SUSTAINABLE WATERWAY TRANSPORT, CLEAN AIR

Socio-economic study CLINSH

Deliverable C1

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CLEAN INLAND SHIPPING

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Glossary

Abbreviation	Meaning
CBA	Cost-Benefit Analysis
CCNR	Central Commission for the Navigation of the Rhine
CCNRI/CCNRII	Emission standards for inland waterway vessels
CEMT	Conférence Européenne des Ministres du Transport
CEMT I-VI	Waterway classes established by the CEMT, laying down maximum vessel dimensions for each class
CLINSH	Clean Inland Shipping project under LIFE+ programme
CO_2-eq	Carbon dioxide equivalent
DPF	Diesel particulate filter, to reduce particulate emissions
dwt	Deadweight tonnage: the total mass a shipping vessel can carry (load, fuel, ballast water), expressed in tonnes
FWE	Fuel water emulsion
GTL	Gas-to-liquids, a synthetic diesel oil made from natural gas
HVO	Hydrotreated Vegetable Oil
IWT	Inland waterway transport
kW	Kilowatt
kWh	Kilowatt-hour
kton	Kiloton
LNG	Liquefied Natural Gas
MJ	Megajoule
NO_x	Collective term for mono nitrogen oxides (NO, NO_2 and NO_3), emissions which lead to smog formation, environmental acidification and respiratory damage
PV	Passenger vessel
PB	Push boat
PM	Particulate matter
$PM_{2.5}$	Particulate matter smaller than 2.5 micrometre
PM_{10}	Particulate matter smaller than 10 micrometre
ppm	Parts per million
SCR	Selective Catalytic Reduction, an exhaust gas treatment system to reduce NO_x emissions
Stage IIIa, IV, V	European emission standards for non-road mobile machinery (NRMM), such as construction equipment, railroad engines, inland waterway vessels, and off-road recreational vehicles (Regulations: 2004/26/EC, (EU) 2016/1628).
TEU	Standard shipping container size expressing container volume: Twenty feet Equivalent Unit
tkm	Tonne-kilometre: unit of transport performance expressing transport of one tonne over one kilometre
TTW	Tank-to-wake emissions: emissions arising from fuel combustion during vehicle use
vkm	Vehicle-kilometre
ZE	Zero-emission

Contents

1 Introduction

Inland shipping is an efficient way of transport especially for heavy bulk goods such as coal, sand, stone, petroleum products, and also for containers. The efficiency is reflected in IWT's relatively low CO_2 emission and energy consumption figures per tonne-kilometre as compared to road transport. However, air polluting emissions of IWT are relatively high. Engine emission standards for IWT allowed high emissions of IWT engines compared to road transport, until the introduction of the new Stage V emission standard for new engines from 2019 on. In addition, engines in IWT have a long lifetime, and are on average much older than in road transport. There are still many engines in the IWT fleet with no emission regulation at all. This is in strong contrast with road transport, where the majority of engines, with a lifetime of about seven years, already meet the latest EURO VI emission standard.

Autonomous engine renewal will decrease the air polluting emissions of the IWT fleet. New engines introduced on the market are required to meet Stage V from 2019 and 2020 on, reducing NO_x and PM emissions drastically (60-90%) when replacing Stage IIIA, CCNRII or older engines. Stage IIIA and CCNRII engines in stock, however, can still be sold up to 2021/2022. As engines in IWT have such a long lifetime, emission reduction by engine renewal alone (baseline) will take a long time. Additional measures are needed to reduce emission on the shorter term and to reach EU and national ambitions to reduce air polluting emissions. This report investigates the potential for accelerated uptake of emission reduction techniques in the inland waterway sector.

1.1 Context

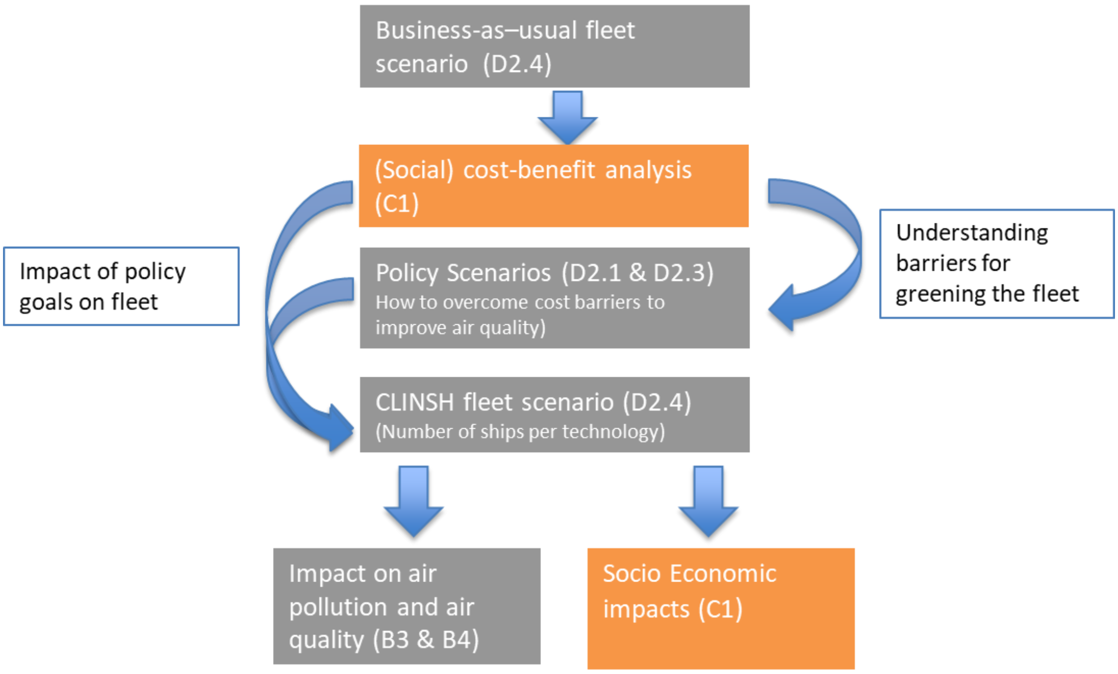
The main objective of CLINSH is to improve air quality in urban areas by accelerating emission reductions in Inland Waterway Transport. Important sub-goals within the CLINSH project are to:

- demonstrate the effectiveness of greening measures in the IWT sector;
- stimulate the sector to take these greening measures;
- contribute to improving air quality.

In Action C1 we assess the social costs and benefits of the different air pollution abatement technologies, by identifying the financial investment and operational costs and the effect on the external costs, related to the emissions of NO_x, PM and also greenhouse gasses (GHG). Together these costs make up the social costs.

The results of the assessment have been used to define the CLINSH scenario, a scenario that minimises the total social costs of IWT, by applying the most societally optimal abatement technology. The effect on the fleet has been elaborated in Action D2.4. In this deliverable on Action C1 we show how the social costs of the CLINSH scenario compare to the social costs in the business-as-usual scenario. The results are used in Action B3 and B4 to calculate the impacts on emissions and air pollution and within Action C1 to report on the social cost effects of the CLINSH scenario as compared to the baseline scenario.

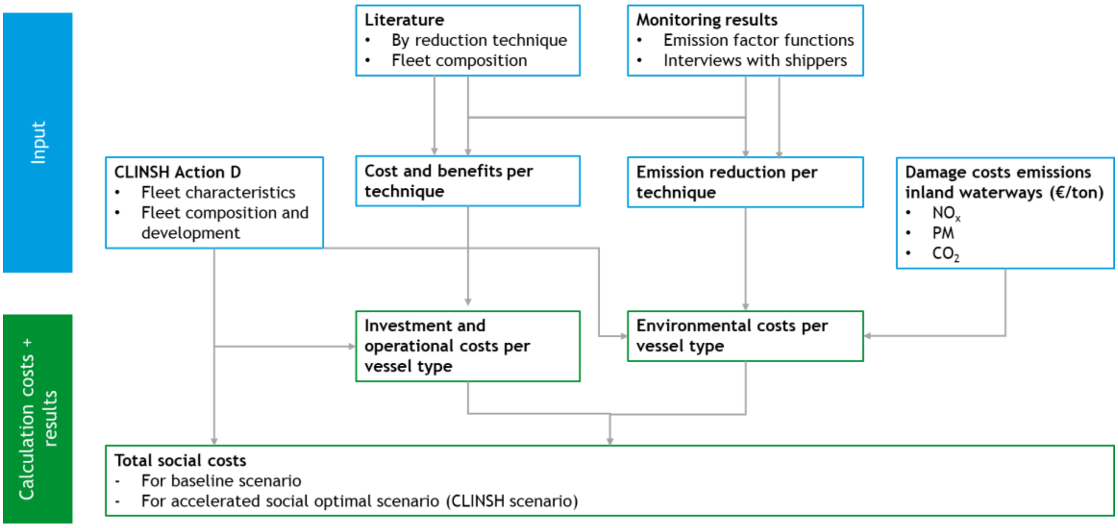
Figure 1 - Interaction of Action C1 with other actions in CLINSH



1.2 Goal

The goal of Action C1 is to provide insight in the costs and benefits with regard to air pollution abatement technologies and fuels for inland waterway transport. In this report we first assess the costs and benefits from the demonstration fleet complemented with values from literature. Secondly, we apply the findings to the baseline and CLINSH scenario to demonstrate what effect the measures can have on the West European IWT fleet in terms of investment costs, total cost of ownership and total social costs.

Figure 2 - Methodology for total social costs calculations



1.3 Scope

The inland waterway fleet in scope is the North West European fleet based on the database developed by the study PROMINENT (Stichting Projecten Binnenvaart, 2016). For this study we have categorised the fleet in 28 vessel categories based on vessel size and operational profile. Every class has been divided in three operational profiles based on low, average and high number of annual sailing hours.

The technologies monitored in CLINSH focus on the reduction of NO_x and PM_{10} emissions and not so much on the reduction of CO_2 emissions. However, since the Paris Agreement, the EU Green Deal, the Mannheim Declaration and the Fit for 55 package, CO_2 reduction in IWT has become an important goal as well. Technologies such as battery electric engines, hydrogen fuelled engines (either in fuel cells or combustions engines) and biofuels are getting more and more attention. Whereas biofuels do not have a significant impact on emissions reduction of air pollutants, battery electric and hydrogen fuelled vessels have no combustion emissions at all, or much lower emissions (in case of H2 in combustion engines). The latter technologies are not yet in operation for IWT, but first pilots are being designed. The Dutch Climate Agreement sets the goal for 150 ships in 2030 with a zero-emission drivetrain. This is still a very limited number as compared to the total of about 9,000 IWT ships in the West European IWT fleet. Up to 2035, we therefore expect zero-emission technologies to play a limited role and mainly for short distance trips. Up to at least 2035, emission reductions of NO_x and PM_{10} should mainly come from other technologies than zero-emission technologies. Therefore the assessment period for the socio-economic focusses on the period up to 2035.

1.4 Readers guide

Within the CLINSH project, several techniques and alternative fuels to reduce air polluting emissions have been applied on ships and have been monitored. Based on the monitoring result, complemented with literature, we describe in Chapter 2 the costs and benefits of the different emission reducing techniques and fuels. In Chapter 3, we describe how social costs are calculated. In

Chapter 4 results are introduced from D2.4 about the development of the fleet. Based on the fleet development two scenarios are developed. A baseline scenario without policies to promote emission reduction and the so-called CLINSH scenario where emission reduction techniques are adopted based on the social optimal options. Chapter 5 discusses the results as well as the main takeaways.

2 Costs and benefits of emission reduction technologies in CLINSH

2.1 Introduction

This chapter starts by introducing the main technologies measured. In Paragraph 2.2 the costs of the technologies are discussed, followed by the environmental benefits in Paragraph 2.3. The costs and benefits for the vessels receiving investment subsidies from CLINSH are shown in Paragraph 2.5. Finally, in Paragraph 2.6, the main conclusions from Chapter 2 are discussed.

One of the unique features of the CLINSH project is the monitoring campaign with a large amount of measurements in real life conditions. NO_x emissions have been measured continuously for a period of two years and, if possible, contain measurements before and after refit of emission reduction technologies. NO_x emissions were also measured on board, in one-off E3 cycle measurements for verification of the continuous measurement, together with PM emissions (not measured continuously). In this section we discuss the main results of the measurements and how we use the results in our modelling.

The following technologies and fuels have been included in the measurements:

- **SCR/SCR+DPF**: aftertreatment devices that reduce NO_x and PM emissions from exhaust gases. A selective catalytic reduction device (SCR) converts NO_x into water and nitrogen (N_2) by adding urea to the exhaust gases. A Diesel Particulate Filter (DPF) filters PM emissions from the exhaust gas.
- **Gas-to-liquid fuel (GTL)**: GTL is a liquid fuel converted from natural gas. GTL can be used as a substitute for diesel and results in lower NO_x and PM emissions compared to diesel.
- **Liquified natural gas (LNG)**: the use of LNG results in lower NO_x and PM emissions compared to diesel. LNG can be used as the single fuel in a mono-fuel engine commonly used in a gas-electric configuration. Another option is the use of LNG in combination with diesel using a dual fuel engine. In this configuration the engine can run fully on diesel, but the objective is to run mainly on LNG and use diesel only for ignition.
- **Fuel water emulsion (FWE)**: the diesel oil is homogenised with fresh water before injection into the engine. Water and fuel are emulsified before injection into the engine. At the beginning of the combustion process the water nucleus is transformed to steam explosively. This 'micro explosion' ruptures each fuel oil droplet and the droplet is reduced to numerous smaller fuel oil droplets. These smaller fuel oil droplets ignite and burn easier than the bigger droplets. PM and soot creation zones are reduced, the thermal effectiveness improves and fuel consumption decreases (Panteia, et al., 2013). Apart from lowering smoke and soot emissions significantly, the system reduces NO_x levels and CO_2 emissions as well.
- **Diesel-electric**: rather than using a diesel engine for propulsion, an electric engine powered by generally two diesel generators is used. This system could reduce emissions as this set-up allows the use of the generators sets at a more optimal engine load[1]. In the future batteries or fuel cells

1 A large share of the engine power is unused by vessels during normal operation. Only in specific situations and during maneuvering the engine load is over 80%. In most cases the average load is between 25 and 50%. Using two generator sets, one of the generator sets can be switched off at low energy demand, allowing the generator set to operate at a more optimal engine load.

can also be used to power the electric motor. This replaces the conventional engine and results in zero-emissions during operation.

- **Euro VI diesel engines**: Euro VI engines are diesel engines with a SCR and DPF integrated. These engines are originally constructed for the automotive sector and follow corresponding emission standards. As these standards are more strict than current inland waterway standards (CCNR2 and Stage V) there are lower emissions of NO_x and PM compared to regular engines.
- **Regular diesel engines**: Emission measurements have also been conducted at unregulated, CCNR1 and CCNR2 diesel engines. Stage V engines have not been included in the monitoring as they were not available, during this project (Except for the Euro VI engines that meet the Stage V standards).

Diesel hydrogen injection (oxyhydrogen) and Biodiesel (HVO) have also been monitored in the CLINSH project but are not included in the underlying assessment. The main reason why biodiesel is not assessed separately, is because it is mainly a CO_2 reducing option with air quality benefits comparable to GTL. It can be applied in addition or instead (GTL) of the other measures to have additional CO_2 reduction.
Hydrogen injection (oxyhydrogen) was not completely analysed, but revealed a 14% NO_x reduction in the monitoring campaign (see Deliverable of Action B3-1). No results on PM reduction were obtained. Based on literature[2] similar results as for FWE are expected.

Besides the technologies in the monitoring campaign also new Stage V engines and battery electric drive have been assessed as options to reduce emissions, based on literature values. The latter has been included to assess the impact on social costs and to compare it to current available technologies. It is assumed, however, that battery electric propulsion will be technically mature and widely available only after 2035. This is also assumed for fuel cell electric drive.

2 Barna, Lelea, Technical Gazette 24, Suppl.2 (2017), 287-294

2.2 Installation and operational costs

The technologies monitored vary greatly in the way emissions are reduced and the equipment required for the emission reduction. For many technologies new hardware is necessary. We have taken cost estimates associated with the new technologies from the literature (in particular various PROMINENT studies). At the same time we have collected information from the monitored vessels which we have used to crosscheck the values provided by the literature. Detailed references for the mentioned figures can be found in Annex A.

Aftertreatment devices (SCR/DPF)

The costs of aftertreatment devices include the following fixed costs: hardware costs of the SCR and DPF devices as well as the installation costs. The costs have been modelled according to literature values, being € 25 per kW for SCR hardware and € 45,000 per engine for installation and design of SCR. For DPF the initial investment costs are set at € 39 per kW for the hardware and € 15,200 per engine for installation and design. For SCR+DPF the total costs range from € 125 and € 185 per kW depending on the number of engines and the installed power per engine. The results from the CLINSH project vessels confirm these results. We find average fixed costs for the monitoring vessels of about € 150 per kW. The expected installation time of five days is confirmed by the vessel owners, though in some cases delays occurred.

The operational costs of aftertreatment devices include maintenance costs and the costs of AdBlue. Literature predicts maintenance costs of € 2 per 1,000 engine hours for both SCR and DPF and AdBlue costs of € 0.28 per litre. The maintenance costs could not be confirmed by vessel owners as no maintenance took place during the monitoring period. One of the vessel owners noted that availability of AdBlue tanking facilities outside the Netherlands is limited and as a result planning is required to not run out of AdBlue.

Gas-to-liquids

The use of GTL does not require additional investments. There are only operational costs and benefits.

The use of GTL results in higher fuel costs as the price of GTL is higher than diesel. We assume a price difference of € 95 per ton fuel, based on a 10% higher fuel price per litre for GTL and a historic (2015-2020) average diesel price of € 700/ton (source: Zandmaatschappij Twenthe BV). The number of stations where GTL can be bunkered is still limited and as a result it could influence the routes on which a vessel can sail. However, it is possible to sail on a mixture of GTL and diesel without technical issues.

The use of GTL does not influence maintenance or any other operational elements significantly.

Liquified natural gas

LNG can be applied in single and dual fuel engines. Both types of engines require significant investments in a new engine, a specific fuel tank and installation costs. The total costs are modelled according to literature. The costs for the engine and installation amount to € 640-€ 1,150/kW for LNG monofuel, and € 330-€ 670 for LNG dual fuel refit. In both cases the costs for the tank as well as the additional tank connection space (covering connections and valves) amount to an additional

€ 540,000 irrespective of the engine size. There is no information from CLINSH vessel owners about retrofitting costs of LNG engines as the monitored LNG vessels were directly build as LNG vessel. There are also opportunity costs due to idling days in the case of retrofit. 28 days are estimated to be needed for the installation of an LNG engine and tank.

The operational costs for LNG engines depend solely on the differences in fuel prices.
The fuel price of LNG is lower than diesel but fluctuates over time. Based on various sources (Interrijn; Pitpoint; DNVGL) we estimate an average cost advantage per MJ of 25% for LNG compared to diesel. As a result fuel costs of LNG vessels are lower compared to a similar diesel powered vessel.

Fuel-water emulsion

FEW uses equipment to emulsify and inject the fuel water emulsion into the engine. Also, water treatment equipment is necessary to ensure sufficient water quality. According to literature investment costs range between € 70 and € 135 per kW depending on the size of the engine. These values are confirmed by the CLINSH monitoring results, though some installations are relatively more expensive in case of smaller engines.

The operational costs include some additional maintenance costs due to the new technology installed. The use of fuel water emulsion results in a reduction in fuel consumption (2-5% according to literature). It is not clear whether these reductions have been achieved by the monitoring vessels as sailing conditions and routes are not constant over time. Therefore we have assumed the literature values which are based on laboratory measurements.

Diesel-electric (and battery electric)

A diesel-electric engine exists of (a) generator set(s) with electric driven propeller(s). Electric power is provided by, in most cases, two or more generator sets. The electric motor is only used for low speed sailing with relatively low power requirements. This is a typical retrofit solution where electric motors are added to the propeller shaft. The investment costs exist of the costs of the generators, electric motor, as well as additional costs involved for the installation. These are around € 850 per kW according to literature, which is confirmed by the CLINSH demonstration ships. The installation takes at least two weeks.

Battery electric propulsion has been included in the analysis for comparison. Instead of generators, a battery needs to be installed. The modelled battery capacity equals two times the daily energy requirement. This means that half of the total battery capacity can be in use while the other half is charging. Based on several sources (see Annex B), average battery costs of € 250/kWh have been assumed, with a battery lifetime of ten years (approximately 1,500 cycles). The assumptions are on the conservative side and battery costs (including longer lifetime) might go down faster than assumed.

Engine replacement (Stage V/Euro VI)

Another technology option included in the analysis is the installation of new engines which pass the latest Stage V emission standard. Currently there are only a number of Stage V engines available for the inland waterway sector, and as a result there is not much information on these engines. In order to meet the emission standards, these engines will be fitted with an SCR and DPF. The literature estimates that full fixed costs for the installation (including all accessory costs) are up to € 350 per kW. This is about € 150 per kW more than a CCNR2 engine. Information from the measurement vessels show that the Stage V cost figures are also applicable for Euro VI engines, though for smaller engines the costs might be somewhat higher.

The maintenance costs are a bit higher than for the CCNR2 due to more advantaged engine technology installed (integrated SCR and DPF). However, the fuel consumption is lower (about 5-10%) because the engines can be tuned specifically on fuel consumption since the SCR/DPF installation results in lower NO_x and PM emissions. CCNR1 and CCNR2 engines are tuned to optimize NO_x emissions and therefore have slightly higher fuel use. Part of the fuel cost benefit for Stage V/Euro VI is nullified by the costs of AdBlue that is required.

2.3 Environmental benefits

The expected emission reduction of the technologies are discussed by various sources including PROMINENT (various studies), DST (various studies) and Panteia (2019). These sources are often using theoretical models or test bank figures rather than real world performances figures.
The measurement results from CLINSH are based on real world performance and therefore help to support and enrich the expected emission reductions from the literature. On the other hand, the measurements from CLINSH are biased by individual vessel performance which would influence the results too much.
The modelling input is thus based on a combination of literature values and real world experience from the CLINSH project. This section discusses the expected emission reductions from the various technologies, the results from the CLINSH measurements and the subsequent assumptions for the cost-benefit modelling.

2.4 Diesel engines

Engines built before 2003 are not regulated and therefore have relatively high emissions without any aftertreatment or alternative fuel. From 2003 on the CCNR implemented a resolution setting emission standard for vessel on the Rhine, the so called CCNR1, and from 2007 on the CCNR2 standard (CCNR, 2003). From 2007 on emissions from IWT are also regulated by the EU Stage IIIA standard in the non-road mobile machinery (NRMM) directive, with the directive treating engines with the CCNR2 standard equal to Stage IIIA. The revision of the NRMM directive introduced a Stage V emission standard for new engines from 2019 (< 300 kW) and 2020 (> = 300 kW) on.

In the monitoring campaign of CLINSH NO_x emission have been measured for CCNR0, 1 and 2 engines and for a Euro VI engine as well. The average of E3 test cycle [3] results are well in line with literature averages and have been applied as average emission factors in the modelling (see Annex C). PM emission factors could not be established in absolute terms from the monitoring results, as the monitoring method (in accordance with DIN EN 13284-1) gives lower absolute values than the measurement procedure prescribed to certify IWT engines according to the emission regulation (ISO 8178-4). Based on (TNO, 2018), (Umwelt Bundesamt, 2018) and several measurement data collected from CLINSH partners, from other sources, it was decided to use the PM literature values reported by the German emission registry (Umwelt Bundesamt, 2018) as depicted in Table **1**.

[3] The E3 test cycle is the official emission test cycle used to legislate engines. The emissions are tested on four different engine power levels.

Table 1 - Emission factors for diesel engines applied in this study

	g/kWh	NO_x	PM
Diesel	CCNRO	11.8	0.4
	CCNR1	9.2	0.13
	CCNR2	6.73	0.13
	Stage V	1.79	0.015
	Euro VI	0.4	0.01

Source: NO_x: monitoring results; PM (TNO, 2018).

Refit aftertreatment devices (SCR/DPF)

The emission reduction levels of aftertreatment devices depend on the type of engine and aftertreatment hardware, the setup of the aftertreatment devices and the environment in which the aftertreatment devices operate (e.g. ambient temperature). According to various sources (Via Donau, 2015) (DST, 2019b) a SCR can lead to a reduction of NO_x from 70% up to more than 90% depending on the system and configuration, while a DPF reduces PM emissions with more than 90%.
The measurement results from the CLINSH project show that reduction levels up to 70% are indeed obtained by some vessels. However, there are also vessels that do not reach the expected reduction levels.
We identified three reasons that can be the cause for these results:

1. The SCR system is not designed or configured to reach 70-90% reduction levels: The SCR system can be dimensioned to reach higher or lower NO_x reduction. In addition the urea injection quantity determines what reduction levels are reached. In general the systems monitored in CLINSH are designed to reach 70-90% reduction levels. However, skippers with CCNR0 or CCNR1 engines might in practise settle for NO_x reduction levels that meet the CCCNR2 emission standard.
2. When very high NO_x reduction levels are pursued, ammonia leakage may occur. The applied measuring methods cannot distinguish between NO_x and NH_3. NO_x emissions may be lower than measured, however, ammonia emissions are also air pollutant.
3. In general for SCR-DPF lower reduction levels can be expected in some cases, as the exhaust aftertreatment devices are not designed in parallel with the engine. As a result the combination performs less good compared to systems that are designed and type-approved as one complete package (e.g. Stage V/Euro VI engines). Also it takes time to adjust the system to the engine. Some systems have shown improvement during the monitoring period.

The measurement results show that in real world performance well-functioning retrofitted aftertreatment systems reduce NO_x emissions by 70%. For the assessment, we assume that a combination of right settings, good monitoring and system adjustment at least 70% NO_x reduction is feasible. For PM an emissions reduction of 90% according to literature (Via Donau, 2015) has been assumed for the modelling.

Gas-to-liquids

The use of GTL results in a reduction of NO_x emissions of about 9% and almost 60% less PM emissions compared to regular diesel according to Shell[4].
The monitoring results show similar values, with an average reduction in NO_x emissions of 10% and PM emissions of 30% compared to the same vessels sailing on diesel. The latter values have been applied in our analysis.

Liquified natural gas

LNG is a cleaner fuel than regular diesel and as a result emissions are considerably lower. It is expected that LNG-powered engines can reach Stage V emission levels without using aftertreatment devices (LNG binnenvaart, 2019).
The measurement results of the CLINSH vessels show that current NO_x levels are on average 2.8 g/kWh. For PM it has been assumed, based on literature, that Stage V levels can be reached (Via Donau, 2015). LNG use results in lower CO_2 emissions of about 10% (CE Delft, 2021).

Fuel-water emulsion

In the literature various reduction levels are reported for FWE. Older sources report higher reduction levels of 25% NO_x and up to 70% PM (Panteia, et al., 2013). The recently updated Greening Tool[5] reports a large range of reduction levels for NO_x emissions (10-50%) and PM emissions (20-70%) depending on the age of the engine, where more reduction can be reached for older engines. (Panteia, et al., 2013) also reports a fuel benefit of 3% which is not included in the greening tool.
The measurement results for FWE in the CLINSH project show no conclusive results as the results vary significantly between vessels. NO_x emissions are reduced between 40% and 0%. The differences in emission reduction levels cannot be explained by the type of engine, the type of vessel or any other relevant explanation. It therefore seems to be difficult to predict what reduction levels can be expected from fuel-water emulsion. Therefore we assume an average emissions reduction based on the CLINSH measurements of NO_x (25%). For PM a 50% reduction is assumed according to literature (Via Donau, 2015).

Diesel-electric

The diesel-electric monitoring results showed no significant reduction as compared to engines of the same emission standard. Therefore the same emission factors as for diesel engines have been applied.

Engine replacement (Stage V/Euro VI Diesel)

Stage V and Euro VI are strict emission standards that diesel engines can only reach by applying aftertreatment devices (SCR and DPF). Unlike retrofitted devices Stage V and Euro VI engines are designed and certificated as a complete package. As a result the engine and aftertreatment devices operate well together and emission reductions up to the emissions standards are expected.
For Stage V engines over 300 kW these are 1.9 g NO_x/kWh and 0.015 g PM/kWh. For Euro VI the standards are stricter with 0.4 g NO_x/kWh and 0.01 g PM/kWh.

4 EIBIP: Gas-to-liquid (GTL) fuel

5 IWT Greening tool

In the CLINSH project two vessels sailing with Euro VI engines are monitored. The measurement results show that these vessels reach emission levels around the emission standard levels. Therefore we presume that real world emissions from forthcoming Stage V engines will also be around the emission standard levels.

Text box 1 – Zero-emission technologies

The technologies monitored in CLINSH focus on the reduction of NO_x and PM_{10} emissions and not (so much) on the reduction of CO_2 emissions. However, since the Paris Agreement, the EU Green Deal, the Mannheim Declaration and the Fit for 55 package, CO_2 reduction in IWT has become an even more important goal. Technologies such as battery electric engines, hydrogen fuelled engines (either fuel cells or combustions engines) and biofuels are getting more and more attention. Biofuels however do not have a significant impact on emission reduction of air pollutants. Battery electric and hydrogen fuelled vessels on the other hand have no combustion emissions at all, or much lower emission in the case of H_2 used in a combustion engine.
The zero-emission technologies are not yet well suited for IWT. ZE technologies are currently at the phase where initial pilots are being designed and policy ambitions are formulated. For example, the Dutch Climate Agreement (and accompanying Green Deal) has set a goal of 150 inland ships in 2030 with a zero-emission drivetrain. This is still a very limited number compared to the total of about 9,000 IWT ships in the West European IWT fleet. Financial and practical restrictions limit large-scale uptake of zero-emission technologies in the short term.

Up to 2035, therefore, zero-emission technologies are expected to play a limited role and will only be used for specific short distance trips. We have included battery electric propulsion in our calculations in order to show the possible effects of the measure. However, zero-emission solutions are not included for the scenario outcomes as they are no suitable option in the short term. Therefore we assume that carbon emission reductions up to 2035 will be mainly the result of increased application of biofuels in regular diesel engines. The use of biofuels does not hamper the functioning of CLINSH technologies. On the contrary, biofuels and CLINSH technologies can support each other in improving environmental performance of inland vessels.

2.5 Cost benefit of subsidized vessels

During the CLINSH project several vessel owners have received subsidies to (partly) finance emission reduction technologies. In total thirteen different vessels have received subsidies contributing towards 50% of the required investments. The techniques installed using CLINSH funding are SCR-DPF for six vessels, FWE for four vessels, diesel-electric for two vessels and Euro VI for one vessel. Another two vessels have started to use GTL within the CLINSH project. The average annual reduction in NO_x emissions for these vessels is about 30 tonne, which is a relative reduction of approximately 25%. The reduction in PM emissions is about 3 tonne per year, which is a relative reduction of approximately 69%.

Table 2 - Costs & benefits of subsidised vessels during CLINSH

Technology	Number of ships	Nox emission (tonne/ year)			PM emission (tonne/ year)			Average funding
		Before (2016)	After (2021)	Reduction %	Before (2016)	After (2021)	Reduction %	
SCR-DPF	6	60	43	28%	2.2	0.2	90%	€ 89,000
FWE	4	50	42	16%	1.8	0.9	50%	€ 60,000
Euro VI engine & hybridisation*	3	5.9	0.6	89%	0.2	0.01	94%	€ 115,000
GTL	2	14	12	15%	0.4	0.3	30%	N.A.
Total	**16**	**130**	**98**	**25%**	**4.7**	**2.0**	**69%**	**€ 1,147,839**

Source: Monitoring results.

* It concerns a shift from CCNR0 engines to Euro VI engine and, Euro VI engine combined with hybridisation, and a shift from CCNR1 to a CCNR2 engine combined with hybridisation.

2.6 Conclusion

This chapter has given an overview of the investment and operational costs, as well as the emission reduction of several emission abatement techniques and alternative fuels for IWT. The data are based on literature and experiences from the CLINSH demonstration fleet.
The main take-away from the monitoring results is that the emission reduction potential of retrofit measures (SCR&DPF, FWE) is often not fully achieved in real world circumstances. The reasons for this are various but include non-perfect operating conditions and a less optimal interaction between emission reduction technology and engine. For systems which are test bank tested and certified as an entire unit (e.g. CCNR1/CCNR2 engines, Euro VI engines) there are less discrepancies with the predicted emission levels expected, as confirmed by the measured CCNR1 and CNNR2 engines.
The emission factor functions resulting from these findings are discussed in deliverable on emission scenarios.

3 Social costs analysis of reduction technologies

3.1 Introduction

This chapter discusses how the total social costs are calculated. Paragraph 3.2 discusses the approach to calculate the total social costs. Paragraph 3.3 shows the results for the total social costs.
In Paragraph 3.4 the conclusions are drawn.

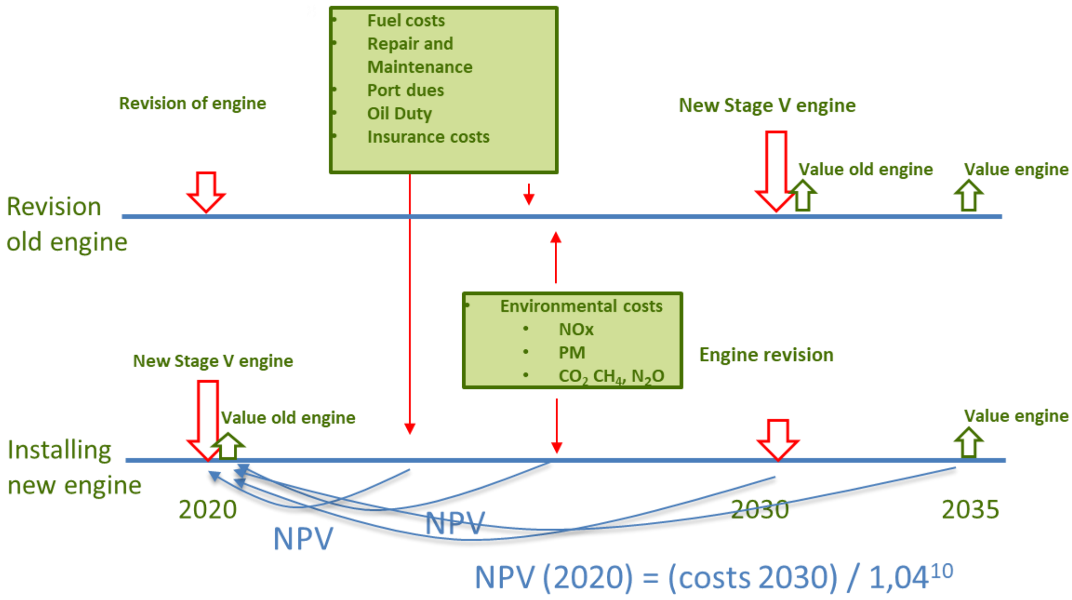
3.2 Approach to calculating total social costs

The goal of the social costs analysis is to include the external costs from emissions associated with the various investment options. By including the environmental costs, we can provide an overview of the value of the investments from a societal perspective. This perspective, in combination with the end user perspective, makes clear which technologies are preferred from different points of view (end user, social or capital perspective).

The costs and benefits are analysed using the Net Present Value (NPV) method to measure the value of investments over time. The NPV represents the sum of all cash flows resulting from an investment or project, discounted to the present. It thus represents the value of the investment in current terms using an interest factor of 4%. We assume that vessel owners invest in emission reduction technologies when engine or vessel revisions are due. Given the uncertainties in future regulation and technical developments, we assess the costs over a period of fifteen years.

Besides the technologies mentioned in Paragraph 2.2 we also consider revision of the current engine as an investment option, being the default to which the ship owner will evaluate his investments. Figure **3** illustrates how the costs of revision of an old engine (age ten years) as compared to the choice to install a new engine are assessed during a period of fifteen years. The illustration shows an engine with a lifetime of 20 years that would need revision after ten years. Buying a new engine gives higher costs in 2020 as compared to revision, and generates some value of the old engine. After ten years the old engine needs replacement by a new engine, whereas the new engine needs to be revised. All the variable costs and environmental costs are assessed for both cases during fifteen years. At the end of the fifteen years the value of the engine on board is valuated. Costs in 2030 are expressed in 2020 values by dividing them by 1.04 to the power 10.

Figure 3 - Illustration of NPV calculation of different spendings within 15 years



Differentiation in vessel categories

As there are major variations between the different vessel categories and the operational use (e.g. power, fuel consumption), different technologies can be beneficial for different parts of the fleet. The costs and benefits are therefore differentiated according to the vessel categories distinguished in Report D2.4:

- passenger vessel < 250 kW;
- passenger vessel 250-500 kW;
- passenger vessel 500-1,000 kW;
- passenger vessel > 1,000 kW;
- push boats < 500 kW;
- push boats 500-2,000 kW;
- push boats ≥ 2,000 kW;
- motor vessels < 80 m length;
- motor vessels dry cargo typical 80 and 86 m ship;
- motor vessels dry cargo typical 105 m ship;
- motor vessels dry cargo 110 m ship;
- motor vessels dry cargo > 130 (135)m ship);
- motor vessels liquid cargo 80-109 m length (typical 86 m ship);
- motor vessels liquid cargo 110 m ship;
- motor vessels liquid cargo > 130 (135 m ship);
- coupled convoys;
- ferry;
- tugboat and workboat.

Differentiation of operational profiles (sailing hours)

Also within vessel categories there are larger differences in the sailing hours and fuel use.
For example, large tank vessels are used to continuously transport fuels from Dutch ports towards Germany resulting in relatively high fuel use. A similar vessel could also be used to bunker maritime vessels inside port areas, which results in much lower annual fuel consumption. A consequence of the large difference in fuel consumption is that different emission reduction technologies are optimal for these individual vessels. This exemplifies that no one-size-fits-all solution is available and that a cost-benefit analysis of the various technologies should consider individual vessel characteristics and operational details.

In order to consider the large spread of sailing hours within vessel categories we have split each vessel category in three segments:

1. High: vessels with high fuel use within their class (top 25%).
2. Average: vessels with average fuel use within their class (medium 50%).
3. Low: vessels with low fuel use within their class (bottom 25%).

These segments are based on AIS data resulting from monitoring during CLINSH project. Overlooking all vessel categories the following pattern was visible: vessels with relatively high number of sailing hours sail 75% more than the average vessels, vessels with low number of sailing hours sail 57% less than average vessels in each category. This approach allows us to model the spread in fuel consumption within vessel categories to a certain extent. The outcomes will show the variety of emission reduction technologies that are interesting for vessels of the same class with different fuel consumption levels.

3.3 Costs and benefits assumptions

The costs and benefits of the various technologies are discussed in Chapter 2.
As discussed in Paragraph 2.2 the investment costs in the literature reflect the actual costs incurred for the monitoring vessels well. The investment costs are costs associated with the hardware, design and installation of the technologies. Some investment costs are independent of size, others do depend on size. The values discussed in Chapter 2 and listed in Annex C are the basis for the investment costs modelling.

Emission reductions

The modelling assumptions are based on the literature and the monitoring results from CLINSH.
The literature values provide a range of emission reduction but often miss real world interpretation.

The monetary valuation of air pollutant emissions is based on the environmental cost factors for NO_x, $PM_{2.5}$ and CO_2 for different EU countries from the Handbook on the external costs of transport (CE Delft; INFRAS;TRT;Ricardo, 2019). A weighted country average is calculated based on the inland transport performance in relevant countries (Eurostat data for Belgium, Germany and the Netherlands). Following CE Delft; INFRAS; TRT; Ricardo (2019) we assume that 5% of emissions occur in urban areas, and 5% in metropolitan areas. The other 90% of emissions are emitted in rural areas. The valuation of CO_2 emissions is based on the costs of mitigation measures in order to prevent temperature rises above two degrees Celsius. The CO_2 price increases towards the future as more expensive measures have to be taken in order to reach sufficient CO_2 reductions. Following CE Delft; INFRAS;TRT;Ricardo (2019) the 2016 price of € 100/ton increases to € 269/ton after 2030.

Between now and 2035 this results in an average CO_2 price of € 167. Table 3 gives an overview of the applied cost factors.

Table 3 - Environmental costs from inland waterway transport emissions CLINSH region

Region	NO_x (€$_{2018}$ per ton)	$PM_{2.5}$ (€$_{2018}$ per ton)	CO_2 (€$_{2018}$ per ton)
Weighted average environmental costs CLINSH region	€ 20,038	€ 123,132	€ 167

Source: Eurostat and CE Delft; INFRAS;TRT;Ricardo, 2019.

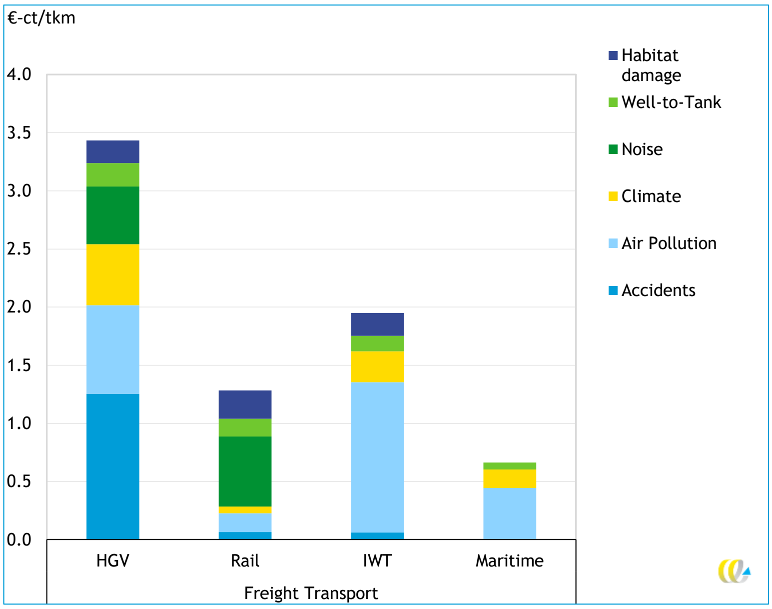
Text box 2 - Valuing environmental costs and comparison of external costs between modes

The costs of air pollution are estimated using a damage cost approach. In this approach the costs for each of the individual effects are calculated and summed up to calculate a total effect. The valuation of air pollution considers the following four types of impacts caused by the transport emissions: health effects (e.g. bronchitis, asthma, lung cancer), crop losses, material building damage as well as biodiversity loss. Put differently, damage costs are the total present value of future costs and benefits related to air pollution. The location of the air pollution has consequences for the damage of air pollutant emissions. In densely populated areas more people are affected by the pollution and as a result the costs of the emissions increases.

In general, there are two major ways in which climate change costs can be calculated: using damage costs or avoidance costs. The damage cost approach values each of the individual effects of climate change and adds these up. The avoidance cost approach centres around the costs of avoiding the effects of climate change up to a desired extent (e.g. specified in a policy target). As disscussed in CE Delft; INFRAS;TRT;Ricardo (2019) an avoidance costs approach is preferred for climate change costs as for a damage costs approach all climate damages need to be fully understood and quantified. Although many of the climate damages are somewhat understood, there are certain feedbacks and potentially extreme events that are not yet fully understood.

For comparison between transport modes it is important to select the correct criteria. In terms of external costs of transport modes it important to include all externalities as well as the differences in loading capacity. Therefore comparisons in external costs between modes are preferably expressed in €/tkm. This type of comparison is made by CE Delft; INFRAS;TRT; Ricardo (2019), the main results for the EU28 are shown in Figure **4**. The results show that maritime and rail transport have lowest environmental costs, while road transport has the highest cost on average. The main costs for inland waterway transport are costs resulting from air pollution. These costs are considerably lower for the other modes. Mainly due to cleaner drivetrains for HGV and Rail and operations in less populated areas (maritime transport).

Figure 4 – Average environmental costs per tkm for various modes



The environmental costs however also depend on the specific vehicle or vessel used, as well as the transport location (in general costs are higher in densely populated areas). Therefore cross-modal comparisons should be taken with care, and the results presented in this study do not directly allow for cross-modal comparison.

Note

In this study (external) costs are presented at vessel or fleet level, rather than costs per tkm. The figures that are presented in the following sections can therefore not easily be compared to other modes, but are merely meant to compare the presented options to each other. Moreover, the results are giving costs as to present value of costs over a period of fifteen years.

3.4 Social cost results

Social cost results for the subsidised CLINSH fleet

Based on the environmental cost factors, the benefits of the subsidised CLINSH ships have been calculated as depicted in Table **4**. Benefits of lower CO_2 emission are expected as well, in particular for the Euro VI engines, but could not be quantified. Next to the benefits, Table **4** shows the amount of funding from the LIFE Program and the social break-even point of the funding. It can be concluded that after 0.9 and 2.6. years the social benefits already outweigh the funding.

Table 4 - Costs & benefits of subsidised vessels during CLINSH

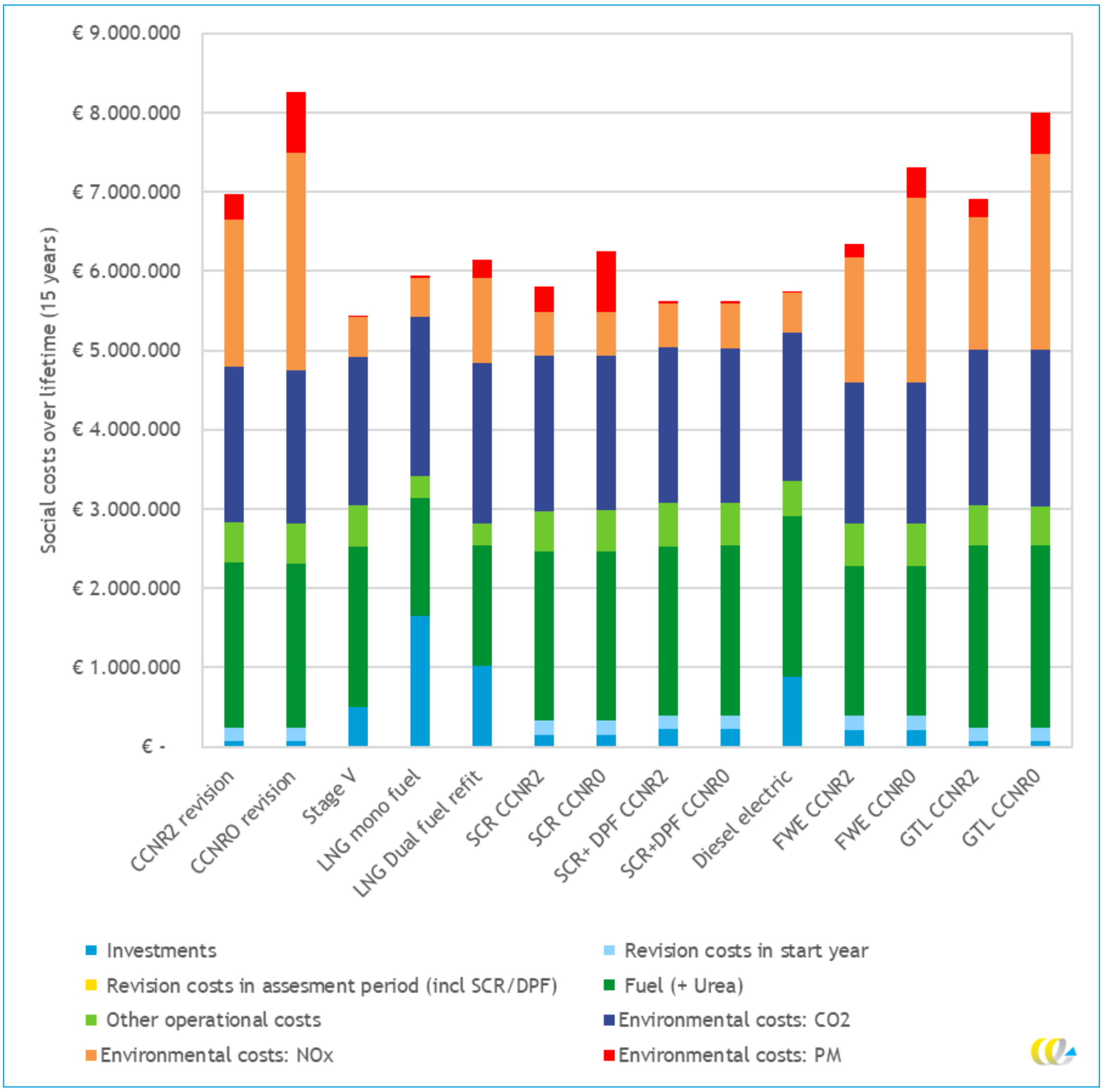
Technology	Number of ships	Annual environmental benefits (tonne/year)			Total funding LIFE program	Social break-even point of funding (years)
		NO_x reduction	PM reduction	Total benefits		
SCR-DPF	6	€ 337,106	€ 248,207	€ 585,312	€ 533,700	0.9
FWE	4	€ 159,560	€ 110,823	€ 270,383	€ 240,000	0.9
Euro VI engine & hybrid	3	€ 104,895	€ 27,868	€ 132,763	€ 344,000	2.6
GTL	3	€ 62,192	€ 43,014	€ 105,206	N.A.	N.A.
Total	**16**	€ 663,753	€ 429,911	€ 1,093,665	**€ 1,177,839**	

Social cost results in general

Figure **5** shows the results of the NPV calculation for a 110 metre dry cargo vessel. The results show the total societal costs for the various costs elements. The main costs of most technologies are fuel costs, costs of CO_2 emissions and emissions of NO_x. The share of initial investment of most technologies is small compared to the other cost elements. This is due to long lifetime of engines. As a result, costs associated with use, like fuel and environmental costs are relatively more important. Only for battery electric vessels there are very high investment costs. This is due to the high price of batteries and the limited lifetime of the batteries. As a result, replacements are required within a fifteen years timeframe.

The results show that, as expected, environmental costs of CCNR2 engines are less compared to engines without CCNR regulation. Another result is that from a societal benefit perspective, battery electric engines are the preferred option due to the absence of emissions (but there may be emissions from electricity generation). However this analysis does not yet take into account the limited applicability of battery electric vessels due to range limitations among others. The Stage V engine is the next best option with lowest social costs.

Figure 5 - Results of NPV calculation for dry cargo 110 m vessel with fifteen years timeframe with medium fuel use



From an end user perspective, which only includes costs borne by the end user, we can see differences in costs between the various technologies. All technologies cost the end user between two and four million euro. LNG, Stage V and diesel/battery electric are technologies with a high level of initial investment. At the same time these technologies result in lower fuel costs. The technologies with the lowest end user costs are revision of current engines, FWE and GTL. However these technologies do often not result in the lowest social costs. Figure 6 and Figure 7 show the results for 110 m vessels with low (figure 6) and high (figure 7) fuel use. At high fuel use, technologies with operational benefits compared to diesel (i.e. LNG), score relatively better.

Figure 6 - Results of NPV calculation for dry cargo 110 m vessel with fifteen years timeframe with low fuel use

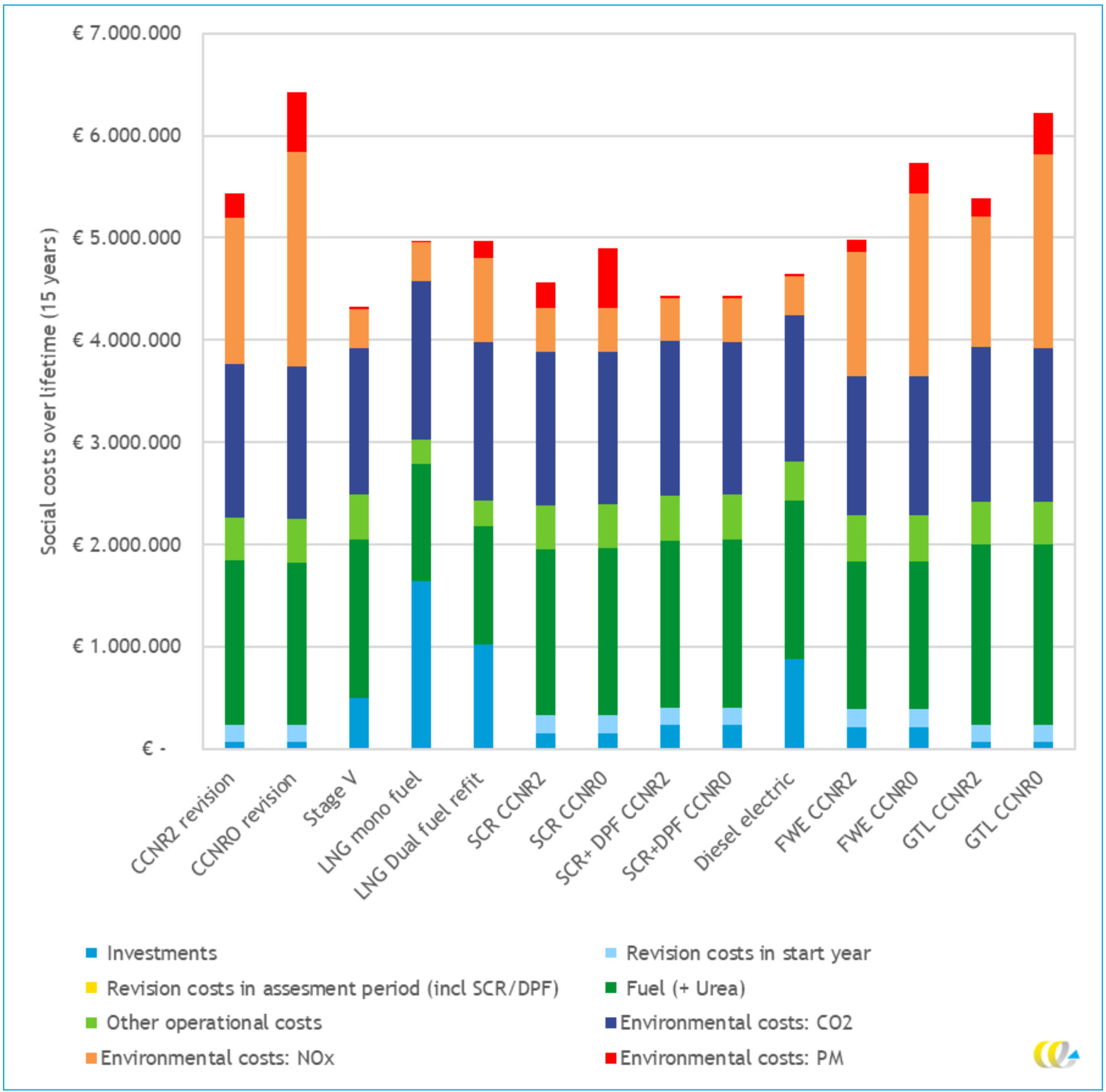
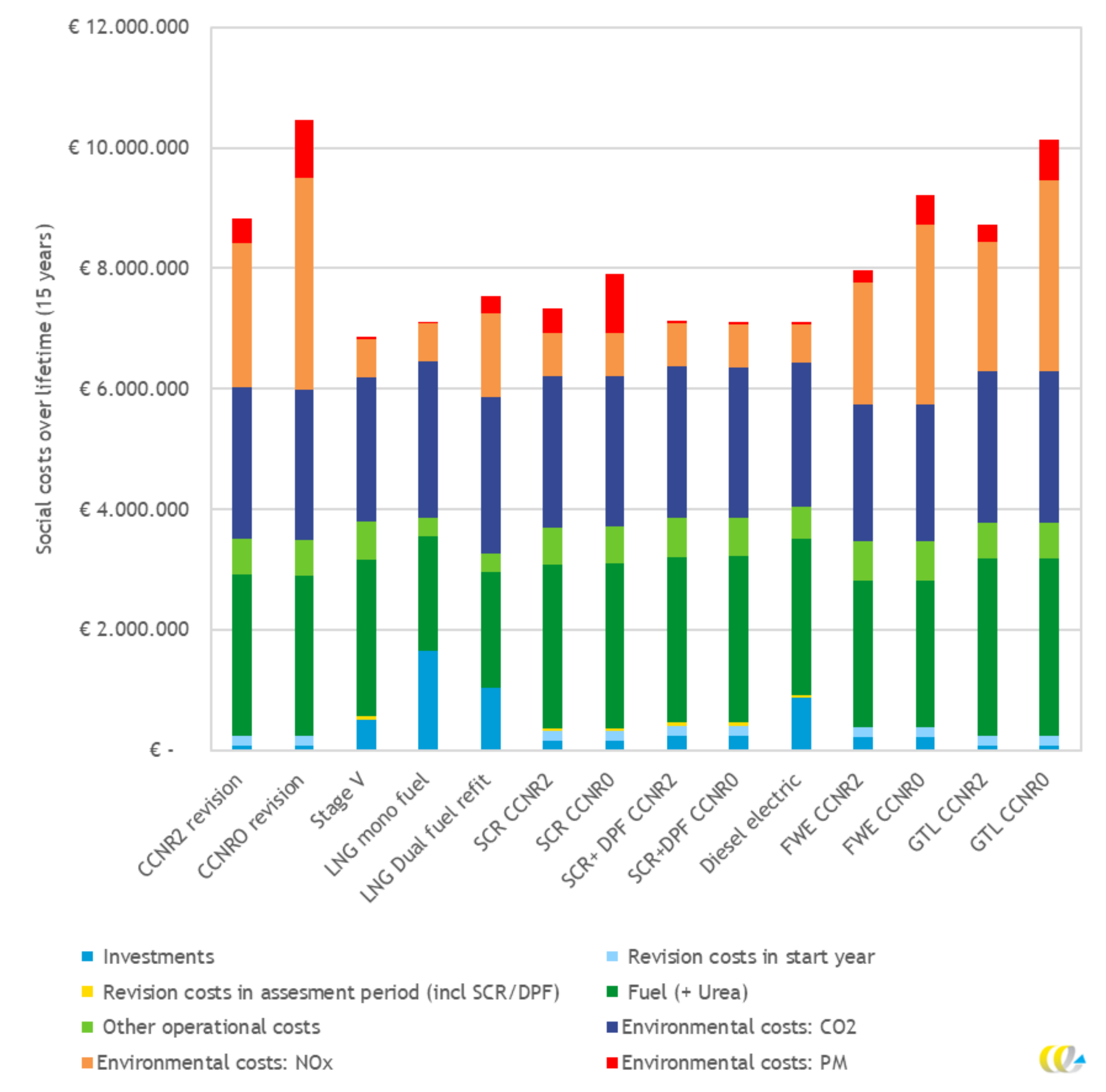


Figure 7 - Results of NPV calculation for dry cargo 110 m vessel with fifteen years timeframe with high fuel use



Text box 3 - Battery electric propulsion

As discussed in Text box 1 battery electric propulsion is not part of the final assessment for the CLIINSH scenario, as we expect that before 2035 the high investment costs, limitations to range and charging equipment are limiting large scale uptake. For specific vessels sailing on fixed routes, like the recently electriffied vessel the Alphenaar, battery electric propulsion could be an option. For illustration, the results shown in Figure **8** inlcude battery electric propoulsion as investment option. The results show that the costs of a battery electric drivetrain are significanlty higher compared to the other options. However the absence of direct emissions does make it the most optimal solution from a social point of view. This example shows that there is a large potential for reduction of environmental costs in the future.

Figure 8 - Results of NPV calculation for dry cargo 110 m vessel with fifteen years timeframe including battery electric

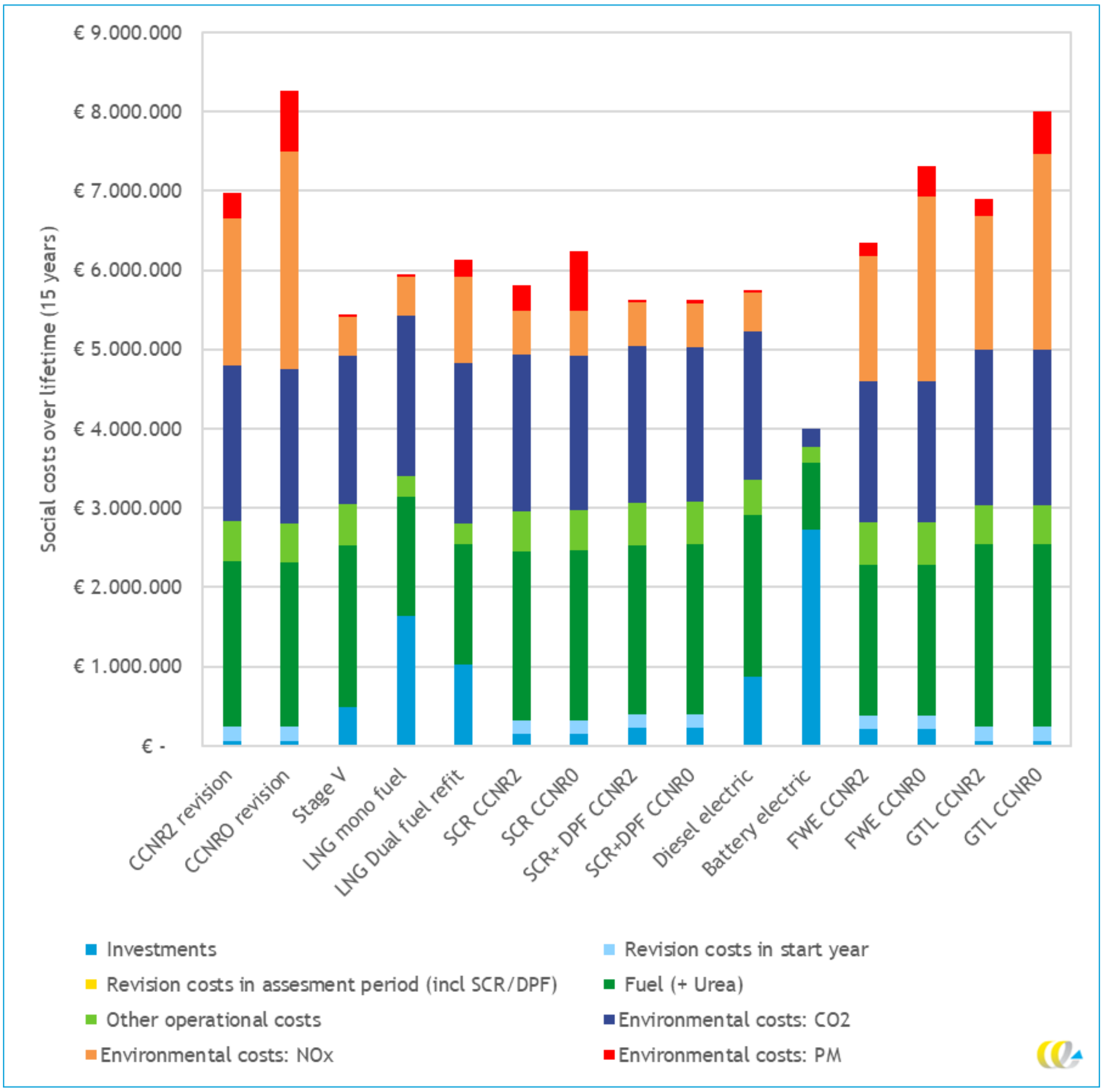
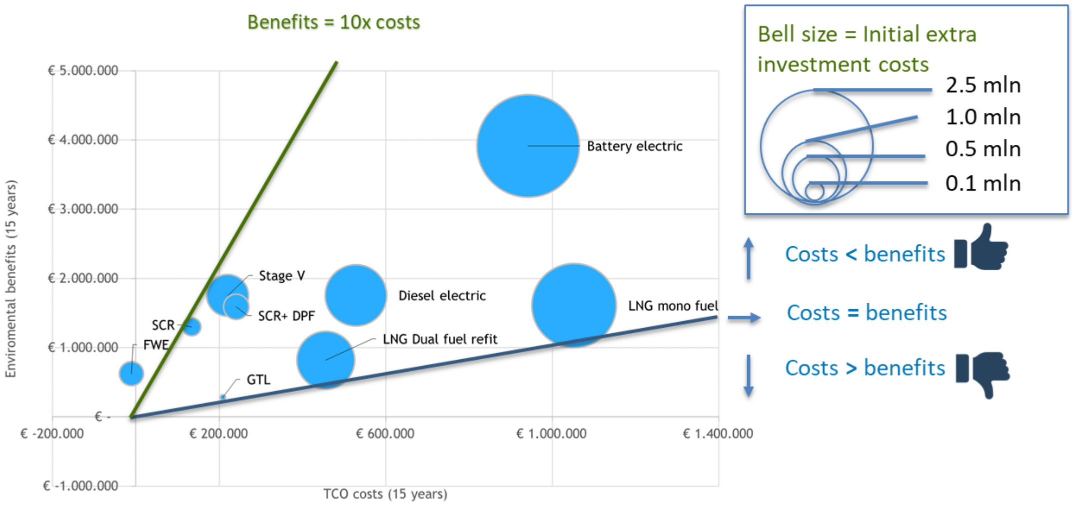


Figure **9** shows a different representation of results of Figure 8. The figure depicts the extra costs (x-axis) and environmental benefits (y-axis) for the different reduction options as compared to engine revision for a 110 metre vessel with a CCNR2 engine and normal fuel use. The bell size represents the investment costs. The figure shows that the largest benefits as well as (investment) costs are associated with battery electric propulsion. Other options with high investment costs are LNG, diesel-electric and to a smaller extent Stage V. The environmental benefits are in magnitude quite comparable for Stage V, SCR-DPF, diesel-electric as well as LNG monofuel. For this specific vessel type all reduction options result in higher environmental benefits as compared to additional costs; they are all above the line where costs equal benefits. For some technologies the benefits outweigh the costs by about a factor ten or more, such as FWE and SCR. This means that the technologies are very

cost effective from a social cost point of view. The socially most optimal solution, however, is battery electric followed by the Stage V engine as the total social costs are the lowest (see Figure 8).
The environmental benefit to cost ratio for FWE and SCR is better than for battery-electric and Stage V, but the extra costs for the latter two are resulting in environmental benefits that are even higher, resulting overall in the lowest social costs.

Figure 9 - Environmental benefits compared to additional TCO costs and investment costs (bubble size) of techniques compared to revision for 110 metre vessel with CCNR2 engine and normal fuel use



The figures presented only show the results for a 110 metre ship. Results for other ships can be viewed with an Excel tool delivered as Annex A to this deliverable. The results vary between the different ship types and fuel consumption profiles.
In the next paragraphs we present the technologies with the lowest costs from both societal and end user (TCO) perspectives.

3.5 Results from the societal perspective

The previous Paragraph 3.4 has shown that the technologies most beneficial for society are not the most advantageous for end users. Battery electric propulsion is most beneficial for society due to the absence of emissions. However the high level of initial investments and practical constraints make battery electric propulsion at this time not ready for large-scale uptake. Therefore battery electric propulsion is not included for the main analysis. For each vessel category the costs for end users and society are calculated similar to the results presented in Figure 5, Figure 6 and Figure 7. The vessel categories are segmented into three levels of fuel use in order to mimic the spread in sailing hours in reality.

Textbox 4 - Disclaimer for outcomes

As shown in Figure **5** to Figure **8** there are multiple reduction options that have environmental benefits. For the CLINSH scenario the options with the lowest social costs are selected in order to show the total potential of accelerated air polution reduction. The CLINSH scenario does not consider real life limitations towards funding, availability of (fuelling) infrastructure and consumer myopia. As a result policy makers as well as vessel owners might prefer other options besides the most social optimal solution calculated. The outcomes presented in Table **5** and Table **6** are thus based on generalised assumptions and might not translate well towards specfiic situations. Policies should promote all options that have significantly higher enviromental benefits compared to (investment) costs. Vessel owners are then able to select the the most optimal solution for their specific situation. Our results show that engine replacement is one of the most social optimal solutions and therefore should be incldued from a social point of view.

The options with lowest cost for CCNR2 engines are shown in Table **5**.
Table 6 shows the options for CCNR0/1 engines. LNG is an interesting option for vessels which have high fuel use levels, while GTL is mainly an interesting option for vessels with low fuel use levels.

Table 5 – Options with lowest social costs in different vessel categories for CCNR2 engines in 2035, without battery electric

Vessel category	Low fuel use	Average fuel use	High fuel use
Passenger vessel < 250 kW	GTL	GTL	Stage V
Passenger vessel 250-500 kW	GTL	SCR	Stage V
Passenger vessel 500-1,000 kW	GTL	SCR	Stage V
Passenger vessel > 1,000 kW	Stage V	Stage V	Stage V
Push boats < 500 kW	Stage V	Stage V	Stage V
Push boats 500-2,000 kW	Stage V	Stage V	Stage V
Push boats ≥ 2,000 kW	LNG monofuel	LNG monofuel	LNG monofuel
Motor vessels < 80 m length	SCR	Stage V	Stage V
Motor vessels dry cargo typical 80 and 86 m ship	Stage V	Stage V	Stage V
Motor vessels dry cargo typical 105 m ship	Stage V	Stage V	Stage V
Motor vessels dry cargo 110 m ship	Stage V	Stage V	Stage V
Motor vessels dry cargo > 130 (135 m ship)	Stage V	Stage V	Stage V
Motor vessels liquid cargo 80-109 m length (86 m ship)	Stage V	Stage V	Stage V
Motor vessels liquid cargo 110 m ship	Stage V	Stage V	Stage V
Motor vessels liquid cargo > 130 (135 m ship)	Stage V	Stage V	Stage V
Coupled convoys	Stage V	Stage V	LNG monofuel
Ferry	GTL	GTL	SCR
Tugboat and workboat	GTL	SCR	Stage V

Table 6 – Options with lowest social costs in different vessel categories for CCNR0 engines in 2035, without battery electric

Vessel categories	Low fuel use	Average fuel use	High fuel use
Passenger vessel < 250 kW	GTL	Stage V	Stage V
Passenger vessel 250-500 kW	SCR	Stage V	Stage V
Passenger vessel 500-1,000 kW	SCR	SCR+DPF	Stage V
Passenger vessel > 1,000 kW	Stage V	Stage V	Stage V
Push boats < 500 kW	Stage V	Stage V	Stage V
Push boats 500-2,000 kW	Stage V	Stage V	Stage V
Push boats ≥ 2,000 kW	LNG monofuel	LNG monofuel	LNG monofuel
Motor vessels < 80 m length	Stage V	Stage V	Stage V
Motor vessels dry cargo typical 80 and 86 m ship	Stage V	Stage V	Stage V
Motor vessels dry cargo typical 105 m ship	Stage V	Stage V	Stage V
Motor vessels dry cargo 110 m ship	Stage V	Stage V	Stage V
Motor vessels dry cargo > 130 (135 m ship)	Stage V	Stage V	Stage V
Motor vessels liquid cargo 80-109 m length (86 m ship)	Stage V	Stage V	Stage V
Motor vessels liquid cargo 110 m ship	Stage V	Stage V	Stage V
Motor vessels liquid cargo > 130 (135 m ship)	Stage V	Stage V	Stage V
Coupled convoys	Stage V	Stage V	LNG monofuel
Ferry	GTL	SCR	Stage V
Tugboat and workboat	GTL	SCR+DPF	Stage V

3.6 Results from the end user perspective

The perspective from end users shows which technology results in the lowest costs for end user costs. This is an interesting perspective as it shows the option most vessel owners will choose in the absence of policies to promote cleaner technologies. Table **7** shows the options with lowest end user cost for CCNR2 engines, Table **8** shows the options for CCNR0 engines. The results for CCNR2 and CCNR0 engines show that revision is the most advantageous option for vessels with CCNR2 engines. For vessels which have higher levels of fuel use the technologies that reduce fuel consumption and costs, like FWE and LNG, become interesting. Stage V engines are equipped with the latest technologies and therefore reduce fuel consumption as well. However, the lower fuel consumption does not cover the higher investment costs.

Table 7 – Options with lowest end user costs in different vessel categories for CCNR2 engines in 20020-2035, without battery electric

Vessel category	Low fuel use	Average fuel use	High fuel use
Passenger vessel < 250 kW	Revision	Revision	Revision
Passenger vessel 250-500 kW	Revision	Revision	Revision
Passenger vessel 500-1,000 kW	Revision	Revision	Revision
Passenger vessel > 1,000 kW	Revision	FWE	LNG Dual fuel refit
Push boats < 500 kW	Revision	Revision	FWE
Push boats 500-2,000 kW	Revision	Revision	Revision
Push boats ≥ 2,000 kW	LNG Dual fuel refit	LNG Dual fuel refit	LNG Dual fuel refit
Motor vessels < 80 m length	Revision	Revision	Revision
Motor vessels dry cargo typical 80 and 86 m ship	Revision	Revision	Revision
Motor vessels dry cargo typical 105 m ship	Revision	FWE	FWE
Motor vessels dry cargo 110 m ship	Revision	FWE	FWE
Motor vessels dry cargo > 130 (135 m ship)	FWE	LNG Dual fuel refit	LNG Dual fuel refit
Motor vessels liquid cargo 80-109 m length (86 m ship)	Revision	FWE	FWE
Motor vessels liquid cargo 110 m ship	Revision	FWE	FWE
Motor vessels liquid cargo > 130 (135 m ship)	Revision	Revision	LNG Dual fuel refit
Coupled convoys	Revision	LNG Dual fuel refit	LNG Dual fuel refit
Ferry	Revision	Revision	Revision
Tugboat and workboat	Revision	Revision	Revision

Table 8 – Options with lowest end user costs in different vessel categories for unregulated engines in 2020-2035, without battery electric

Vessel category	Low fuel use	Average fuel use	High fuel use
Passenger vessel < 250 kW	Revision	Revision	Revision
Passenger vessel 250-500 kW	Revision	Revision	Revision
Passenger vessel 500-1,000 kW	Revision	Revision	Revision
Passenger vessel > 1,000 kW	Revision	FWE	LNG Dual fuel refit
Push boats < 500 kW	Revision	Revision	Revision
Push boats 500-2,000 kW	Revision	Revision	Revision
Push boats ≥ 2,000 kW	LNG Dual fuel refit	LNG Dual fuel refit	LNG Dual fuel refit
Motor vessels < 80 m length	Revision	Revision	Revision
Motor vessels dry cargo typical 80 and 86 m ship	Revision	Revision	Revision
Motor vessels dry cargo typical 105 m ship	Revision	FWE	FWE
Motor vessels dry cargo 110 m ship	Revision	Revision	FWE
Motor vessels dry cargo > 130 (135 m ship)	FWE	LNG Dual fuel refit	LNG Dual fuel refit
Motor vessels liquid cargo 80-109 m length (86 m ship)	Revision	Revision	FWE
Motor vessels liquid cargo 110 m ship	Revision	FWE	FWE
Motor vessels liquid cargo > 130 (135 m ship)	Revision	Revision	LNG Dual fuel refit
Coupled convoys	Revision	LNG Dual fuel refit	LNG Dual fuel refit
Ferry	Revision	Revision	Revision
Tugboat and workboat	Revision	Revision	Revision

4 Socio-economic effects of baseline and CLINSH scenario

4.1 Introduction

In this chapter we describe the total social costs of two scenarios towards 2035, with regard to the adaptation of NO_x and PM emission abatement techniques in IWT. Paragraph 4.2 introduces the fleet development results from Task D2.4 , which form the base for two scenarios. It concerns a baseline scenario and a scenario with accelerated emission reduction, referred to as the CLINSH scenario. In Paragraph 4.3 the socio-economic results for both scenarios are discussed.

4.2 Fleet development results (D2.4)

Assumptions for the baseline scenario

The two scenarios that have been investigated in CLINSH are a baseline scenario and the so-called CLINSH scenario. The scenarios are described for the year 2020 and to 2035 with measures taken in the period 2022-2035. From 2022 all new engines installed need to meet the Stage V emission requirements. In the baseline scenario, we assume that engine renewal as described in Chapter 1 leads to the introduction of new Stage V diesel engines. We assume that no other emission reduction technologies will be installed in the baseline scenario, as there are not sufficient financial or regulatory incentives to do so. We do not take into account any effects from ambitions set in the Mannheim Declaration (35% reduction of pollutants and GHG emissions in 2035), the Dutch Climate Agreement (150 electric drivetrains in 2030, 35-50% reduction of air polluting emissions in 2035), EU Green Deal, Fit for 55 package or any other policy ambition in the baseline, as policies and regulations to reach these ambitions are still in development and it thus remains uncertain how and if these targets will be reached.

Table **9** and Table **10** show the number of vessel per technology in 2020 and 2035 in the baseline scenario.

Table 9 - Number of vessels per technology for baseline scenario in 2020

Vessel category	Unregulated	CCNR1	CCNR2	Stage V	LNG monofuel	SCR + DPF
Passenger vessel < 250 kW	458	23	40	-	-	-
Passenger vessel 250-500 kW	191	10	26	-	-	-
Passenger vessel 500-1,000 kW	44	3	13	-	-	-
Passenger vessel > 1,000 kW	25	49	86	-	-	-
Push boats < 500 kW	118	6	32	-	-	-
Push boats 500-2,000 kW	14	30	41	-	-	3
Push boats ≥ 2,000 kW	0	0	12	-	-	-
Motor vessels < 80 m length	797	452	376	-	-	-
Motor vessels dry cargo typical 80 and 86 m ship	293	235	142	-	-	24
Motor vessels dry cargo typical 105 m ship	55	90	94	-	-	8
Motor vessels dry cargo 110 m ship	3	187	164	-	-	12
Motor vessels dry cargo > 130 (135 m ship)	3	85	122	-	-	7
Motor vessels liquid cargo 80-109 m length (typical 86 m ship)	61	98	197	-	-	13
Motor vessels liquid cargo 110 m ship	4	148	336	-	10	18
Motor vessels liquid cargo > 130 (135 m ship)	1	34	126	-	-	6
Coupled convoys	5	41	86	-	2	5
Ferry	335	76	195	-	6	-
Tugboat and workboat	413	3	64	-	-	-
Total	**2,819**	**1,571**	**2,155**	**-**	**18**	**96**

Table 10 - Number of vessels per technology for baseline scenario in 2035

Vessel category	Unregulated	CCR1	CCNR2	Stage V	LNG monofuel	SCR + DPF
Passenger vessel < 250 kW	289	23	40	169	-	-
Passenger vessel 250-500 kW	140	10	26	51	-	-
Passenger vessel 500-1,000 kW	35	3	13	9	-	-
Passenger vessel > 1,000 kW	18	48	86	78	-	-
Push boats < 500 kW	47	6	62	43	-	-
Push boats 500-2,000 kW	-	10	26	47	-	3
Push boats ≥ 2,000 kW	-	-	-	13	-	-
Motor vessels < 80 m length	252	387	488	252	-	-
Motor vessels dry cargo typical 80 and 86 m ship	107	234	240	128	-	25
Motor vessels dry cargo typical 105 m ship	1	67	136	46	-	9
Motor vessels dry cargo 110 m ship	0	141	161	81	-	13
Motor vessels dry cargo > 130 (135 m ship)	0	26	81	124	-	8
Motor vessels liquid cargo 80-109 m length (typical 86 m ship)	19	94	226	40	-	13
Motor vessels liquid cargo 110 m ship	0	114	327	106	12	20
Motor vessels liquid cargo > 130 (135 m ship)	0	10	81	80	-	6
Coupled convoys	0	10	48	80	1	5
Ferry	280	76	197	59	6	-
Tugboat and workboat	240	3	64	173	-	-
Total	**1,429**	**1,263**	**2,302**	**1,579**	**19**	**103**

Assumptions for the CLINSH scenario

The CLINSH scenario focusses on applying NO_x and PM_{10} reducing measures up to 2035 to the part of the fleet that will not renew their engines autonomously between 2020 and 2035[6]. We assume that in 2035 on these ships the NO_x and PM_{10} reduction measures will have been implemented with the lowest social costs measured over a period of fifteen years. The results thus show the full potential for accelerated emission reduction in the inland waterway sector. The CLINSH scenario assumes that policy instruments that will be in place (see Deliverable 2.3 and D2.1), will overcome the gap between the extra TCO costs and make the options with the lower social optimal costs also attractive for the ship owners to invest in. This can be either by applying taxes (e.g. based on the (parially) internalisation of external costs, or by investment or operational subsidies.

In the CLINSH scenario, for each ship category with a differentiation towards low, medium and high fuel consumption, the best option from a social costs point of view is chosen (see Paragraph 3.3), resulting in a scenario with the lowest social costs. The CLINSH scenario is based on 'the winner takes it all' technology within a ship type/fuel consumption category to illustrate the effects of policy, supporting techniques with lowest social costs. In practise, however, given that policy support is in place to support abatement tecnhnologies, ship owners might also choose the second or third best

6 The same amount of Stage V engines enters the fleet autonomously in the CLINSH scenario compared to the baseline scenario.

option in the model, either because it is the better option in their specific situation or because they have a personal (non-monetary) preference for a certain technology.
The measures are assumed to be taken during engine revision, assuming that engine revision will take place for all ships during this period. Given the uncertainties of future emission regulations a lifetime of fifteen years is assumed, although actual lifetimes of engines and reduction technologies can be longer. Revision of the current engine or early placement of a Stage V engine can be outcomes as well, when one of these options results in the lowest social costs. Measures reducing CO_2 only, like biofuels, are not considered in the CLINSH scenarios as such, as they do not have a significant (positive or negative) effect on pollutant emissions as compared to their fossil fuel counterparts.

The results of the CLINSH scenarios are depicted in Table **11**. The table shows that for many vessels early placement of a Stage V engine is the social optimal reduction option.

Table 11 - Number of vessels by technology in 2035 for CLINSH scenario

Vessel category	Revision (CCR0/ 1 or 2)	Stage V	LNG monofuel	SCR	SCR + DPF	Diesel-electric	GTL
Passenger vessel < 250 kW	0	413	0	0	0	0	108
Passenger vessel 250-500 kW	0	170	0	50	0	0	6
Passenger vessel 500-1,000 kW	0	21	0	16	19	0	3
Passenger vessel > 1,000 kW	0	230	0	0	0	0	0
Push boats < 500 kW	0	158	0	0	0	0	0
Push boats 500-2,000 kW	0	84	0	0	3	0	0
Push boats ≥ 2,000 kW	0	13	0	0	0	0	0
Motor vessels < 80 m length	0	1,257	0	122	0	0	0
Motor vessels dry cargo typical 80 and 86 m ship	0	709	0	0	25	0	0
Motor vessels dry cargo typical 105 m ship	0	249	0	0	9	0	0
Motor vessels dry cargo 110 m ship	0	383	0	0	13	0	0
Motor vessels dry cargo > 130 (135 m ship)	0	232	0	0	8	0	0
Motor vessels liquid cargo 80-109 m length (typical 86 m ship)	0	379	0	0	13	0	0
Motor vessels liquid cargo 110 m ship	0	547	12	0	20	0	0
Motor vessels liquid cargo > 130 (135 m ship)	0	172	0	0	6	0	0
Coupled convoys	0	123	16	0	5	0	0
Ferry	0	148	6	227	0	0	237
Tugboat and workboat	0	250	0	32	122	0	77
Total	**0**	**5,538**	**34**	**447**	**244**	**0**	**431**

* The options Dual fuel LNG refit and FWE are not displayed. For none of the ship categories these options have the lowest social costs.

4.3 Socio-economic results

The results from the fleet development are combined with the cost and benefit calculations in order to determine the costs of the baseline scenario and the CLINSH scenario for the entire fleet. The results for the total social costs are shown in Table **12**. The second column shows the costs for the baseline scenario, while the third column presents the costs for the CLINSH scenario. The difference (fourth column) should be interpreted as the maximum costs reduction due to accelerated emission reduction in the inland waterway sector.

The social costs for the CLINSH scenario are lower for most vessels due to the application of emission reduction technologies. These technologies result in lower damage costs as a result of lower emissions. The vessel categories with the largest potential for social costs reduction are the larger cargo vessels as well as the passenger vessels above 1,000 kW. These categories consist of a significant amount of vessels with relatively high sailing hours. The CLINSH scenario results in a social cost reduction of about 5 billion euro compared to the baseline scenario.

Table 12 – Total social costs per ship category for baseline and CLINSH scenario in 2020-2035 period

Million euros	**Total social costs baseline 2020-2035**	**Total social costs CLINSH scenario in 2020-2035**	**Difference (Baseline-CLINSH)**
Passenger vessel < 250 kW	€ 192	€ 176	€ 17
Passenger vessel 250-500 kW	€ 217	€ 188	€ 29
Passenger vessel 500-1,000 kW	€ 88	€ 74	€ 13
Passenger vessel > 1,000 kW	€ 2,546	€ 2,054	€ 492
Push boats < 500 kW	€ 325	€ 262	€ 64
Push boats 500-2,000 kW	€ 378	€ 344	€ 34
Push boats ≥ 2,000 kW	€ 593	€ 593	€ 0
Motor vessels < 80 m length	€ 1,705	€ 1,361	€ 344
Motor vessels dry cargo typical 80 and 86 m ship	€ 2,334	€ 1,781	€ 553
Motor vessels dry cargo typical 105 m ship	€ 1,811	€ 1,404	€ 407
Motor vessels dry cargo 110 m ship	€ 2,855	€ 2,205	€ 649
Motor vessels dry cargo > 130 (135 m ship)	€ 2,503	€ 2,184	€ 319
Motor vessels liquid cargo 80-109 m length (typical 86 m ship)	€ 2,362	€ 1,787	€ 575
Motor vessels liquid cargo 110 m ship	€ 4,454	€ 3,509	€ 945
Motor vessels liquid cargo > 130 (135 m ship)	€ 1,552	€ 1,382	€ 170
Coupled convoys	€ 1,514	€ 1,326	€ 188
Ferry	€ 427	€ 397	€ 30
Tugboat and workboat	€ 285	€ 254	€ 31
Total	**€ 26,139**	**€ 21,280**	**€ 4,859**

The investment costs are higher for the CLINSH scenario due to the adaptation of emission reduction technologies. The investment costs for both scenarios are shown in Table **13**. The additional investment is also expressed in terms of euro per litre fuel. This shows that the additional costs are lowest per litre fuel for the larger vessels types. These vessels have higher fuel use and as a result a higher utilisation of the emission reduction technologies. Also, the fixed costs can be spread out over a higher quantity of fuel used.

Table 13 – Total investment costs per ship category for baseline and CLINSH scenario in 2020-2035 period

Million euros (except last column)	**Total investment costs baseline in 2020-2035**	**Total investment costs CLINSH scenario in 2020-2035**	**Additional investment costs**	**Additional investment costs (euro per litre fuel) (15 years)**
Passenger vessel < 250 kW	€ 26	€ 51	€ 25	€ 0.40
Passenger vessel 250-500 kW	€ 20	€ 49	€ 28	€ 0.45
Passenger vessel 500-1,000 kW	€ 7	€ 15	€ 9	€ 0.36
Passenger vessel > 1,000 kW	€ 84	€ 164	€ 80	€ 0.07
Push boats < 500 kW	€ 15	€ 34	€ 20	€ 0.15
Push boats 500-2,000 kW	€ 32	€ 48	€ 16	€ 0.10
Push boats ≥ 2,000 kW	€ 21	€ 21	€ 0	€ 0.00
Motor vessels < 80 m length	€ 83	€ 233	€ 150	€ 0.24
Motor vessels dry cargo typical 80 and 86 m ship	€ 90	€ 232	€ 142	€ 0.16
Motor vessels dry cargo typical 105 m ship	€ 54	€ 133	€ 78	€ 0.11
Motor vessels dry cargo 110 m ship	€ 101	€ 233	€ 132	€ 0.12
Motor vessels dry cargo > 130 (135 m ship)	€ 100	€ 153	€ 53	€ 0.04
Motor vessels liquid cargo 80-109 m length (typical 86 m ship)	€ 66	€ 189	€ 122	€ 0.13
Motor vessels liquid cargo 110 m ship	€ 145	€ 345	€ 200	€ 0.11
Motor vessels liquid cargo > 130 (135 m ship)	€ 104	€ 169	€ 65	€ 0.09
Coupled convoys	€ 73	€ 140	€ 66	€ 0.09
Ferry	€ 55	€ 108	€ 53	€ 0.41
Tugboat and workboat	€ 47	€ 78	€ 31	€ 0.34
Total	**€ 1,123**	**€ 2,393**	**€ 1,270**	**€ 0.12**

As expected the higher investment costs increases the Total Cost of Ownership (TCO) for the various vessel types. However the additional Total Cost of Ownership TCO costs are lower compared to the additional investment costs. This is a consequence of the (expected) improvement in fuel consumption of mainly Stage V engines, which reduces the fuel costs for the CLINSH scenario. As a result the additional costs for the CLINSH scenario in terms of TCO are smaller than the investment costs.

Table 14 – Total TCO per ship category for baseline and CLINSH scenario in 2020-2035 period

Million euros (except last column)	Total TCO costs baseline 2020- 2035	Total TCO costs CLINSH scenario 2020-2035	Additional TCO costs	Additional TCO (euro/ litre diesel) (15 years)
Passenger vessel < 250 kW	€ 97	€ 116	€ 19	€ 0.23
Passenger vessel 250-500 kW	€ 115	€ 130	€ 15	€ 0.17
Passenger vessel 500-1,000 kW	€ 48	€ 54	€ 7	€ 0.18
Passenger vessel > 1,000 kW	€ 1,044	€ 1,086	€ 42	€ 0.03
Push boats < 500 kW	€ 127	€ 141	€ 13	€ 0.07
Push boats 500-2,000 kW	€ 204	€ 212	€ 8	€ 0.04
Push boats ≥ 2,000 kW	€ 293	€ 293	€ 0	€ 0.00
Motor vessels < 80 m length	€ 703	€ 811	€ 108	€ 0.12
Motor vessels dry cargo typical 80 and 86 m ship	€ 906	€ 989	€ 83	€ 0.06
Motor vessels dry cargo typical 105 m ship	€ 706	€ 751	€ 45	€ 0.04
Motor vessels dry cargo 110 m ship	€ 1,120	€ 1,195	€ 75	€ 0.05
Motor vessels dry cargo >1 30 (135 m ship)	€ 1,077	€ 1,111	€ 33	€ 0.02
Motor vessels liquid cargo 80-109 m length (typical 86 m ship)	€ 904	€ 971	€ 66	€ 0.05
Motor vessels liquid cargo 110 m ship	€ 1,783	€ 1,895	€ 112	€ 0.04
Motor vessels liquid cargo > 130 (135 m ship)	€ 742	€ 785	€ 43	€ 0.05
Coupled convoys	€ 793	€ 818	€ 25	€ 0.02
Ferry	€ 207	€ 238	€ 31	€ 0.15
Tugboat and workboat	€ 165	€ 192	€ 27	€ 0.18
Total	**€ 11,035**	**€ 11,787**	**€ 753**	**€ 0.05**

5 Conclusions

5.1 Introduction

This chapter concludes the main takeaways of this study. First the results for the socio-economic analysis are summarised in Paragraph 5.2. This shows that there is a large potential to reduce social costs through accelerated adoption of emission reduction techniques in the inland waterway sector. Paragraph 5.3 discusses the main implications for policy as well as other points for discussion.

5.2 Main results of socio-economic analysis.

The socio-economic results show that investing in emission abatement techniques for IWT for many techniques results in net social benefits. For the ships that received funding within the CLINSH project to install emission abatement techniques, the funding is already paid back by social benefits within 0.9 or 2.6 year.
Based on the results of the monitoring of the CLINSH ships and literature, this study has developed two future scenarios for the development of the inland waterway fleet. In the so-called baseline scenario there is no additional uptake of emission reduction techniques except the autonomous inflow of new Stage V engines because older engines are being replaced. The second scenario, the so-called CLINSH scenario is aimed at accelerated emission reductions. In this scenario all vessels that do not already plan to replace their existing engine take actions to reduce emissions. This can be by prematurely replacing old engines, installing emission reduction techniques or sailing on cleaner fuel. For each ship category the best option from a social costs point of view has been chosen for the CLINSH scenario.

Table **15** summarises the results for the social costs calculations for the baseline and the CLINSH scenario. The costs are summarised under costs associated to investment and usage of the vessel (TCO costs), as well as the cost of emissions (CO_2, NO_X, PM). For reference the total investment costs have been included as well. These are higher than the total costs of ownership as certain reduction techniques, mainly Stage V and LNG, result in a decrease in fuel consumption and thus fuel costs. The cost increase is also expressed in terms of costs per litre.

Table **15** shows that there is a potential to reduce social costs by almost five billion euro by accelarated uptake of emission reduction techniques. This would require an intial investment of 1,1 billion euro and vessel owners would occur 760 million euro in additional costs over a fifteen years lifetime. Environmental benefits would, however, increase with 5.6 billion euro due to lower health and climate costs among others. Though the increase in TCO costs is large in absolute terms, expressed per litre of diesel the increase comes down to a 5.3 €ct/ litre.

Table 15 - Costs for greening the IWT fleet, including autonomous engine renewal

	Total social costs Baseline scenario 2020-2035	*Total social costs CLINSH scenario in 2020-2035*	*Difference*
Number of vessels involved, West-Europe*	6,572	6,572	
Social costs with 15 years lifetime (mio €)	€ 26,139	€ 21,280	€ -4,859
TCO (Total costs of ownership) with 15 years lifetime (mio €)	€ 10,751	€ 11,512	€ 761
CO_2 costs with 15 years lifetime (mio €)	€ 8,074	€ 7,867	€ -207
NO_x costs with 15 years lifetime (mio €)	€ 6,051	€ 1,788	€ -4,263
PM costs with 15 years lifetime (mio €)	€ 1,264	€ 112	€ -1,151
Initial investment costs (mio €)	€ 1,123	€ 2,393	€ 1,270
Diesel consumed over 15 years (mio litres)	14,662	14,286	-376
TCO increase per litre of diesel (€ per litre)	€ 0.733	€ 0.806	€ 0.053**

*) Excluding vessels already using LNG, SCR(+DPF), diesel-electric.

**) Based on average of fuel use in baseline and CLINSH scenario.

5.3 Discussion and policy suggestions

As already discussed in Chapter 3 there are more options that have potential to greatly reduce emisisons and have a good ratio between costs and benefits. In the CLINSH scenario only the most optimal solution is considered, applying a ’winner-takes-it-all’ method per ship category . In practise, however, given that policy support is in place to support abatement tecnhnologies, ship owners might also choose the second or third best option in the model, either because it is the better option in their specific situation or because they have a personal (non-monetary) preference fo a certain technology. Ideally, policy instruments should therefore support multiple emission reduction options to allow the ship owners to choose the technology which is optimal for their individual circumstances.

The modelling in this report has assumed that vessel owners replace existing engines on average after one or two revisions. This is however not a strict condition and many engines are able to keep running for a longer period as long as they are revised on time. Historically there were reasons to upgrade to newer engines as these generally had lower fuel consumption for a reasonable premium. In the case of Stage V engines this changed due to there more soffisticated emission reduction techique. The additional investment required for Stage V engines increased significantly compared to CCNR2 engines. Therefore we expect that many vessel owners will evade switching to Stage V engines for as long as possible when no support is provided. Therefore, as Stage V engines are often the most optimal solution, remotorisation should ideally be included in future emission reduction policies.

Currently there is no direct penalty for vessels which emit high quantities of air pollutants. However, this could change in the future as port authorities and policy makers are planning measures to improve air quality. There is thus a possible competitive advantage for cleaner vessels in the future. Simultaneously, a cleaner inland waterway fleet increases the competitive position of inland waterway transport compared to rail and road transport. The CLINSH scenario put in reality thus has the potential to increase transport demand for vessel owners and the inland fleet as a whole. However, in case externalities remain largely unpriced, the benefits of the competitive advantage are small.

Other: Additional employment impacts

An increased demand for emission reduction technologies and fuels leads to other, secondary effects not included in the analysis earlier. These effects include shifts in market power, effects towards labour market, modal shift effects, and changes towards other externalities. These effects will be discussed in short below.

The increased output of emission reduction technologies and fuels does not necessarily lead to increased economic growth. The monetary flows required for the emission reduction technologies and fuels are being redistributed away from other sectors within the economy. It depends on the relative profitability of these sectors and the profitability of the emission reduction technologies and fuels whether there is a net increase in wealth. The increased demand for emission reduction technologies and fuels does increase the competitive position of the suppliers of these technologies and fuels. They are able to increase their output as well as increasing their selling prices, which increases profit in these sectors. At the same time the higher selling prices increase the costs for vessel owners and subsidy providers. The exact level of the redistribution and scarcity effects is difficult to calculate and falls outside of the scope of this study.

The increased demand for emission reduction technologies and fuels increases the demand for workers in this field. For economies with a well-functioning job market it is assumed that these workers are originating from other sectors and that the increase in output does not necessarily lead to an increase in the size of the workforce (CPB & PBL, 2013). In the case of imperfections in the labour market, for example due to limitations in mobility of labour, there are possible decreases in unemployment. The countries within the CLINSH region have job markets that are functioning well, and as a result positive indirect employment effects are only limited.

Some of the emission reduction technologies and fuels also have a limited effect on other externalities. New engines have stricter noise standards which reduces health costs for vessel crews and nuisance for residents close to fairways.

6 References

Brandstoftafel scheepvaart, 2014. *Visie Duurzame Brandstoffenmix : Deelrapport Brandstoftafel Scheepvaart,* s.l.: s.n.

CCNR, 2003. *Najaarszitting/ HERBSTSITZUNG/ SESSION D'AUTOMNE 2003.* [Online] Available at: https://www.ccr-zkr.org/13020400-nl.html

CCNR, 2018. *Inlad Navigation in Europa Market Observation,* Strasbourg: Central Commission for the Navigation of the Rhine (CCNR).

CE Delft; INFRAS;TRT;Ricardo, 2019. *Handbook on the external costs of transport,* Delft: CE Delft.

CE Delft, 2021. *STREAM Freight Transport 2020,* Delft: CE Delft.

CE Delft; INFRAS; TRT, 2019. *Handbook on the external costs of transport - version 2018,* Delft: CE Delft.

CPB & PBL, 2013. *Algemene leidraad voor maatschappelijke kosten-batenanalyse.,* Den Haag: Centraal Planbureau (CPB) ; Planbureau voor de Leefomgeving (PBL).

Dahlke-Wallat, F. & Friedhoff, B., 2020. *Study "Assessment of technologies in view of zero-emission IWT“ : Part of the overarching study „Financing the energy transition towards a zero-emission European IWT sector“, presentation,* Duisburg: Development Centre for Ship Technology and Transport Systems (DST e.V.).

De Raad van de gemeente Rotterdam, 2019. *Havenbeheersverordening Rotterdam 2020,* Rotterdam: s.n.

DST, 2019a. *GRENDEL-GReen and EfficieNt DanubE fLeet: Fact Sheet no.1 : Gas and Gas-electric Propulsion,* Duisburg: Development Centre for Ship Technology and Transport Systems (DST).

DST, 2019b. *GRENDEL- GReen and EfficieNt DanubE fLeet: Fact Sheet No. 3 : After-treatment,* Duisburg: Development Centre for Ship Technology and Transport Systems (DST).

DST, 2020a. *GRENDEL-GReen and EfficieNt DanubE fLeet: Fact Sheet no.2 : Diesel-Electric Propulsion,* Duisburg: Development Centre for Ship Technology and Transport Systems (DST).

DST, 2020b. *GRendel-GReen and EfficieNT DanubE fLeet: Fact Sheet no.4 : Fuel Cell Propulsion,* Duisburg: Development Centre for Ship Technology and Transport Systems (DST).

DST, 2020c. *GRENDEL-GReen and EfficieNt DanubE fLeet: Fact Sheet no.5 : Battery Electric Propulsion,* Duisburg: Development Centre for Ship Technology and Transport Systems (DST).

DST, 2020d. *GRENDEL-GReen and EfficieNt DanubE fLeet: Fact Sheet no.6 : Drop-in Fuels,* Duisburg: Development Centre for Ship Technology and Transport Systems (DST).

DST, 2020e. *GRENDEL-GReen and EfficieNt DanubE fLeet: Fact Sheet no.7 : Euro VI Truck and NRE Engines,* Duisburg: Development Centre for Ship Technology and Transport Systems (DST).

Earl, T. et al., 2018. *Analysis of long haul battery electric trucks in EU : Marketplace and technology, economic, environmental, and policy perspectives, amended paper presented in: 8th Commercial Vehicle Workshop Graz, 17-18 May 2018,* Brussels: European Federation for Transport and Environment (T&E).

EICB, 2017. *Breakthrough LNG Deployment in Inland Waterway Transport : 1.1 Execution of ex-ante cost/benefit analyses for the best available LNG technologies for vessels,* Rotterdam: Expertise- en InnovatieCentrum Binnenvaart (EICB).

EICB, 2021. *Greeningtool.* [Online] Available at: https://www.inlandwaterways.nl/greeningtool#

Federaal Planbureau & FOD Mobiliteit en Vervoer, 2019. *Vooruitzichten van de transportvraag in België tegen 2040,* Brussel: Federaal Planbureau & Federale Overheidsdienst Mobiliteit en Vervoer.

Havenbedrijf Rotterdam, 2011. *Port Compass : Havenvisie 2030,* Rotterdam: Havenbedrijf Rotterdam.

Hekkenberg, R. G., 2014. *A building cost estimation method for inland ships, paper presented at the European Inland Waterway Navigation Conference 10-12 September 2014, Budapest, Hungary,* Delft: Delft University of Technology,Department of Ship Design, Production and Operation.
Hulskotte, J., 2018. *EMS-protocal Emissies door Binnenvaart: Verbrandingsmotoren,* s.l.: Taakgroep Verkeer en Vervoer (Emissieregistratie).
ICCT, 2018. *Costs of Emission Reduction Technologies for Diesel Engines Used in Non-Road Vehicles and Equipment,* Washington D.C.: International Council on Clean Transportation (ICCT).
Infras; ifeu, 2013. *Aktualisierung der Emissionsberechnung für die Binnenschifffahrt und Übertragung der Daten in TREMOD,* Heidelberg: IFEU Heidelberg und INFRAS.
Intraplan consult GmbH & BAG-Luftverkehr, 2019. *Gleitende Mittelfristprognose für den Güter- und Personenverkehr. Mittelfristprognose Winter 2018/19,* Munchen/Koln: s.n.
Kennisinstituut voor Mobiliteitsbeleid (KiM), 2018. *Kerncijfers Mobiliteit 2018,* Den Haag: Kennisinstituut voor Mobiliteitsbeleid (KiM).
Kruyt, B., 2019. *Varen op batterijen : Nut en noodzaak. MEC Modulair Energie Concept. Presentatie Marine Industry Gorinchem, 8 mei 2019,* Gorinchem: s.n.
LNG binnenvaart, 2019. *Breakthrough LNG deployment in Inland Waterway Transport,* Papendrecht: LNG binnenvaart.
Multronic, 2015. *PROMINENT: D2.2 Ex-ante cost/benefit analysis of business cases for standard after-treatment configurations. Analysis of the costs and benefits of the application of after-treatment,* s.l.: PROMINENT.
Panteia, et al., 2013. *Contribution to Impact Assessment of measures for reducing emissions of inland navigation,* Zoetermeer: Panteia.
Panteia, 2014. *Contribution to the problem definition in the context of the preparation of the Impact assessment : Regarding the recognition of professional qualifications and training in inland navigation,* Zoetermeer: Panteia.
Panteia, 2017. *Middellange Termijn Prognoses voor de binnenvaart : Vervoer in relatie tot Nederland, periode 2017-2021,* Zoetermeer: Panteia.
Panteia, 2018. *Middellange Termijn Prognoses voor de binnenvaart. Vervoer in relatie tot Nederland, periode 2018 - 2022,* Zoetermeer: Panteia.
Panteia, 2019. *Op weg naar een klimaatneutrale binnenvaart per 2050 : Transitie- en rekenmodel binnenvaart,* Zoetermeer: Panteia.
Rijkswaterstaat, 2017. *Deelrapportage Vaarwegen voor de Nationale Markt- en Capaciteitsanalyse (NMCA),* s.l.: Rijkswaterstaat Water Verkeer en Leefomgeving (WVL).
STC-NESTRA & RebelGroup & EICB, 2015. *Inventarisatie milieupresentaties bestaande binnenvaartvloot West-Europa,* Rotterdam: STC-NESTRA.
STC-NESTRA, 2018a. *PROMINENT: D 6.7 Assessment, Recommendation and Roadmap,* s.l.: STC-NESTRA.
STC-NESTRA, 2018b. *PROMINENT: D 6.8 Roll-out plan for innovative greening technologies and concepts,* s.l.: STC-NESTRA.
Stichting Projecten Binnenvaart, 2016. *D1.1 List of operational profiles and fleet families. Identification of the fleet, typical fleet families & operational profiles on European inland waterways,* s.l.: s.n.
Stichting Projecten Binnenvaart, 2016. *PROMINENT : D1.1 List of operational profiles and fleet families. Identification of the fleet, typical fleet families & operational profiles on European inland waterways,* s.l.: PROMINENT.

Stichting Projecten Binnenvaart, 2017. *PROMINENT: D2.6 Ex-ante cost/benefit analysis of business cases for standard LNG Configurations : Analysis of the costs and benefits of the application of LNG as alternative fuel for inland vessels,* s.l.: PROMINENT.
TNO ; STC-NESTRA, 2017. *PROMINENT: D3.5: Ex-ante cost/benefit analysis of systems for certification, monitoring and enforcement : Certification, monitoring and enforcement,* s.l.: s.n.
TNO, 2014. *Beoordeling van verontreinigende emissies met Shell GTL Fuel bij middelzware en zware voertuigen, binnenvaartschepen en mobiele machines ,* Delft: TNO.
TNO, 2015. *Bijlagen visie On-Board-Monitoring in de binnenvaart, notitie,* Delft: TNO.
TNO, 2015. *LNG for trucks and ships: fact analysis : Review of pollutant and GHG emissions, final,* Delft: TNO.
TNO, 2018. *EMS-protocol Emissies door Binnenvaart : Verbrandingsmotoren, versie 5,* sl: Taakgroep Verkeer en Vervoer (Emissieregistratie).
TNO, 2018. *PROMINENT: D2.8 / D2.9 Standardized model and cost/benefit assessment for right-size engines and hybrid configurations,* s.l.: TNO.
Umwelt Bundesamt, 2018. *Politikszenarien für den Klimaschutz VII Treibhausgas-Emissionsszenarien bis zum Jahr 2035,* Dessau-Roßlau: Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit.
VBD, 2001. *Auswirkungen von Ubergangsbestimmungen in den technischen Vorschriften fUr Binnenschiffe, Hauptstudie,* Duisburg: Europäisches Entwicklungszentrum fÍir Binnen- und Klüstenschifffahrt, Versuchsanstalt für Binnenschiffbau e.V..
Via Donau, 2015. *PROMINENT :D1.2 : List of best available greening technologies and concepts,* Wenen: Via Donau.
Via Donau, 2018. *PROMINENT: D6.4 Final pilot-review report,* Wenen: Via Donau.

A Additional figures

Additional figures such as Figure 5 and Figure 9 are provided in an Excel tool for other vessel classes.

B Cost-benefit assumptions

B.1 General assumption diesel ships

Table 16 - Vessel category characteristics

Vessel category	Average total propulsion power (IVR based)	Sailing hours (STC Nestra)	kW according to PROMINENT
Passenger vessel < 250 kW	126	940	126
Passenger vessel 250-500 kW	429	695	429
Passenger vessel 500-1,000 kW	693	735	693
Passenger vessel > 1,000 kW	1,519	1,750	1,492
Push boats < 500 kW	247	1,420	400
Push boats 500-2,000 kW	847	3,000	1,249
Push boats ≥ 2,000 kW	3,458	7,258	4,080
Motor vessels < 80 m length	302	1,500	321
Motor vessels dry cargo typical 80 and 86 m ship	669	1,600	728
Motor vessels dry cargo typical 105 m ship	963	1,886	1,286
Motor vessels dry cargo 110 m ship	1,416	1,943	1,527
Motor vessels dry cargo > 130 (135 m ship)	2,456	2,831	1,492
Motor vessels liquid cargo 80-109 m length *(typ. 86 m ship)*	954	1,707	1,210
Motor vessels liquid cargo 110 m ship	1,598	1,943	1,550
Motor vessels liquid cargo > 130 (135 m ship)	2,772	2,831	2,359
Coupled convoys	2,237	2,513	2,351
Ferry	644	750	644
Tugboat and workboat	500	916	500

Table 17 - Annual diesel consumption differentiated to 25% lowest, 50% average and 25% highest energy consumption averages

	High fuel use (m^3/year)	Normal fuel use (m^3/year)	Low fuel use (m^3/year)
Passenger vessel < 250 kW	22	11	4
Passenger vessel 250-500 kW	53	27	12
Passenger vessel 500-1,000 kW	77	46	19
Passenger vessel > 1,000 kW	767	433	232
Push boats < 500 kW	133	82	52
Push boats 500-2,000 kW	231	160	105
Push boats ≥ 2,000 kW	2,323	2,100	1,926
Motor vessels < 80 m length	81	47	23
Motor vessels dry cargo typical 80 and 86 m ship	170	133	97
Motor vessels dry cargo typical 105 m ship	396	311	228
Motor vessels dry cargo 110 m ship	393	307	235
Motor vessels dry cargo > 130 (135 m ship)	593	472	396
Motor vessels liquid cargo 80-109 m length *(typical 86 m ship)*	323	272	193
Motor vessels liquid cargo 110 m ship	475	355	221
Motor vessels liquid cargo > 130 (135 m ship)	551	352	240
Coupled convoys	784	551	392
Ferry	45	22	8
Tugboat and workboat	42	21	9

Based on: AIS data analysis, (Stichting Projecten Binnenvaart, 2016), (STC-NESTRA & RebelGroup & EICB, 2015).

Table 18 - Idling costs per day differentiated to 25% lowest, 50% average and 25% highest energy consumption averages

	High fuel use (€/day)	Normal fuel use (€/day)	Low fuel use (€/day)
Passenger vessel < 250 kW	527	344	239
Passenger vessel 250-500 kW	1,744	1,173	849
Passenger vessel 500-1,000 kW	2,539	1,892	1,337
Passenger vessel > 1,000 kW	5,346	4,074	3.308
Push boats < 500 kW	292	231	195
Push boats 500-2,000 kW	879	723	603
Push boats ≥ 2,000 kW	4,444	4,408	4,079
Motor vessels < 80 m length	270	232	199
Motor vessels dry cargo typical 80 and 86 m ship	589	526	465
Motor vessels dry cargo typical 105 m ship	1,049	930	813
Motor vessels dry cargo 110 m ship	869	771	690
Motor vessels dry cargo > 130 (135 m ship)	1,282	1,174	1,106
Motor vessels liquid cargo 80-109 m length *(typical 86 m ship)*	945	875	765
Motor vessels liquid cargo 110 m ship	1,692	1,468	1,219
Motor vessels liquid cargo > 130 (135 m ship)	3,354	2,788	2,471
Coupled convoys	1,738	1,535	1,397
Ferry	775	466	288
Tugboat and workboat	577	362	242

Based on: AIS data analysis, (Stichting Projecten Binnenvaart, 2016), (STC-NESTRA & RebelGroup & EICB, 2015).

Table 19 - Port dues per annum differentiated to 25% lowest, 50% average and 25% highest energy consumption averages

	High fuel use (€/annum)	Normal fuel use (€/annum)	Low fuel use (€/annum)
Passenger vessel < 250 kW	6,465	4,222	2,934
Passenger vessel 250-500 kW	21,403	14,392	10,416
Passenger vessel 500-1,000 kW	31,159	23,225	16,414
Passenger vessel > 1,000 kW	65,613	50,000	40,599
Push boats < 500 kW	4,223	3,345	2,822
Push boats 500-2,000 kW	63,526	52,197	43,543
Push boats ≥ 2,000 kW	90,575	89,834	83,132
Motor vessels < 80 m length	5,813	5,000	4,276
Motor vessels dry cargo typical 80 and 86 m ship	8,949	8,000	7,074
Motor vessels dry cargo typical 105 m ship	12,409	11,000	9,615
Motor vessels dry cargo 110 m ship	15,770	14,000	12,526
Motor vessels dry cargo >130 (135 m ship)	29,489	27,000	25,438
Motor vessels liquid cargo 80-109 m length *(typical 86 m ship)*	9,547	8,839	7,734
Motor vessels liquid cargo 110 m ship	16,130	14,000	11,627
Motor vessels liquid cargo > 130 (135 m ship)	57,737	48,000	42,539
Coupled convoys	36,220	32,000	29,114
Ferry	-	-	-
Tugboat and workboat	5,337	3,345	2,239

Based on : AIS data analysis, (Stichting Projecten Binnenvaart, 2016), (STC-NESTRA & RebelGroup & EICB, 2015).

Table 20 - Investment costs Diesel engines

Investment	Value	Unit	Source
New price engine CCNR 0-2	220	Euro/kW	(Hekkenberg, 2014) and PROMINENT D2.8 Page nr 30 (TNO, 2018)
New price Stage V engine	354	Euro/kW	theicct.org/publications/emission_reduction_tech_cost_non_road_diesel (ICCT, 2018); Costs of Emission Reduction Technologies…
Revision costs	50% of engine costs		Bijlagen visie On-Board-Monitoring in de binnenvaart (TNO, 2015)
Idling days new engine installation	10		Estimate based on greening tool
Idling days revision	5	Days	Estimate based on greening tool

Table 21 – Other costs Diesel engines

Operational values	Value	Unit	Source
Fuel consumption	See Table 17		
Diesel price	697	Euro/ton	www.oliecentrale.nl/producten/lijstprijs-brandstoffen
Add blue consumption	0.048	Liter/kg diesel	PROMINENT (D2.2), Page 23. Section 2.4. 1 (Multronic, 2015)
Fuel based maintenance cost	0.12	Euro/m^3	Section 6.3, Pg: 30, Document D2.8/2.9 PROMINENT ((TNO, 2018)
Power based maintenance cost	4.6	Euro/kW	Section 6.3, Pg: 30, Document D2.8/2.9 PROMINENT (TNO, 2018)

B.2 LNG (monofuel & dual fuel)

Table 22 - Investment costs per vessel category for LNG, additional to diesel

Vessel class	Additional engine costs monofuel LNG engine (compared to diesel) (€)	Additional engine costs dual fuel LNG engine (compared to diesel) (€)	Installation costs (tank above deck) (€)	Installation costs (tank below deck) (€)
Passenger vessel < 250 kW	79,915	24,317	47,493	68,390
Passenger vessel 250 - 500 kW	272,435	82,896	161,907	233,146
Passenger vessel 500 - 1,000 kW	439,641	133,774	261,277	376,238
Passenger vessel > 1,000 kW	946,500	288,000	562,500	810,000
Push boats < 500 kW	286,894	92,234	174,540	231,385
Push boats 500-2,000 kW	895,825	288,000	545,000	722,500
Push boats ≥ 2,000 kW	1,920,425	648,000	690,000	887,500
Motor vessels < 80 m length	175,787	52,772	103,383	134,996
Motor vessels dry cargo typical 80 and 86 m ship	398,670	119,681	234,463	306,159
Motor vessels dry cargo typical 105 m ship	704,244	211,415	414,174	540,825
Motor vessels dry cargo 110 m ship	807,825	216,000	532,500	692,500
Motor vessels dry cargo >130 (135 m ship)	861,500	288,000	532,500	692,500
Motor vessels liquid cargo 80-109 m length *(typ.l86 m ship)*	662,624	198,921	389,698	508,863
Motor vessels liquid cargo 110 m ship	871,000	216,000	507,500	667,500
Motor vessels liquid cargo > 130 (135 m ship)	1,085,000	432,000	572,500	745,000
Coupled convoys	1,227,500	432,000	600,000	785,000
Ferry	352,670	105,872	207,409	270,833
Tugboat and workboat	273,812	82,199	161,032	210,274

Table 23 - LNG investment costs

LNG investment values	Value	Unit	Source
Tank connection space (for all categories of ships)	377,500	Euro	Pg: 40 Act 1.1 Ex ante cost-benefit analysis
Tank (for all categories of ships)	165,000	Euro	Pg: 40 Act 1.1 Ex ante cost-benefit analysis
Opportunity cost	28	Days	Pg: 40 Act 1.1 Ex ante cost-benefit analysis

Table 24 - LNG operational costs

LNG operational values	Value	Unit	Source
Fuel price (LNG)	523 (75% of diesel price 693)	Euro/ton	75% of diesel price based on prices between 2015 and 2020. DNVGL; Interrijn; Pitpoint
Estimated annual savings on port dues	13.55	%	Pg:40 Act 1.1 Ex ante cost benefit analysis
Maintenance costs	Similar to diesel CCNR 2 engine		Assumption
Revision costs	Same as diesel		Assumption

Table 25 - LNG environmental cost figures

LNG environmental values	Value	Unit	Source
Energy efficiency (LNG monofuel)	0.36	%	Life cycle assessment of marine fuels (Chalmers university, 2011)
Energy efficiency (LNG dual fuel)	0.41	%	Life cycle assessment of marine fuels (Chalmers university, 2011)
Energy efficiency (Conventional CCNR2 diesel engine)	0.41	%	Life cycle assessment of marine fuels (Chalmers university, 2011)
Methane emissions (LNG Only)	4	g/kWh	For other dual or monofuel engines (TNO, 2017) /4g/kwh = 0.53MJ (This is the value taken)
CO_2 emission/LT (LNG) WTW	3.69	kg/kg	STREAM 2020 (Max 10% reduction - Salih Karaarslan 2017)
NO_x emissions (LNG)/Phase V @ 1.8 g/kwh	1.79	g/kWh	0.0052 reduction compared with diesel (Salih Karaarslan)
NO_x emission LNG dual fuel	4.06	g/kWh	PROMINENT D1.2; page 69
PM emission (LNG) and Stage V > 300 kW	0.015	g/kWh	Matthijs: 0,015 according to NRMM; 0,000185g/kwh (CCNR2 to NRMM Stage 5) (Pg:34 Salih Karaarslan)
PM emission LNG dual fuel	0.133	g/kWh	PROMINENT D1.2; page 69 : 50-90& reduction

B.3 Aftertreatment devices

Table 26 - Aftertreatment devices investment values

Aftertreatment devices investment values	Value	Unit	Source
SCR (investment costs - kW dependent) @ 30,000 hours (Less than 2,000 kW)	25	Euro/kW	PROMINENT (D2.2), Page 23. Section 2.4.1
SCR (investment costs - kW dependent) @ 30,000 hours (More than 2,000 kW)	53	Euro/kW	PROMINENT (D2.2), Page 23. Section 2.4. 1
DPF (investment costs - kW dependent) @ 30,000 hours	39	Euro/kW	PROMINENT (D2.2), Page 24. Section 2.4. 2
DPF (investment costs - kW dependent) @ 30,000 – 60,000 hours	82	Euro/kW	PROMINENT (D2.2), Page 24. Section 2.4. 2
SCR design and installation costs (Per unit/per engine)	45,000	Euro per engine	PROMINENT (D2.2), Page 24. Section 2.4. 1
DPF design and installation costs	15,200	Euro per engine	€-
SCR + DPF (investment cost - fixed) @ 30,000 hours (For high speed engines)	15,200	Euro/kW	PROMINENT (D2.2), Page 24. Section 2.4. 1
SCR + DPF (investment cost - % increase from high speed engines)	1	%	PROMINENT (D2.2), Page 24. Section 2.4. 1
SCR + DPF (investment cost - Fixed) @ 30,000 hours (for medium speed engines) (Costs determined based on 50% higher than high speed engines)	22,800	Euro/kW	PROMINENT (D2.2), Page 24. Section 2.4. 1
Opportunity costs	5	Days	IWT Greening tool
Time needed for installation	5	Days	PROMINENT D2.2 Annex A2

Table 27 – Aftertreatment devices operational values

Aftertreatment devices operational costs	Value	Unit	Source
SCR - Maintenance costs (includes repair) for every 1,000 engine hours	2.00	Euro/1,000kWh	PROMINENT (D2.2), Page 23. Section 2.4. 1
DPF - Maintenance costs (includes repair) for every 1,000 engine hours + filter cleaning @ 3,000 hours	2.34	Euro/1,000kWh	PROMINENT (D2.2), Page 23. Section 2.4. 1
Urea consumption of CCNR2 engines (to reduce NO_x to 1.8 g/kwh)	0.05	Litre/kg diesel	PROMINENT (D2.2), Page 23. Section 2.4. 1
Urea consumption of CCNR1 and CCCNR0 engines (to reduce NO_x to 1.8g/kwh)	0.09	Litre/ kg diesel	PROMINENT (D2.2), Page 24. Section 2.4. 1
Lifetime of the system (SCR + Catalyst)	30,000	Hours	PROMINENT (D2.2), Page 23. Section 2.4.1

Table 28 - Aftertreatment devices environmental values

Aftertreatment environmental values	Value	Unit	Source
NO_x emission (SCR Only)	1.00	g/kWh	PROMINENT (D2.2), Page 23. Section 2.4. 1
NO_x emission (SCR + DPF)	1.00	g/kWh	PROMINENT (D2.2), Page 23. Section 2.4. 1
PM emission (SCR + DPF)	0.02	g/kWh	PROMINENT (D2.2), Page 23. Section 2.4. 1
PM emission (SCR Only) CCNR 2 (Same as diesel value)	0.19	g/kWh	The information in PROMINENT is contradicting from no increase/decrease of PM to 0-20%. CCNR2 Values are used
PM emission (SCR Only) CCNR 0 (Same as diesel value)	0.44	g/kWh	Assuming PM emission can be reduced optimizing on fuel consumption

B.4 Diesel-electric/Battery electric

Table 29 - Investment costs Diesel-electric/Battery electric

Diesel-electric/Hybrid investment	Value	Unit	Source
Generator set	350	Euro/kW	Table 7, Pg: 30, Document D2.8/2.9 PROMINENT
Electromotor + Controller	500	Euro/kW	Table 7, Pg: 30, Document D2.8/2.9 PROMINENT
Additional equipment cost (€) - Retrofit (Deinstallation/rebuild engine room)	45,000	Per engine	Based on PROMINENT (D2.2), Page 24. Section 2.4. 1
Fuel based maintenance cost	0.12	Euro/m³	Section 6.3, Pg: 30, Document D2.8/2.9 PROMINENT
Idling days	14	Days	Estimated based on greening tool
Battery costs 2020	500	Euro/kWh	BloombergNEF (2019): 137 Euro per kW, Bloomberg EV Outlook 2021 Interreg : 500 eur/kwh, Interreg Factsheet TESLA trucks around 150 € per kW (T&E paper),
Battery costs 2030	250	Euro/kWh	
Battery costs 2040	150	Euro/kWh	
Battery replacement	xx	€-	
Lifetime electro motor	Similar to diesel engines	Years	Assumption

Table 30 - Operational costs Diesel-electric

Diesel-electric/ Hybrid operational values	Value	Unit	Source
Fuel based maintenance cost	0.12	Euro/m³	Section 6.3, Pg: 30, Document D2.8/2.9 PROMINENT
Power based maintenance cost	5	Euro/kW	Section 6.3, Pg: 30, Document D2.8/2.9 PROMINENT
Engine revision	63	Euro/kW	Section 6.3, Pg: 30, Document D2.8/2.9 PROMINENT
Diesel-electric fuel savings	0.02	%	At a certain speed point, it is said to have 2% fuel savings (Page 20 Document D2.8/2.9 PROMINENT)
Engine revision time	6	Years	Pg:30, Document D2.8/2.9 PROMINENT
Engine revision (euro/kw)	63	Euro/kW	Pg:30, Document D2.8/2.9 PROMINENT
Engine revision time frame	6	Years	Pg:30, Document D2.8/2.9 PROMINENT
Electricity costs	0.05	Euro/kWh	Inter Fact sheet 5 & PANTEIA
Battery lifetime	10	Years	EICB presentation

Table 31 - Environmental values Diesel-electric

Diesel-electric/hybrid environmental values	Value	Unit	Source
Diesel-electric fuel savings	2	%	At a certain speed point, it is said to have 2% fuel savings (Page 20 Document D2.8/2.9 PROMINENT)
NO_x emissions	Same as applied engine technology (CCNR 1,2, Stage V)		
PM emissions	Same as applied engine technology		

B.5 Fuel-water emulsion

Table 32 - Investment costs FWE

FWE investment	Value	Unit	Source
Hardware costs per kW	61	Euro/kW	Greening tool
Hardware costs fixed	7,500	Per ship	Greening tool
Yard time	3	Days	Pg: 198, (Panteia, 2014)
Installation costs	10,000	Euro	IWT Greening tool
Reverse osmosis unit	6	Euro/kW	Data from overview fleettender (Ship of 1250 kw)
Measurement after installation costs	3,500	Euro	Data from overview fleet tender

Table 33 - Operational values FWE

FWE operational values	Value	Unit	Source
Reduction in fuel consumption	0.05	Euro	Greening tool
Maintenance costs	0.25	Euro/hour	IWT greening tool (Based on 250 euro per 1,000 engine hours)
Life span	8	Years	IWT Greening tool

Table 34 - Environmental values FWE

FWE environmental values	Value	Unit	Source
NO_x reduction	15	%	Greening tool/monitoring
PM Reduction	50	%	Greening tool

B.6 GTL

Table 35 – operational values GTL

GTL operational values	Value	Unit	Source
Additional costs GTL per liter	10	%	www.oliecentrale.nl/producten/lijstprijs-brandstoffen, information from skippers
Fuel price GTL	767	Euro/ton	Derived from diesel price

Table 36 - Environmental values GTL

GTL environmental values	Value	Unit	Source
NO_x reduction	10	%	www.eibip.eu/publication/gas-to-liquid-gtl-fuel/
PM Reduction	30	%	www.eibip.eu/publication/gas-to-liquid-gtl-fuel/

C Emission factors

Table 37 - Emission factors applied in model

	g/kWh	NO_x	PM
Diesel	CCNRO/1	9.93	0.265
	CCNRO	11.8	0.4
	CCNR1	9.2	0.13
	CCNR2	6.73	0.13
	Stage V	1.79	0.015
	Euro VI	0.4	0.01
SCR/DPF	CCNRO	3.54	0.04
	CCNR1	2.76	0.013
	CCNR2	2.019	0.013
SCR	CCNRO	3.54	0.4
	CCNR1	2.76	0.13
	CCNR2	2.019	0.13
LNG	Existing	2.77	0.015
	Stage V	1.79	0.015
FWE	CCNRO	10.03	0.2
	CCNR1	7.82	0.065
	CCNR2	5.7205	0.065
GTL	CCNRO	10.62	0.28
	CCNR1	8.28	0.091
	CCNR2	6.057	0.091

Source: NO_x values for CCNR0, 1, 2 are based on the monitoring results. PM values for CCNR0, 1, 2 engines are based on (Infras; ifeu, 2013). The other values are based on the reduction values in Annex B, which are partly based on the monitoring results and partly on literature (see Annex B). Values are not exactly the same as reported in B3 as the analysis of this report was finished before the final reporting in B3.

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