050 due to long engine lifetimes. On average, engines need to be revised and replaced after 30 and 60 years, respectively. In reality, the economic lifetime of engines could be shorter due to cost developments, which would strengthen the effect of a ban on diesel engines. On the other hand, IWT operators may anticipate on a ban and install a combustion engine in the year before the ban is introduced, for instance. This would weaken the effect of a ban on combustion engines. Given this potential anticipation by IWT operators and the long lifetimes of ship engines, the emission reductions for 2050 cannot be ensured when introducing a ban on diesel engines.

The Netherlands seeks to introduce a ban on new diesel engines for cars in 2030. Setting the ban on new diesel engines for ships in the same year results in only minor additional emission reductions in 2050. When extending a ban in 2030 to the revision of all combustion engines, emissions are reduced up to 76%, 83%, and 75% in 2050 for NO_x, PM and CO_2 emissions, respectively.

Hydrogen blending obligation

Fourth, a hydrogen blending obligation could be introduced. This is quite an intense policy intervention because it forces all IWT operators to adjust their engines and install hydrogen storage tanks. In practice, such a policy could be shaped as a CO_2 cap on ship emissions. This offers IWT operators freedom to switch to other CO_2-reducing options, such as the installation of batteries. Such a direct regulation must be supported by subsidies to cover a large part of the investment and to prevent IWT operators to go bankrupt. A total investment of €0.25-1.8 billion would be required to make ships fit for 55% hydrogen combustion, depending on the introduction year of the blending obligation. For instance, a large part of the fleet has already shifted to hydrogen-powered drivetrains in the base scenario in 2040, which requires a smaller total fleet investment. In addition, other policies can stimulate IWT operators to install a hydrogen-powered drivetrain before the introduction year of the blending obligation, which would lower the total fleet investment.

As a result of the hydrogen blending obligation, CO_2 and PM emissions are reduced significantly. NO_x emissions, however, are only reduced when additional SCR equipment is installed, which has not been assumed. The hydrogen blending obligation may incentivize some IWT operators to use a larger share of hydrogen in the fuel mix than the obliged blending percentage because cost for adjusting the engine are incurred anyway. However, a larger share of hydrogen in the fuel mix would require additional investments in a larger storage tank.

Imposing direct regulations, such as a ban on new diesel engines or a hydrogen blending obligation, is considered inefficient from an economic perspective. Eventually, direct regulations lead to higher costs because IWT operators do not have the opportunity to pick technologies with the lowest marginal abatement costs (CCNR, 2021d). Here, economic instruments would provide more freedom of choice.

5.3 Alternative scenarios

As the overall financial capacity of the IWT sector is very limited due to the small average company size, IWT operators are often unable to finance hydrogen-powered drivetrains (CCNR, 2021e). Sometimes investments in new Stage-V diesel engines are already problematic. Hence, policies that make hydrogen-powered drivetrains more attractive and help finance the investment are deemed necessary. Current grants schemes on both national and EU level are only ensured for the short term and insufficient to close the financial gap between hydrogen- and diesel-powered drivetrains in most cases.

In the base scenario, emission reductions do not meet the objectives for 2050 yet. Therefore, this study developed two alternative scenarios that help achieve the emission targets. The CO_2 emission targets for 2024 are impossible to meet due to the model's constraints on the number of ships that can shift to a hydrogen-powered drivetrain before 2025. It is assumed that the regulations and infrastructure are not in place yet for large scale adoption of hydrogen before 2025.

Alternative scenario 1
In the first alternative scenario emission targets for 2030 and 2050 are met by introducing a 20% hydrogen blending obligation in 2030 and HBE obligation. Regarding the latter, the total fuel consumption must be renewable in 2050 and the HBE price rises to 34[€/GJ]. The HBE obligation ensures that all ships shift to a hydrogen-powered fuel cell before 2050, while the hydrogen blending obligation ensures that the intermediate emission targets in 2030 are met.

In reality, a hydrogen blending obligation would not be necessary when the HBE obligation levels are set in accordance with emission targets. In that case, the HBE policy ensure that emission goals for PM and CO_2 are met virtually. Although, insufficient ships may shift to a hydrogen-powered drivetrain, these ships pay indirectly for HBE certificates that are purchased from other sectors in which there is an excess of HBE certificates. These other sectors would then consume more renewable energy than is obliged under the HBE policy. However, to realize sufficient actual emission reductions within the sector, a hydrogen blending obligation in 2030 would be necessary. In practice, such a blending obligation can be introduced as a CO_2 cap on ship emissions. This offers IWT operators freedom to switch to other CO_2-reducing options, such as batteries.
Due to the low financial capabilities of IWT operators, the first alternative scenario would still require funding from the government. To make all remaining diesel-powered ships fit for 20% hydrogen combustion in 2030, a total investment of €500 million would be required under the current model's assumptions. It seems reasonable to refund a certain percentage of the investment through subsidies. Also, rising diesel prices, as a consequence of the HBE obligation, may be problematic

for some IWT operators. Although these additional costs can be passed on to shipping companies, financial support through subsidies on hydrogen-powered drivetrains would be desired to create a level playing field with other countries and modes of transport. Especially considering that the energy transition in the IWT sector is potentially more expensive than for road transport due to higher marginal abatement cost. The provisioning of subsidies is elaborated upon in alternative scenario 2.

In this first alternative scenario, the achievement of PM and CO_2 emission goals is not dependent on the assumptions made in this study. For instance, if the hydrogen price development falls short and fewer ships switch to a hydrogen-powered drivetrain, fuel suppliers must still purchase sufficient HBE certificates to meet the HBE obligation levels. Moreover, IWT operators are still forced to comply with the hydrogen blending obligation. However, additional financial support may be required to help finance the transition, especially when policies are not introduced at EU level. In the first alternative, emissions are fully eliminated in 2045. Stricter regulations (i.e. stricter blending obligations and higher HBE obligation levels in earlier years) could ensure that emissions are fully eliminated earlier than 2045.

Alternative scenario 2

In the second alternative scenario emission targets for 2030 and 2050 are met by introducing a CO_2 tax and subsidies on the capital investment of fuel cell systems, which are financed through an innovation fund. The CO_2 price increases the cost of diesel and the subsidies lower the cost of fuel cells, which both have significant first-order effects on the emission reduction in 2050, according to the sensitivity analysis. A CO_2 price is able to reduce emissions significantly, but additional subsidies are necessary to meet the emission targets.

The CO_2 price in the second alternative scenario is set in accordance with IEA's sustainable development scenario and rises to 160 [€/t] in 2050. Here, the CO_2 price is assumed to be determined exogenously because market mechanisms are hard to model. Ideally, the CO_2 price is aligned across neighboring countries and other modes of transport to create a level playing field. This would allow IWT operators to pass on the additional costs to their customers without the risk of losing them. A level playing field could be created by including the entire EU IWT sector in the ETS system. A quantity-based CO_2 price that is determined endogenously by the ETS, would ensure emissions reductions, while the effect of a national price-based CO_2 tax depends on the fuel and capital cost development. Moreover, IWT operators are often risk averse and may not install a hydrogen-powered drivetrain when the TCO for a hydrogen-powered drivetrain proves to be the lowest.

In addition to the CO_2 tax, €700 million of subsidies must be provided in the second alternative scenario, given the model's assumptions. This would be sufficient to bridge the hydrogen-powered fuel cell TCO and diesel-powered combustion engine TCO. However, the allocation of subsidies is complex. The funding rates and subsidy caps used in the second alternative scenario are only effective under the model's assumption, which can differ in reality. For instance, in the model, TCO for new diesel-powered combustion engines have been based on a cleaner but more expensive diesel Stage-V engine. However, even financing such a Stage-V diesel engine may be problematic for some IWT operators, which implies that higher subsidies would be required to support these IWT operators. Furthermore, based on Austrian experience, the funding rate should be set as high as possible to counteract the limited investment capacity of the sector (CCNR, 2021d). Funding rates of at least 50% of the total capital investment are preferred for greening technologies (CCNR, 2021b) and often even higher for fuel cell investments (CCNR, 2021d). However, setting funding rates too high results in unnecessary public costs, while setting funding rates too low prevents IWT operators from installing a hydrogen-powered drivetrain. The funding rate could be optimized based on ship characteristics, although this make the process more cumbersome. For instance, high funding rates would apply for smaller ships with lower operating hours that are struggling to offset a large capital investment by savings on fuel cost.

Anyway, a large fund for subsidies is required to transition of IWT sector towards hydrogen. The size of the fund should also be seen relative to the environmental costs that originate from emissions in the IWT sector. These environmental costs are currently over €1 billion annually, according to the environmental prices specified by CE Delft (2018c).

When introducing the innovation fund to finance the hydrogen transition, finding the right balance between an attractive and effective fund is crucial. The attractiveness of a fund refers to simplified application procedures, uniform interpretation of rules, development of synergies with other programs, the availability of pre-finance, et cetera (CCNR, 2021d). Furthermore, reliable information should be offered to IWT operators on the existence of funding and financing options. An effective fund ensures that the fund is optimally used, which requires project beneficiaries to prepare and implement eligible projects, and involves a certain level of checks and controls (CCNR, 2021d).
In conclusion, in the second alternative scenario, emission reductions are only ensured when quantity-based economic instruments are used. For instance, the IWT sector could be included in the ETS. The effect of price-based instruments, such as national CO_2 taxes and subsidies, is highly uncertain because the required tax and funding rates depend on the cost development. Setting rates too low would not incentivize sufficient IWT operators to install a hydrogen-powered drivetrain. In order to reach emissions targets, these rates must be constantly adjusted, which is a cumbersome process. Moreover, quantity-based economic instruments ensure that marginal abatement costs are minimized.

5.4 Recommendations to policymakers

Policymakers need to create an attractive environment where regulations are in place, and the business case for hydrogen is ensured to facilitate the hydrogen transition in the Dutch IWT sector. More specifically this involves action on infrastructure and regulations, and the introduction of economic policies. These focus points have been explained below.

Infrastructure and regulation

At the moment, there is a lack of regulation about safety requirements for bunkering infrastructure and aboard ships. The permitting process for bunkering infrastructure is cumbersome and should be clarified as the bunkering infrastructure is an important prerequisite for the transition. The results indicate that frequent bunkering behavior allows to decrease the size of a hydrogen storage tank aboard ships and decrease cost significantly. The bunkering infrastructure must facilitate the loading and unloading of portable storage containers to minimize bunkering times. Furthermore, a legal basis is necessary for transporting hydrogen through pipelines and a licensing system must be set up to license measuring equipment and qualify service engineers.

Multiple technologies (e.g., batteries and methanol) are being developed that allow to decarbonize the IWT sector. As long as no technology has obtained a dominant status, IWT operators are reluctant to choose a new technology. Preferably, IWT operators shift to HVO, which presumably allows decarbonizing the IWT sector to a large extent and does not require large capital investments. However, HVO may not results inthe desired real emission reductions (see section 2.1.4) and it is recommended to acknowledge that. This could be put into action by clearly distinguishing between zero-emission drivetrains and emission-reducing drivetrains in the provisioning of subsidies, for instance.

Economic policies

In general, policymakers must focus on introducing or extending economic instruments rather than imposing direct regulations (e.g. bans) because the latter restricts the choice of freedom (CCNR, 2021e). It is recommended to focus on quantity-based economic instruments, such as the ETS and HBE regime. These instruments ensure that CO_2 emission goals are reached virtually when the CO_2 cap or HBE obligation levels are set in accordance with the emission goals. Price-based economic instruments bring along too much uncertainty. For instance, the hydrogen and fuel cell prices must fall to a certain level for the price-based economic instrument to be effective at predetermined levels of economic incentives. Moreover, it is difficult to estimate the level of economic incentives that is required to persuade risk averse IWT operators. Using quantity-based economic instruments, the level of required economic incentives is determined by market mechanisms. Note that these quantity-based instruments do not ensure the actual realization of intermediate emission goals, because HBEs or CO_2 allowances can be traded with other sectors that are easier to decarbonize. However, when the quantity restrictions do not allow any CO_2 emissions to be emitted (i.e. the CO_2 cap in the ETS is zero), there is no room for any trade.

The HBE regime and ETS not only make fossil fuels more expensive but also make renewable fuels cheaper because renewable energy producers can generate additional revenues by selling CO_2 allowances or HBE certificates. The main benefit of the HBE regime is the possibility to distinguish between sustainable fuels through the use of a multiplier. For instance, the use of hydrogen could potentially be valued higher than biodiesel. However, the HBE regime is currently implemented under Dutch legislation in the transport sector and HBEs cannot be traded with other countries and non-transport sectors. Therefore, when shipping costs rise as a consequence of the HBE regime, companies may decide to ship their cargo through other countries. On the other hand, the ETS allows to trade CO_2 allowances with other EU countries and sectors. When introducing the ETS in conjunction with the HBE regime, policymakers must prevent double burdening of the IWT sector. It would be disproportional to require HBE certificates and CO_2 allowances when using fossil fuels.

The incorporation of the IWT sector in the ETS or the introduction of an HBE obligation would enable policymakers to control the CO_2 emission reductions. Although NO_x and PM emission reductions are often related to CO_2 emission reductions, these emission reductions are more uncertain. For instance, when IWT operators decide to install a hydrogen-powered combustion engine to reduce CO_2 emissions, NO_x emissions remain similar to NO_x emissions from diesel-powered engines. In order to ensure virtual NO_x and PM emission reductions, the quantity-based economic instruments must also restrict these emissions. Alternatively, direct regulations such as bans on new combustion engines can stimulate IWT operators to install hydrogen-powered fuel cells that are associated with zero emissions.

The quantity-based economic instruments still offer a IWT operators the opportunity to choose from a wide range of sustainable alternatives. Hydrogen is considered a promising alternative that offers many benefits over biodiesel and batteries, for instance (see section 2.1.4). However, hydrogen applications are still expensive and therefore economic policies must help to finance the initial capital investment and ensure fuel cost reductions over time. Such policies can persuade risk averse IWT operators because the business case for hydrogen is ensured in the long term. An innovation fund could help to finance large capital investments, while competitive hydrogen prices in the future could be ensured by the introduction of a sliding feed-in premium (FIP), for instance. Here, the gap (corrected for energy contents) between the market price (i.e., diesel price) and a reference price for hydrogen is renumerated (IRENA, 2018). When the diesel price exceeds the reference price, the premium is zero. However, the introduction of FIPs is associated with high risks for governments. Hydrogen cost reductions can also be ensured on the supply side of hydrogen. SDE++ schemes could be extended for hydrogen production plants to boost reductions in production costs. These schemes would make the operation of hydrogen plants more attractive, which increases production. In turn, higher production levels result in economies of scale and accelerated technological development that drive down hydrogen production cost. As mentioned, the use of multipliers for hydrogen under the HBE regime would also help lowering the production cost and make hydrogen more competitive with biodiesel, for instance.

An innovation fund that would help finance the capital investment for hydrogen applications must mainly be filled by government contributions. Preferably, such an innovation fund is managed by a separate organization and designed as a ‘one-stop shop’ at which IWT operators only need to submit a request for funding (CCNR, 2021e). Subsequently, this organization assesses the additional total costs of ownership associated with using a hydrogen-powered drivetrain. Based on the assessment, the organization arranges both the subsidies and loans needed. Loans can be used to help finance the remaining investment that is not subsidized (CCNR, 2021e). Furthermore, the organization managing the innovation fund would also provide technical, financial, and legal support. IWT operators often struggle to put together a new project application and call in external support (CCNR, 2021e). Hence, the organization could also assist in drafting new project applications. To create awareness about the fund, stories about successful projects shall be used to share knowledge and activate potentially interested parties to use the services (CCNR, 2021e). Small companies often relate and react to good practice examples (CCNR, 2021e). In addition, funding rates and pre-finance availability are important factors considered by beneficiaries when deciding whether to submit a project proposal. A funding rate of at least 50% would be preferred as well as an initial financial remuneration to kickstart the project (CCNR, 2021e). This financial support contributes to a level playing field with other modes of transport, given the higher marginal abatament costs in the IWT sector.

When covering the IWT sector by the HBE regime, the HBE obligation levels should be set in accordance with the emission goals. For 2030, this would correspond to a higher level than the intended 5 PJ. When including the IWT sector in the ETS, the minimum tonnage for ships in the 'Fit for 55 Pacakge' must be revisited. Currently, only ships beyond 5000 tons are included in the ETS, which only holds for 2% of the ships in the Dutch IWT sector. For instance, a minimum tonnage of 250 tons would include 70% of the ships in the IWT sector in the ETS. Note that this excludes push boats (12% of total fleet) that are listed with low tonnages in the IVR database. To include the entire IWT sector, the minimum tonnage condition should be removed.

6 Conclusion

In this thesis, the opportunities for hydrogen in the IWT sector were outlined, given the characteristics of the Dutch IWT sector, the potential of hydrogen applications, and the technical requirements for producing, distributing, and applying hydrogen. Second, the assumptions and methods for calculating the total cost of ownership, emissions and hydrogen demand have been outlined. Third, a base scenario was constructed, and policy measures were tested in the model. Next, alternative scenarios were constructed to achieve the emissions targets set for the Dutch IWT sector. Finally, policy recommendations have been proposed that would facilitate the hydrogen transition.

The developed transition model simulates the decision-making process of IWT operators from an economic perspective and provides insight into the effect of policy measures to help answer the main research question: *What policy measures would facilitate the hydrogen transition in the Dutch inland waterway transport (IWT) sector and contribute to reaching emissions targets?.*

First of all, a prerequisite for the transition is the introduction of relevant regulation and bunkering infrastructure. Policymakers must ensure that the permitting process for bunkering infrastructure is improved, and a legal basis for transporting hydrogen through pipelines is set up. Second, the results indicate that emissions targets specified in the Green Deal were not achieved in the base scenario. Therefore, policy measures are necessary that increase the installation of hydrogen applications to reach emissions targets. Regarding these policy measures, economic policies are preferred because they offer IWT operators freedom of choice and minimize marginal abatement costs. Here, quantity-based economic instruments are favored over price-based economic instruments. Quantity-based economic instruments ensure that emission targets are realized virtually, while the effect of price-based economic instruments is subject to uncertainties related to cost developments, for instance. The introduction of an HBE obligation or the inclusion of the IWT sector in the ETS are effective quantity-based economic instruments. These instruments ensure a realization of CO_2 emission targets. NO_x and PM emissions are likely to be reduced significantly but IWT operators are free to use fuels or drivetrains that are associated with these emissions. Quantity-restrictions on NO_x and PM emissions could ensure realization of these emissions. Alternatively, direct regulations (e.g. a ban on combustion engines) could contribute to the realization of emission targets.

When covering the IWT sector by the HBE regime, the HBE obligation levels should be set in accordance with the emission goals. For 2030, this would correspond to a higher level than the intended 5 PJ. It is recommended to introduce a multiplier for hydrogen in order to create a level playing field with other renewable fuels, such as biodiesel. When including the IWT sector in the ETS, the minimum tonnage for ships in the 'Fit for 55 Package' must be revisited. Currently, only ships beyond 5000 tons are included in the ETS, which only holds for 2% of the ships in the Dutch IWT sector. Removing the minimum tonnage condition would include all ships in the ETS. When introducing the ETS in conjunction with the HBE regime, policymakers must prevent double burdening of the IWT sector. In addition to these polices, subsidies must be provided to compensate for the higher marginal abatement costs of hydrogen at the moment and create a level playing field with other transport modes, countries and fuels. These subsidies can be provided from an innovation fund that is managed by an organization that provides technical, financial and legal support.

The results in this thesis are based on several assumptions related to technical and economic developments. It is assumed that regulations and sufficient hydrogen (bunkering) infrastructure are in place in 2025. Also, rational decision-making is assumed, which means IWT operators are confident about future technological and economic developments.

This research mainly focused on a techno-economic trade-off between hydrogen and diesel. To built further on this research, several areas are important to investigate. In the short term, the role of Dutch authorities in the development of hydrogen (bunkering) infrastructure is relevant to research. Furthermore, future research could focus on multi-criteria decision-making considering criteria such as upcoming legislation, safety, the availability of (bunkering) infrastructure, and premiums that companies are prepared to pay for green logistics. Additionally, the missed revenues associated with lost cargo space related to a larger storage tank need to be mapped.

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Appendices

A: Descriptive statistics IVR database

	count ships	average length	min length	max length	average building year	average kW
BILGEBOOT	24	2918	1845	4046	1970	161
BRANDBLUSVAARTUIG	1	1765	1765	1765	2016	736
BUNKERBOOT	65	2739	1670	3976	1971	182
BUNKERSTATION	9	4516	2713	9892	1979	352
DIENSTVAARTUIG	6	1889	1323	2684	1984	137
DRIJVEND WERKTUIG	13	3047	998	6996	1979	274
DUWBOOT	7	1993	720	3200	1994	1045
MOTORBEUNSCHIP	194	6297	1915	9000	1963	386
MOTORDEKSCHUIT	85	2512	1035	6668	1939	128
MOTORONDERLOSSER	14	4977	2652	7326	1969	354
MOTORTANKSCHIP	772	8917	1545	14715	1995	890
MOTORVRACHTSCHIP	2678	7532	1220	13500	1968	604
ONDERLOSSER	3	4105	3400	5084	1957	246
OPEN RONDVAARTBOOT	3	998	995	999	2016	60
OPLEIDINGSSCHIP E.D.	4	6196	5000	8976	1951	373
OVERIGE VAARTUIGEN	28	3886	1069	12290	1949	227
PASSAGIERSSCHIP - HOTEL	142	5530	1505	13481	1958	533
PASSAGIERSSCHIP - RONDVAART	392	2567	10	11000	1966	218
PASSAGIERSSCHIP VAN HET AMSTERDAMSE GRACHTENTYPE	87	1873	1014	2407	1979	97
PATROUILLEVAARTUIG	20	1750	1355	2500	1995	760
PLEZIERVAARTUIG - JACHT	73	2526	1450	5016	1943	153
POMPOVERSLAGBOOT	1	3197	3197	3197	1931	220
PONTON - DEKSCHUIT	11	2285	1914	3548	1952	167
RO-RO MOTORVRACHTSCHIP	4	10979	10923	10998	1979	1111
RO-RO MVS OPLEGGER	1	10850	10850	10850	1974	650
SLEEPBOOT	539	1417	655	8820	1955	351
SLEEPBOOT MET DUWSTEVEN	66	1569	660	2815	1960	290
SLEEP-DUWBOOT	19	1289	850	2378	1979	327
SLEEPTANKSCHIP	3	2772	2733	2846	1936	166
SLEEPVRACHTSCHIP	1	6713	6713	6713	1929	402
TANKDUWBAK	1	4200	4200	4200	2015	251
VEERBOOT	4	7541	1625	13540	1979	4226
VEERPONT	54	2827	850	11027	1981	394
VEERPONT VOET/FIETS	23	2340	900	3365	1996	310
VRACHTDUWBAK	5	7882	4384	10980	2012	530
ZEESCHIP	6	8524	8327	8720	2007	933
ZEILEND PASSAGIERSSCHIP	24	2474	2084	5844	1936	177

B: Map harbors and hydrogen pipelines

Figure 32: Map of harbors and overlapping future hydrogen pipelines (Bureau Voorlichting Binnenvaart, 2021)

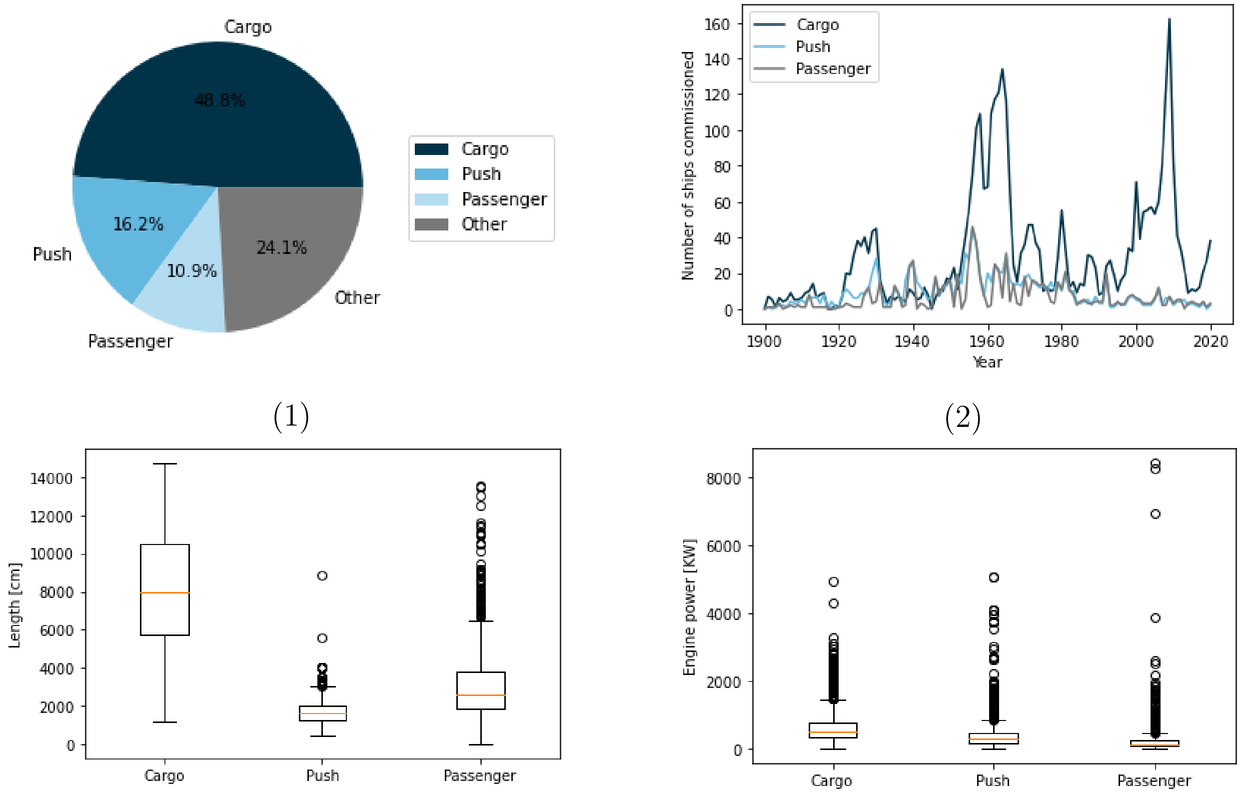
C: Database composition

1. Overview of database

Access has been granted to the IVR database 2021, which reports the following characteristics of each ship:

- Ship type
- Country of registration
- Loading capacity
- Ship construction year
- Engine construction year
- Length
- Total engine power
- Engine Rounds Per Minute (RPM)

Some descriptive statistics on the data has been generated, which are displayed in Figure 33. The figure describes the share of different ship types, the trends in commissioning years, and the statistics on the fleet's length and engine power.



(1) (2)

(3) (4)

Figure 33: Descriptive statistics of IVR datatbase, including (1) share of ship types in the Dutch fleet, (2) trends in the commissioning of ships, (3) boxplot on the ship length in the Dutch fleet, and (4) boxplot on the engine power in the Dutch fleet

For certain ships, the data in the database is incomplete and must be estimated. Also, the database does not contain information about some relevant attributes necessary for modeling decision-making behavior and emissions, such as the ships' effective operational hours and the average distance covered per trip. These attributes have been added to the database based on assumptions.

2. Addition of missing data

Total engine power

For some ships, the total engine power is unknown. A statistical correlation between the length of a ship and total engine power is hypothesized. At first, missing values of both the ship's length and total engine power were deleted. Next, a Pearson's correlations test was performed on the remaining data, excluding push boats. Push- and tugboats are excluded because those are often shorter (see Fig. 33.3). The test shows a correlation of 0.705 with a p-value of 0.0. This proves a statistically significant correlation. The ratio of 0.105 [kW/cm] between the average engine power and average ship length allows determining the total engine power for missing values.

When only calculating the correlation for push- and tugboats, the Pearson's correlations test returns a correlation of 0.41 and a p-value of 7.0eˆ-17. Although the correlation is a little weaker, it is yet a moderate positive correlation that is statistically significant. For push- and tugboats the engine power/length ratio is 0.224 [kW/cm]. Whenever the ship length is unknown, the average engine power of the ship type is assigned. The average engine power is 643, 416, and 306 kW for cargo ships, push boats, and passenger ships, respectively.

Rounds per minute (RPM)

For some ships, the ship's engine RPM is unknown. The unknown RPM values in the IVR database have been set equal to a ship type's average. The average RPM for each ship type has been presented in Appendix D. For instance, unknown values for motor cargo ships have been set to 1645 RPM. The average RPM of all ship types is 1732, which is in line with the assumption made by CE Delft (2004), presuming an RPM of 1800 for all IWT vessels.

3. Addition of extra columns

Effective operational hours

The effective operational hours of each ship are estimated based on Table 3. EICB (2015) also provides separate classifications for push boats and coupled convoys. In this study, the ship types represented in the database as 'Duwboot,' 'Sleepboot,' Sleep-Duwboot,' and 'Sleepboot met duwsteven' are classified as push boats. Coupled convoys cannot directly be derived from the IVR dataset and are therefore not considered. The lifetime of engines in passenger ships is set equal to 24 years, as explained in section 2.1.2.

Average load

The average power load for an average IWT vessel is 37.2% of the full load capacity (Sluiman et al., 2019). The average load is relevant for calculating emissions, storage capacity, and fuel costs.

Engine revision year

The engine revision year is determined by adding the engine's lifetime to the engine's construction year (EICB, 2015). If the engine's construction year is not available, the engine's construction year is set equal to the construction year of the ship. When the engine's calculated replacement year lies in the past, it is assumed the engine has been replaced in that year. Hence, the new engine revision year will be one lifetime after the replacement year (e.g., a ship built in 1970 with a lifetime of 24 years, has been revised in 1994 and is replaced in 2018. Hence, the future engine revision year is 2042).

Engine replacement year

The engine's replacement year is determined by adding twice the engine's lifetime to the engine's construction year (EICB, 2015). The engine's lifetime is based on the engine construction year and specified in Table 3. Additionally, 40% of the engines that ought to be replaced between 2020 and 2025 are already replaced before 2020 to install a cheaper CCR-II engine (expert consultation). From 2020 onwards, the construction of new CCR-II engines was not allowed anymore.

Scrap year of ship

The scrap year has been set equal to the building year plus four times the engine's lifetime. On average, this means 49.1 ships per year are being scrapped. The annual reports of IVR of 2017, 2018, 2019, and 2020 (IVR, 2021) show an average of 68.8 ships being scrapped each year in the entire database. In the database of IVR, 53% of the ships are registered in the Netherlands (IVR, 2021a). Hence, annually 36.5 (0.53 * 68.8) ships would be expected to be scrapped each year. Considering that not all scrapped ships are reported to the IVR, it is reasonable to set the scrap year to four times the engine lifetime. Moreover, experts confirm this is a solid assumption, especially for cargo vessels.

NO_x, PM, and CO_2 emissions

The emissions are calculated based on Table 4, in which ships' emissions [g/kWh] are classified based on their construction year. CO_2 emissions have been based on the fuel consumption specified for various construction year ranges.

Average distance in hours

The average distance in hours of an exemplary route is required to estimate the size of the fuel tank. MariGreen (2018) has determined exemplary routes for cargo vessels, push boats, cabin vessels, and Rhine ferries. The exemplary routes take 78 hours, 39 hours, 72 hours for a round trip for cargo vessels, push boats, and cabin vessels, respectively. For Rhine ferries, the average distance in hours is not specified. In MariGreen (2018) study, it is assumed that ferries only bunker once every four days. From the data provided in the MariGreen study (250 kW engine power and total energy requirement at shaft of 8800 kWh), it can be derived that the operation time between bunkering is 94.6 hours assuming an average load of 37.2%.

The ship types present in the IVR database have been linked to the categories specified in MariGreen (2018) as presented in Table 19. Some ship types in the IVR database do not fit into those categories and are classified as ‘other’. Most ‘other’-classified ships operate on a local scale and sail short routes. Hence, the average distance for those ships is set to 10 hours. Nonetheless, the ‘other’-category is not included in most analyses performed in this thesis.

Table 19: Ship type classification

Ship types MariGreen	**Ship types IVR database**
Cargo ships	Motorbeunschip, motoronderlosser, Motortankschip, Motorvrachtschip, Onderlosser, RO-RO MVS Oplegger, RO-RO Motorvrachtschip, Zeeschip
Push boat	Duwboot, Sleepboot, Sleep-duwboot, Sleepboot met duwsteven
Cabin vessel	Passagiersschip - Hotel, Passagiersschip - Rondvaart, Passagiersschip van het Amsterdamse grachtentype
Rhine ferry	Veerboot, Veerpont, Veerpont voet/fiets
Other	Bilgeboot, Brandblusvaartuig, Bunkerboot, Bunkerstation, Dienstvaartuig, Drijvend werktuig, Motordekschuit, Open rondvaartboot, Opleidingsschip, Overige vaartuigen, Pattrouillevaartuig, Pleziervaartuig - Jacht, Pompoverslagboot, Ponton - dekschuit, Skutsje, Tankduwbak, Vrachtduwbak, Zeilend passagiersschip

On top of the theoretical size of the storage tank, TNO (2019) includes a 20% margin for peak demands and an additional safety margin of 20% for unforeseen circumstances during the trip, such as bad weather. These assumptions have been incorporated in this study.

It is expected that from 2030 onwards, there are sufficient locations with bunkering stations, and hence, it would be possible to bunker after a one-way trip. The average distance of a one-way trip is based on the ship’s upstream trip, as specified by MariGreen (2018). The upstream trips take 50 hours, 26 hours, 48 hours for the exemplary routes of cargo vessels, push boats, and cabin vessels, respectively. On average, this corresponds to 66% of the round trip distance. This ratio is also assumed for Rhine ferries. The ‘other’ category already covers relatively short distances, which are assumed to remain unchanged.

4. Filter of database

For analyses in the base scenario, cargo ships, push boats, and passenger ships registered in The Netherlands are included. Other ships are excluded because they are considered too heterogeneous.

D: Average RPM ship type

Type	**Average RPM**
’BILGEBOOT’:	1635
’BRANDBLUSVAARTUIG’:	1800
’BUNKERBOOT’:	1867
’DIENSTVAARTUIG’:	2367
DRIJVEND WERKTUIG’:	1707
’DUWBOOT’:	1773
’MOTORBEUNSCHIP’:	1556
’MOTORDEKSCHUIT’:	1513
’MOTORONDERLOSSER’:	1488
’MOTORTANKSCHIP’:	1614
’MOTORVRACHTSCHIP’:	1645
’ONBEKEND’:	1800
’ONDERLOSSER’:	1833
OPLEIDINGSSCHIP E.D.	1800
OVERIGE VAARTUIGEN	1881
PASSAGIERSSCHIP - HOTEL	1172
PASSAGIERSSCHIP - RONDVAART	1493
PASSAGIERSSCHIP VAN HET AMSTERDAMSE GRACHTENTYPE	2091
’PATROUILLEVAARTUIG’:	1800
PLEZIERVAARTUIG - JACHT	1798,0

E: Statistical test on sensitivity analysis sample

A two-sided one sample t-test has been conducted on the dataset (N=5787) and sample (N=200) mean regarding the variables engine power, ship length, and ship building. These are continues variables and follow a normal probability distribution. Furthermore, the sample is a random sample from the dataset (Newbold et al., 2013). Hence, the assumptions for a one sample t-test are satisfied. The null hypothesis (H_0) and (two-sided) alternative hypothesis (H_1) of the one sample t-test can be expressed as:

H_0: The dataset mean is equal to the sample mean
H_1: The dataset mean is not equal to the sample mean

Here, the dataset and sample mean refer to mean values for the variables engine power, ship length, and ship building year. The results in Table 20 indicate that none of the is significant at a significance level of 10%. Hence, the null hypothesis cannot be rejected. The t-statistic measures mean difference between the dataset and the sample relative to the variation in the sample data. The greater the t-statistic, the greater evidence against the null hypothesis (Newbold et al., 2013).

Table 20: One sample t-test results

	Dataset mean	**Sample mean**	**T-statistic**	**Two-sided p-value**
Engine power	531	633	1.451	0.147
Ship length	5754	5821	1.650	0.101
Ship building year	1941	1948	0.595	0.553

A two-sided one proportion z-test to check for any significant statistical differences between the dataset and the sample regarding the ship types included. To perform a one proportion z-test, the sample must be sampled randomly from the dataset and the dataset must be at least 10 times as large as the sample. These conditions can be satisfied. However, the third condition is $n \times p \geq 10$, where n is the sample size and p is the true population proportion (Newbold et al., 2013). This condition cannot be satisfied for some ship types that are under represented in the dataset. In total these ship types comprise less than 5% of the dataset. When excluding these ship types the one proportion z-test can be performed. the The null hypothesis (H_0) and (two-sided) alternative hypothesis (H_1) of the one proportion z-test can be expressed as:

H_0: The dataset proportion is equal to the sample proportion
H_1: The dataset proportion is not equal to the sample proportion

The results in Table 21 indicates that the null hypothesis cannot be rejected for any ship type because the p-values exceed a significance level of 10%. The z-statistic indicates how many standard deviations the sample proportion deviates from the dataset proportion, where a negative t-statistic indicates a lower sample proportion than the dataset proportion (Newbold et al., 2013). The larger the z-statistic (either positive or negative), the greater the probability that the null hypothesis is rejected.

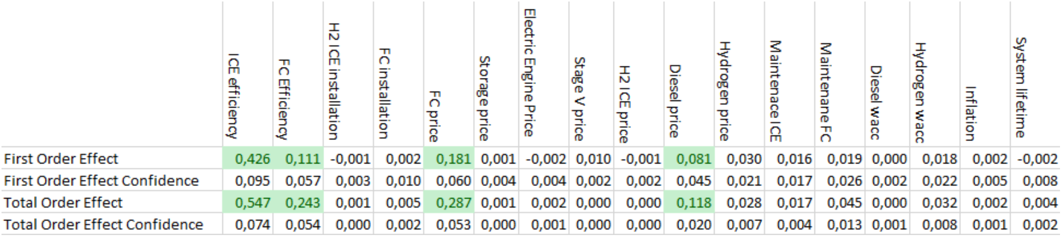
In conclusion, the null hypotheses cannot be rejected and therefore it can be concluded that ther random sample accurately represents the dataset.

Table 21: One proportion z-test results

Ship type	**Dataset proportion**	**Sample proportion**	**Z-statistic**	**Two-sided p-value**
MOTORBEUNSCHIP	0,034	0,040	0,572	0,567
MOTORONDERLOSSER	0,003	0,007	0,867	0,386
MOTORTANKSCHIP	0,133	0,137	0,165	0,869
MOTORVRACHTSCHIP	0,463	0,460	-0,114	0,909
RO-RO MOTORVRACHTSCHIP	0,001	0,007	1,278	0,203
DUWBOOT	0,032	0,030	-0,235	0,814
SLEEPBOOT	0,094	0,077	-1,106	0,269
SLEEP-DUWBOOT	0,060	0,067	0,490	0,624
SLEEPBOOT MET DUWSTEVEN	0,015	0,013	-0,205	0,838
PASSAGIERSSCHIP - HOTEL	0,025	0,037	1,086	0,278
PASSAGIERSSCHIP - RONDVAART	0,072	0,060	-0,842	0,400
VEERPONT	0,018	0,020	0,272	0,785
VEERPONT VOET/FIETS	0,004	0,007	0,536	0,592

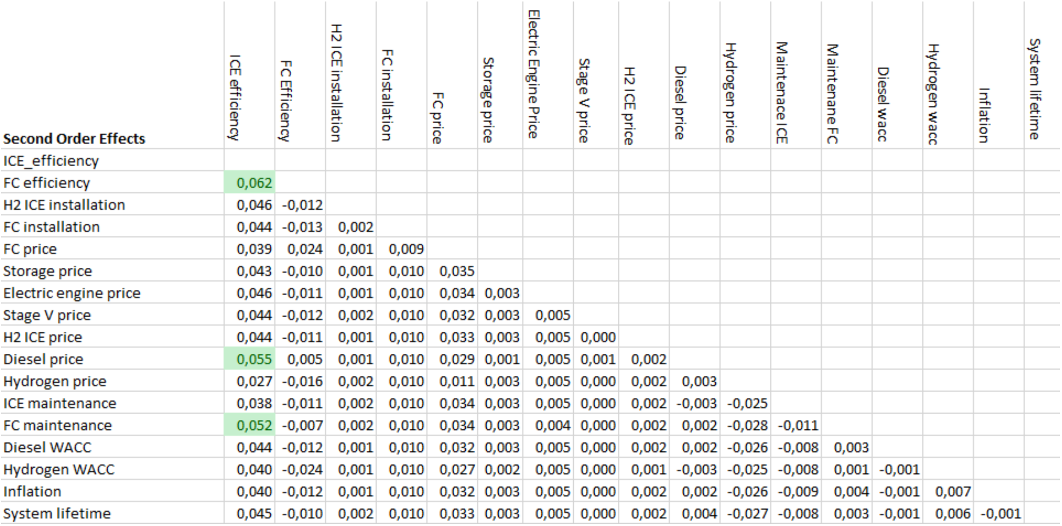
F: Output sensitivity analysis

NO_x emissions



	ICE efficiency	FC Efficiency	H2 ICE installation	FC installation	FC price	Storage price	Electric Engine Price	Stage V price	H2 ICE price	Diesel price	Hydrogen price	Maintenace ICE	Maintenane FC	Diesel wacc	Hydrogen wacc	Inflation	System lifetime
First Order Effect	0,426	0,111	-0,001	0,002	0,181	0,001	-0,002	0,010	-0,001	0,081	0,030	0,016	0,019	0,000	0,018	0,002	-0,002
First Order Effect Confidence	0,095	0,057	0,003	0,010	0,060	0,004	0,004	0,002	0,002	0,045	0,021	0,017	0,026	0,002	0,022	0,005	0,008
Total Order Effect	0,547	0,243	0,001	0,005	0,287	0,001	0,002	0,000	0,000	0,118	0,028	0,017	0,045	0,000	0,032	0,002	0,004
Total Order Effect Confidence	0,074	0,054	0,000	0,002	0,053	0,000	0,001	0,000	0,000	0,020	0,007	0,004	0,013	0,001	0,008	0,001	0,002

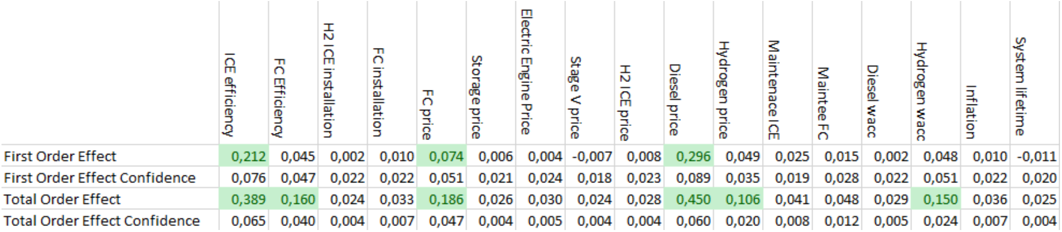
Figure 34: First and total-order effects of input variables on NO_x emissions in 2050 (statistically significant effects highlighted in green)



Second Order Effects	ICE efficiency	FC Efficiency	H2 ICE installation	FC installation	FC price	Storage price	Electric Engine Price	Stage V price	H2 ICE price	Diesel price	Hydrogen price	Maintenace ICE	Maintenane FC	Diesel wacc	Hydrogen wacc	Inflation	System lifetime
ICE_efficiency																	
FC efficiency	0,062																
H2 ICE installation	0,046	-0,012															
FC installation	0,044	-0,013	0,002														
FC price	0,039	0,024	0,001	0,009													
Storage price	0,043	-0,010	0,001	0,010	0,035												
Electric engine price	0,046	-0,011	0,001	0,010	0,034	0,003											
Stage V price	0,044	-0,012	0,002	0,010	0,032	0,003	0,005										
H2 ICE price	0,044	-0,011	0,001	0,010	0,033	0,003	0,005	0,000									
Diesel price	0,055	0,005	0,001	0,010	0,029	0,001	0,005	0,001	0,002								
Hydrogen price	0,027	-0,016	0,002	0,010	0,011	0,003	0,005	0,000	0,002	0,003							
ICE maintenance	0,038	-0,011	0,002	0,010	0,034	0,003	0,005	0,000	0,002	-0,003	-0,025						
FC maintenance	0,052	-0,007	0,002	0,010	0,034	0,003	0,004	0,000	0,002	0,002	-0,028	-0,011					
Diesel WACC	0,044	-0,012	0,001	0,010	0,032	0,003	0,005	0,000	0,002	0,002	-0,026	-0,008	0,003				
Hydrogen WACC	0,040	-0,024	0,001	0,010	0,027	0,002	0,005	0,000	0,001	-0,003	-0,025	-0,008	0,001	-0,001			
Inflation	0,040	-0,012	0,001	0,010	0,032	0,003	0,005	0,000	0,002	0,002	-0,026	-0,009	0,004	-0,001	0,007		
System lifetime	0,045	-0,010	0,002	0,010	0,033	0,003	0,005	0,000	0,002	0,004	-0,027	-0,008	0,003	-0,001	0,006	-0,001	

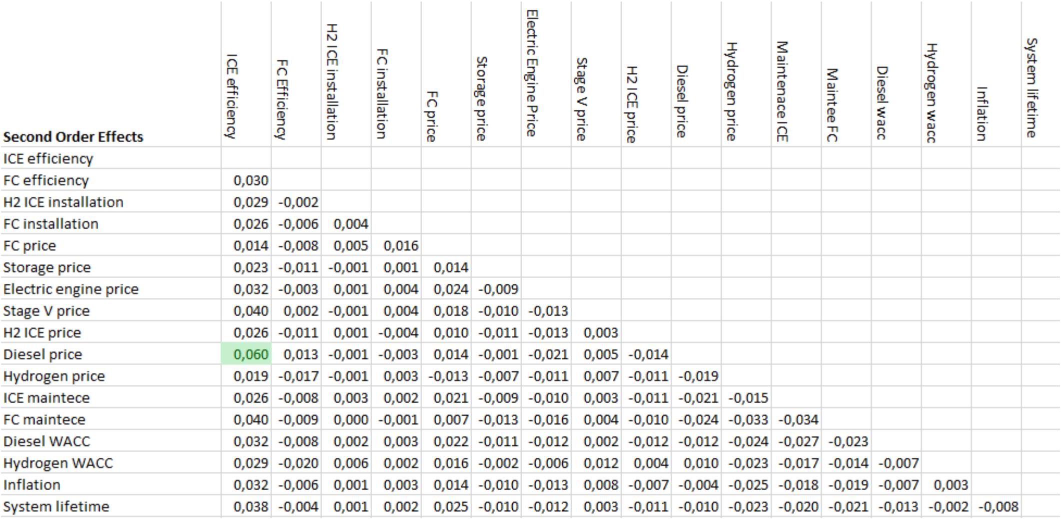
Figure 35: Second-order effects of input variables on NO_x emissions in 2050 (statistically significant effects highlighted in green)

PM emissions



	ICE efficiency	FC Efficiency	H2 ICE installation	FC installation	FC price	Storage price	Electric Engine Price	Stage V price	H2 ICE price	Diesel price	Hydrogen price	Maintenace ICE	Maintee FC	Diesel wacc	Hydrogen wacc	Inflation	System lifetime
First Order Effect	0,212	0,045	0,002	0,010	0,074	0,006	0,004	-0,007	0,008	0,296	0,049	0,025	0,015	0,002	0,048	0,010	-0,011
First Order Effect Confidence	0,076	0,047	0,022	0,022	0,051	0,021	0,024	0,018	0,023	0,089	0,035	0,019	0,028	0,022	0,051	0,022	0,020
Total Order Effect	0,389	0,160	0,024	0,033	0,186	0,026	0,030	0,024	0,028	0,450	0,106	0,041	0,048	0,029	0,150	0,036	0,025
Total Order Effect Confidence	0,065	0,040	0,004	0,007	0,047	0,004	0,005	0,004	0,004	0,060	0,020	0,008	0,012	0,005	0,024	0,007	0,004

Figure 36: First and total-order effects of input variables on PM emissions in 2050 (statistically significant effects highlighted in green)



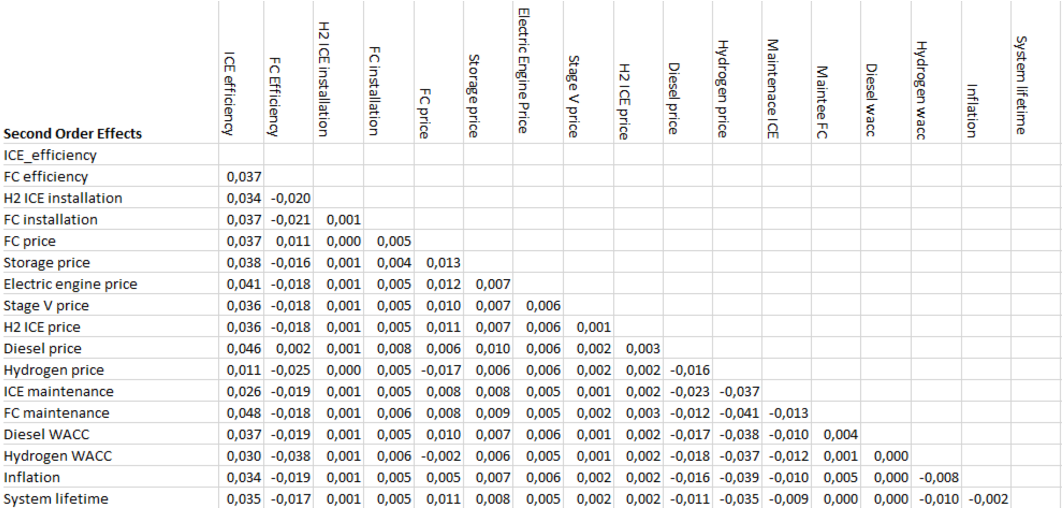
Second Order Effects	ICE efficiency	FC Efficiency	H2 ICE installation	FC installation	FC price	Storage price	Electric Engine Price	Stage V price	H2 ICE price	Diesel price	Hydrogen price	Maintenace ICE	Maintee FC	Diesel wacc	Hydrogen wacc	Inflation	System lifetime
ICE efficiency																	
FC efficiency	0,030																
H2 ICE installation	0,029	-0,002															
FC installation	0,026	-0,006	0,004														
FC price	0,014	-0,008	0,005	0,016													
Storage price	0,023	-0,011	-0,001	0,001	0,014												
Electric engine price	0,032	-0,003	0,001	0,004	0,024	-0,009											
Stage V price	0,040	0,002	-0,001	0,004	0,018	-0,010	-0,013										
H2 ICE price	0,026	-0,011	0,001	-0,004	0,010	-0,011	-0,013	0,003									
Diesel price	0,060	0,013	-0,001	-0,003	0,014	-0,001	-0,021	0,005	-0,014								
Hydrogen price	0,019	-0,017	-0,001	0,003	-0,013	-0,007	-0,011	0,007	-0,011	-0,019							
ICE maintece	0,026	-0,008	0,003	0,002	0,021	-0,009	-0,010	0,003	-0,011	-0,021	-0,015						
FC maintece	0,040	-0,009	0,000	-0,001	0,007	-0,013	-0,016	0,004	-0,010	-0,024	-0,033	-0,034					
Diesel WACC	0,032	-0,008	0,002	0,003	0,022	-0,011	-0,012	0,002	-0,012	-0,012	-0,024	-0,027	-0,023				
Hydrogen WACC	0,029	-0,020	0,006	0,002	0,016	-0,002	-0,006	0,012	0,004	0,010	-0,023	-0,017	-0,014	-0,007			
Inflation	0,032	-0,006	0,001	0,003	0,014	-0,010	-0,013	0,008	-0,007	-0,004	-0,025	-0,018	-0,019	-0,007	0,003		
System lifetime	0,038	-0,004	0,001	0,002	0,025	-0,010	-0,012	0,003	-0,011	-0,010	-0,023	-0,020	-0,021	-0,013	-0,002	-0,008	

Figure 37: Second-order effects of input variables on PM emissions in 2050 (statistically significant effects highlighted in green)

CO_2 emissions

	ICE efficiency	FC Efficiency	H2 ICE installation	FC installation	FC price	Storage price	Electric Engine Price	Stage V price	H2 ICE price	Diesel price	Hydrogen price	Maintenace ICE	Maintenane FC	Diesel wacc	Hydrogen wacc	Inflation	System lifetime
First Order Effect	0,400	0,106	0,001	0,003	0,163	-0,004	-0,004	-0,001	-0,002	0,093	0,046	0,020	0,014	0,000	0,032	0,005	-0,003
First Order Effect Confidence	0,090	0,064	0,004	0,009	0,062	0,006	0,005	0,003	0,003	0,054	0,029	0,017	0,023	0,003	0,029	0,008	0,013
Total Order Effect	0,517	0,233	0,001	0,005	0,269	0,002	0,002	0,001	0,001	0,150	0,064	0,018	0,040	0,001	0,064	0,006	0,015
Total Order Effect Confidence	0,076	0,058	0,000	0,002	0,064	0,001	0,001	0,000	0,000	0,025	0,017	0,005	0,012	0,000	0,014	0,002	0,003

Figure 38: First and total-order effects of input variables on CO_2 emissions in 2050 (statistically significant effects highlighted in green)



Second Order Effects	ICE efficiency	FC Efficiency	H2 ICE installation	FC installation	FC price	Storage price	Electric Engine Price	Stage V price	H2 ICE price	Diesel price	Hydrogen price	Maintenace ICE	Maintee FC	Diesel wacc	Hydrogen wacc	Inflation	System lifetime
ICE_efficiency																	
FC efficiency	0,037																
H2 ICE installation	0,034	-0,020															
FC installation	0,037	-0,021	0,001														
FC price	0,037	0,011	0,000	0,005													
Storage price	0,038	-0,016	0,001	0,004	0,013												
Electric engine price	0,041	-0,018	0,001	0,005	0,012	0,007											
Stage V price	0,036	-0,018	0,001	0,005	0,010	0,007	0,006										
H2 ICE price	0,036	-0,018	0,001	0,005	0,011	0,007	0,006	0,001									
Diesel price	0,046	0,002	0,001	0,008	0,006	0,010	0,006	0,002	0,003								
Hydrogen price	0,011	-0,025	0,000	0,005	-0,017	0,006	0,006	0,002	0,002	-0,016							
ICE maintenance	0,026	-0,019	0,001	0,005	0,008	0,008	0,005	0,001	0,002	-0,023	-0,037						
FC maintenance	0,048	-0,018	0,001	0,006	0,008	0,009	0,005	0,002	0,003	-0,012	-0,041	-0,013					
Diesel WACC	0,037	-0,019	0,001	0,005	0,010	0,007	0,006	0,001	0,002	-0,017	-0,038	-0,010	0,004				
Hydrogen WACC	0,030	-0,038	0,001	0,006	-0,002	0,006	0,005	0,001	0,002	-0,018	-0,037	-0,012	0,001	0,000			
Inflation	0,034	-0,019	0,001	0,005	0,005	0,007	0,006	0,002	0,002	-0,016	-0,039	-0,010	0,005	0,000	-0,008		
System lifetime	0,035	-0,017	0,001	0,005	0,011	0,008	0,005	0,002	0,002	-0,011	-0,035	-0,009	0,000	0,000	-0,010	-0,002	

Figure 39: Second-order effects of input variables on CO_2 emissions in 2050 (no statistically significant effects)