Sustainable, safe and economically feasible energy concepts and technologies for European Inland Shipping

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

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Abstract

In line with the targets of PROMINENT to achieve reduction of air pollutant emissions and energy consumption of inland waterway transport, in particular in WP2 advanced concepts for mass introduction will be developed aiming at this. In SWP2.2 of this project the focus is on the development of SCR (selective catalytic reduction) and SCR+DPF (diesel particulate filter), aiming at a standardisation which would make it possible for a large share of the fleet to reduce air pollutant emissions to levels set by new emission standards. The development of such a configuration will be tested during pilots, performed in WP5.

For a further roll-out of after-treatment in inland waterway transport, it is important to get an insight of the economic feasibility, the costs and benefits of applying an after-treatment system. A major difficulty is that the benefits of applying SCR and SCR+DPF are limited to reduction of air pollutant emissions. Discount on the port dues is currently the only financial benefit that can be achieved. This benefit is yet limited to the Rhine/ARA region, on which these benefit can cover up to only 15% of the annual costs of SCR+DPF.

Because of this, the cost effectiveness has been analysed, taken into account the costs, benefits (of the discount on the port dues) and the effects of applying SCR and SCR+DPF. To come to this, the following steps have been taken:

- Cost calculation for each of the vessel types:
  - Calculation of the average annual (base line) costs of transport per vessel type;
  - Calculation of the costs of the application of SCR and SCR+DPF per vessel type;
  - Calculation of the effects of SCR and SCR+DPF, expressed in:
    - Percentage additional annual costs compared to the base line costs;
    - Extra costs of application per kg NOx (for SCR) and PM reduction (additionally for DPF);
- Cost calculation for the representative journeys:
  - Calculation of the average annual (base line) costs of transport per representative journey;
  - Calculation of the costs of the application of SCR and SCR+DPF per representative journey;
  - Calculation of the benefits by the discount on the port dues (and the percentage of the annual costs covered by this discount);
  - Calculation of the effects of SCR and SCR+DPF, expressed in:
    - Percentage extra annual costs compared to the base line costs;
    - Extra costs of application per tonnes cargo transported;
    - Extra costs of application per kg NOx (for SCR) and PM reduction (additionally for DPF).

The absolute annual costs of applying SCR or SCR+DPF are low for the fleet families with smaller vessels (motor vessels <80m, motor vessels 80-109m, motor vessels liquid cargo 80-109m and push boats <500kW) and high for fleet families with the (larger) convoys (Push boats >= 2,000kW, Danube push boats and coupled convoys), because of the combination between high installed power, more operating hours and a high fuel consumption. The (relative) annual cost increase shows a more diverse picture, with a relative low cost increase for the passenger vessels and larger motor tank vessels (>=110m), whilst the smallest motor vessels dry cargo (of 38.5m) and the Danube push boats with 4 units have higher cost increases. The costs per kg NOx and PM reduction are relatively low for the Danube push boats, but also the Western-European pushed convoys with 6 barges, the medium and large motor cargo vessels and the smaller motor tank vessels. These costs are relatively high for smaller motor cargo vessels and smaller push boats.

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ASC	Ammonia Slip Catalyst
CCNR	Central Commission for the Navigation of the Rhine, used as reference to the emission standards CCNR Stage-I and CCNR Stage-II
CO	Carbon monoxide
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EU NRMM	European Union Non-Road Mobile Machinery, engine emission standard
HC	Hydrocarbon
IWT	Inland waterway transport
kW	kilowatt
kWh	kilowatt-hour
LNG	Liquefied Natural Gas
NOx	Nitrogen oxides
PM	Particulate matter
SCR	Selective Catalytic Reduction

Introduction

PROMINENT

The European research project PROMINENT (Promotion of Innovation in Inland Waterway Transport) aims at the development of standardised concepts for reducing emissions in a main share of the European inland fleet. The target is that in 2020 these concepts will be applicable to at least 70% of the European inland fleet and that the implementation costs of these concepts will be reduced by 30%. In WP2 of this project advanced concepts for mass introduction are developed, which will be demonstrated in pilots performed in WP5 and in WP6 the roll-out of these technologies will be performed.

Identification of fleet families and operational profiles

In SWP 1.1 of PROMINENT a study was performed to gain insight into the composition of the European inland waterway fleet and the operational use of these vessels. This resulted in an identification of the groups of comparable vessels ('fleet families') and a selection of the main representative IWT journeys. For most of the representative IWT journeys the operational profiles (providing a power distribution over time) were described. Based on these operational profiles, it was possible to calculate the fuel consumption and fuel costs for the journeys.

Best available technologies

In SWP 1.2 of PROMINENT best available technologies were identified. For the identification of best available technologies and the further development for concepts for mass implementation, an understanding of the fleet and how this fleet is used is essential. As there are major variations between the different vessel types and the operational use (in e.g. power, fuel consumption), different technologies can be beneficial for different parts of the fleet.

In the D1.2 report, the combination of SCR and DPF was identified as the most effective way to reduce NOx and PM emissions. However, currently there is no positive business case for the use of the after-treatment configuration as it leads to increased capital and operational costs and there is no obligation yet for further reducing air pollutant emissions by existing inland vessels. There is only some benefit from reducing air pollutant emissions by the discount on port dues in a few inland and sea ports.

Advanced concepts for mass introduction

In WP2 of PROMINENT the development of advanced concepts for mass introduction has been targeted, these concepts are LNG, diesel after-treatment, energy-efficient navigation, right-sizing and hybrid configuration. For the first three concepts pilot projects will be performed, in WP2 pilot test specifications are defined and cost-benefit analyses are performed. For right-sizing and hybrid configuration a mathematical model will be further developed.

Pilot 'Diesel after-treatment'

As it is one of the most effective ways to reduce air pollutant emissions, a pilot for diesel after-treatment will be performed. In the pilot in WP5 of this project, two standardised pilot after-treatment systems will be produced and installed, which should result in strong air pollutant emission reductions of 90-95% compared to engines that comply to the current EU NRMM Stage IIIA and CCNR Stage II emission standards. These pilots will aim at achieving performance levels equal to the new EU NRMM Stage V emission standards. Specifications for these pilots are defined in the D2.1 report.

Roll-out

The aim of the PROMINENT project is not only to develop and demonstrate the advanced concepts, but also to roll-out these concepts to achieve the mass introduction. Building further on the activities in WP2 and the pilots, and evaluating the outcomes of these, the roll-out of these concepts will be the aim of WP6 of PROMINENT. This will be done by cost-benefit analyses of the use and application of these concepts and will result in the I-STEER app, which will provide end-users with an advice on the costs and benefits for the application of the concepts on their own vessels.

Ex-ante cost effectiveness analysis

Based on the information from WP1 on the fleet families and operational profiles and the first information on best available technologies, together with the pilot test specification, first analyses of the costs and benefits of the several concepts will be made. Such an ex-ante cost benefit analysis is also performed for the after-treatment configurations. This ex-ante cost benefit analysis includes a ‘base-line’ cost calculation concerning the annual fixed costs (insurance, depreciation, interest, repair and maintenance, port dues and other fixed costs), labour costs and fuel costs.

However for after-treatment, there are hardly any (financial) revenues. Therefore an analysis of costs and benefits from the perspective of a vessel owner/investor is not useful. Instead, a cost effectiveness analysis for after-treatment, in which assess the effectiveness of the proposed measure in terms of emission savings per unit of costs is assessed was perforemd.

For the cost effectiveness of SCR and DPF, the costs of installing such a system will be calculated as well as the operational costs (repair and maintenance and the consumption of urea). These cost calculations will be performed on the specific business cases of the different vessel types as well as the representative journeys (from D1.1). Besides, the benefits (discount on the port dues) and the effects of the application on the business case will be taken into account as well as expressed in the cost effectiveness of the measure in terms of the cost per unit of emission reduction (NOx and PM reduction).

1. Introduction to after-treatment configurations

This chapter is taken from the (confidential) D2.1 report on the pilot test specifications and serves as an introduction to after-treatment configurations and the emission values to be used in the pilot.

The problematic emissions from combustion in Diesel engines are nitrogen oxides (NO_X) and particulates or soot (PM). To reduce these emissions different types of emission after-treatment devices are used:

1) A Diesel Oxidation Catalyst, DOC, is used to eliminate CO, HC and some PM (via reduction of the volatile fraction of carbon, wet soot reduction).
2) A Diesel Particulate Filter, DPF, is used to trap particulate matter, PM.
3) Selective Catalytic Reduction, SCR, is used to reduce NO_X. Additionally, there will be some PM reduction.
4) An Ammonia Slip Catalyst, ASC, is used to reduce excess ammonia.

Whether a DOC and DPF or an SCR system or both depends are installed depends on the targeted emission reduction and the engine out emissions. It is possible to combine devices or to use them individually.

1.1 Diesel Oxidation Catalyst

The Diesel Oxidation Catalyst is generally the first catalyst placed after the engine and is used to promote oxidation of several exhaust gas components mainly[1]:

Carbon Monoxide (CO)

$$2\,CO + O_2 \rightarrow 2\,CO_2$$

Hydrocarbons (HC)

$$HC + O_2 \rightarrow CO_2 + H_2O$$

Nitrogen Oxide (NO)

$$2\,NO + O_2 \rightarrow 2\,NO_2$$

Carbon monoxide is oxidized to carbon dioxide while hydrocarbons are oxidized to carbon dioxide and water. Both these reactions are desirable from emissions impact point of view (the resulting gases have lower negative impacts on the environment and climate and on air quality (human health).

Oxidation catalysts have a tendency to promote oxidation of all components in the engine exhaust including NO to NO_2. This reaction can be of concern to certain systems where NOx reduction is not addressed by means of an SCR. However, NO_2 generated in the DOC can be effectively used to facilitate the regeneration of the DPF or to enhance the performance of certain SCR catalysts. When an SCR system is applied, a DOC can alter the ratio between NO and NO_2, which in most conditions is in the order of 9 to 1 for raw emissions.

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[1] www.dieselnet.com is the source of all chemical formula's unless stated differently

1.2 Diesel Particulate Filter

Diesel Particulate Filters are primarily used to reduce particulate emissions or soot from the engine exhaust gases. They are made up of a honeycomb ceramic matrix made from a material like silicon carbide which is sleeved inside a metal housing. The ceramic matrix itself has many microscopic channels that run parallel and are alternately connected to each other, as can be seen in *Figure 1*.

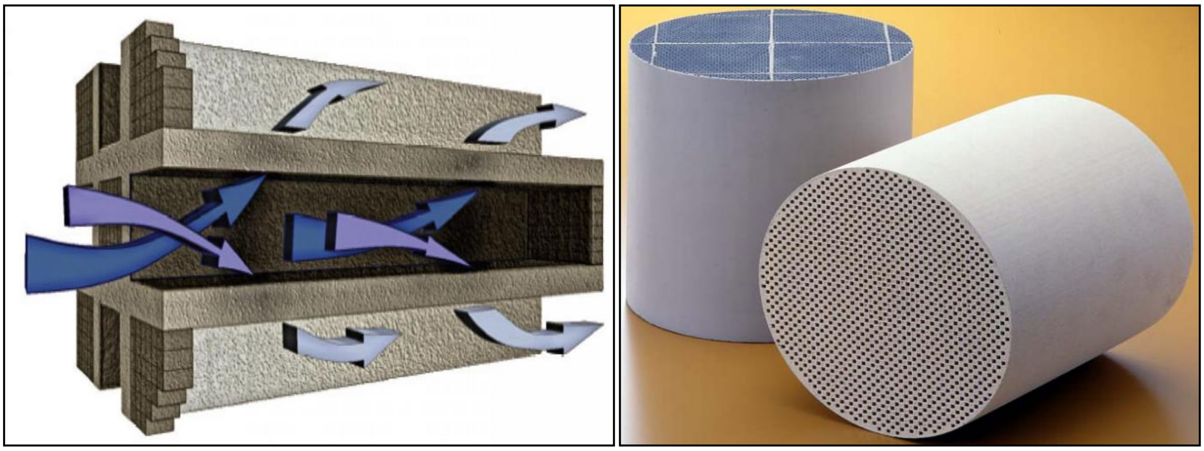

Figure 1: DPF structure (NGK Insulators, Ltd., 2001)

As the exhaust gas enters the filter, the particles of carbon or soot are trapped in the input channel while the gaseous content of the exhaust gas flows through the porous walls of the ceramic filter. The filter is designed to hold a certain quantity of soot. During the course of its operational hours, it gets loaded due to the high deposition of soot. This can result in increased back pressure on the engine and when not properly acted upon may lead to clogging of the filter. The diesel particulate filter must be cleaned of the particles regularly to prevent it from becoming blocked and its function thereby being affected. During the regeneration phase, the particles of carbon stored in the filter are burnt off at a temperature of approx. 500 °C. The actual ignition temperature of the particulates is about 600-650 °C. This exhaust gas temperature can only be reached on a diesel engine at full throttle. The reactions occurring during the regeneration process are primarily divided into two categories:

1. Oxidation of Carbon by Oxygen

$$C + O_2 \rightarrow CO_2$$

$$2\,C + O_2 \rightarrow 2\,CO$$

2. Oxidation of Carbon by Nitrogen Dioxide

$$NO_2 + C \rightarrow NO + CO$$

$$2\,NO_2 + 2\,C \rightarrow N_2 + 2\,CO_2$$

The regeneration process of the DPF can be divided into two types – Active and Passive Regeneration

1. Passive Regeneration

During passive regeneration the soot oxidation temperature is lowered, achieved by introducing an oxidation catalyst into the system, which can be achieved during normal engine operation. This type of regeneration can be achieved in the following 3 ways, of which the setup is sketched in *Figure 2*.

Fuel Borne Catalyst: The catalyst is directly built into the soot particles by introducing an additive to the fuel known as a fuel borne catalyst. The resulting reaction is catalytic oxidation of carbon by oxygen.

Coated DPF: In this case a catalyst, generally platinum is coated onto the filter surface that promotes the oxidation of soot carbon through a combination of oxygen and nitrogen dioxide reaction mechanisms.

Continuously Regenerating Technology: In this type of system, an NO_2 generating catalyst, usually a DOC coated with platinum, is placed upstream of the main DPF filter. This catalyst generates NO_2 which then oxidizes the collected soot in the filter.

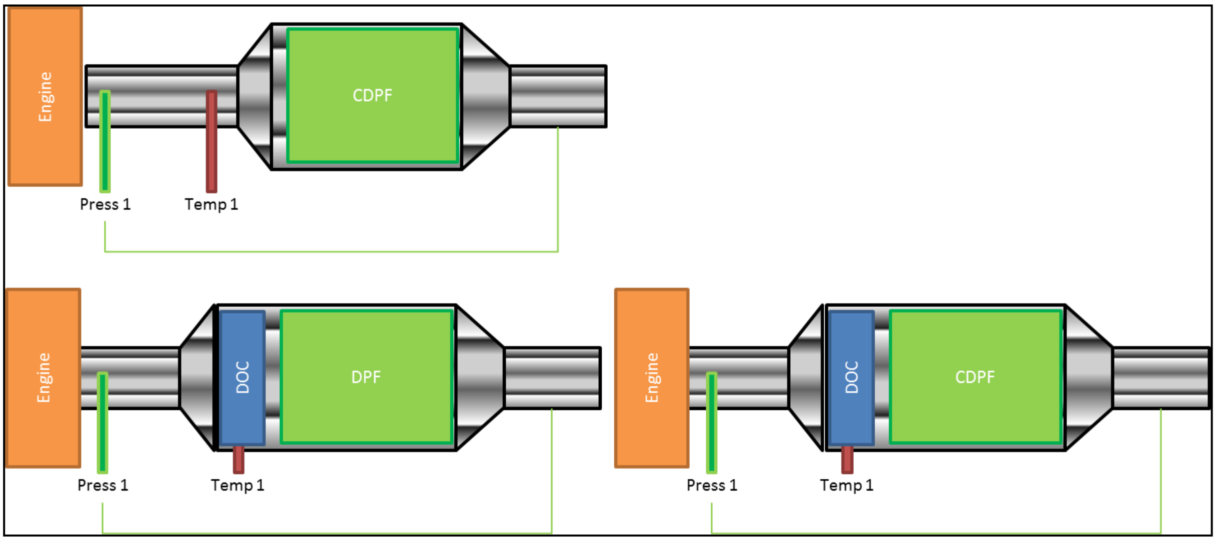

Figure 2: Passive regenerated systems

2. Active Regeneration

During active regeneration, the exhaust gas temperature in the DPF is raised to the oxidation temperature of soot by means of an external source of heat energy. This energy can be obtained by combusting diesel upstream of the filter or by means of an electrical heater placed before the filter. In *Figure 3* the layout of a typical actively regenerated system is given.

Diesel Injection: In this case, diesel is injected into the exhaust gases just before the DPF. The fuel atomizes, vaporizes and combusts to increase the temperature of the exhaust gases to about 600 °C thus leading to oxidation of soot by oxygen mechanism.

Electrical Heater: Alternatively, an electrical heater can be used to increase the soot temperature up to regeneration levels. In general the energy can be supplied to the exhaust gas, the filter substrate or directly to the soot particles. However, the most common form of electrical heating method involves heating the exhaust gas by placing an electric heater upstream of the DPF.

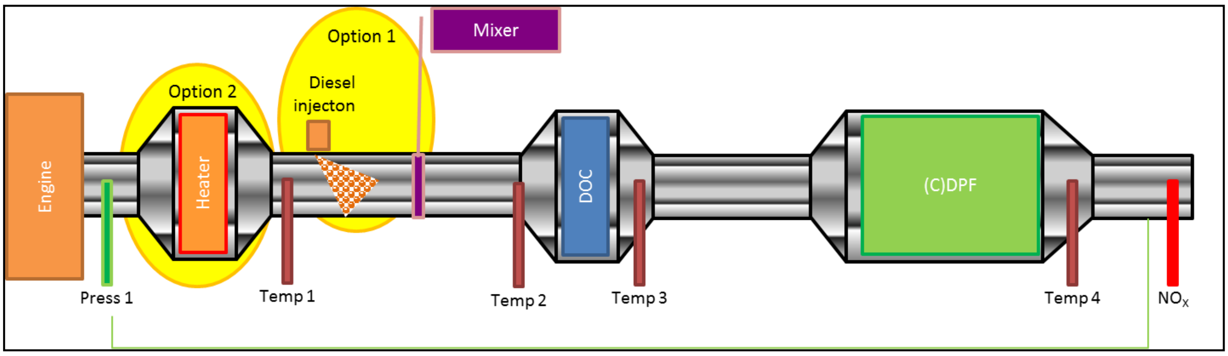

Figure 3: Active Regenerated Systems with DOC

1.3 Selective Catalytic Reduction

The basic principle of SCR exhaust after treatment is the reduction of NO_X inside a catalyst by means of the reagent ammonia (NH_3). As ammonia (NH_3) is difficult to handle, it is stored on board of the vehicle in the form an aqueous urea solution. The aqueous dilution of urea with 32.5* mass percentage of urea is known under the trade name “AdBlue”.

The urea solution or AdBlue is injected into the exhaust gas upstream of the SCR catalyst and is dispersed into fine droplets or a mist allowing a fast thermolysis and hydrolysis to obtain NH_3.

The subsequent generation of NH_3 in the hot exhaust gasses proceeds in the following three steps:[2]

1. Evaporation of water from a fine spray of AdBlue droplets

$$\begin{array}{ccccc} (NH_2)_2CO + 6.9\ H_2O & \rightarrow & (NH_2)_2CO & + & 6.9\ H_2O \\ \text{(Aqueous solution)} & & \text{(Solid/liquid)} & & \text{(Gaseous)} \end{array}$$

2. Thermolysis of urea into ammonia and iso-cyanic acid

$$\begin{array}{ccccc} (NH_2)_2CO & \rightarrow & NH_3 & + & HNCO \\ \text{(Solid/liquid)} & & \text{(Solid/liquid)} & & \text{(Gaseous)} \end{array}$$

3. Hydrolysis of iso-cyanic acid

$$\begin{array}{ccccccc} HNCO & + & H_2O & \rightarrow & NH_3 & + & CO_2 \\ \text{(Gaseous)} & & \text{(Gaseous)} & & \text{(Gaseous)} & & \text{(Gaseous)} \end{array}$$

The ammonia thus produced during the thermolysis of urea is then used to reduce NO_x to N_2 (Nitrogen) in the reducing catalytic converter. Under normal conditions there are two predominant SCR reactions in a catalytic converter – a fast reaction and a slow/standard reaction.

The dominant reaction mechanism of NO_x with ammonia is:

$$4\ NO \quad + \quad 4\ NH_3 \quad + \quad O_2 \quad \rightarrow \quad 4\ N_2 \quad + \quad 6\ H_2O$$

During this reaction, nitric oxide (NO) is reduced to Nitrogen (N_2) and the consumption of NH_3 is one mole per one mole of NO. This reaction is optimum when the temperature is in the range of 250 °C to 450 °C.

At temperatures lower than 200 °C, the performance of the above reaction is too low for use in practical applications to reduce NO_x. At temperatures below 300 °C the dominant NOx reducing reaction is the fast reaction, which is as follows:

$$NO \quad + \quad NO_2 \quad + \quad 2\ NH_3 \quad \rightarrow \quad 2\ N_2 \quad + \quad 3\ H_2O$$

This reaction includes reduction of both NO an NO_2 and dominates at requires a NO/NO_2 ratio of 1. This reaction requires an equimolar mixture of NO and NO_2 to allow for a higher NOx conversion, and the effect is most pronounced at temperatures below 300 °C.

The slow reaction reducing NO_2 to N_2 is as follows:

$$6\ NO_2 \quad + \quad 8\ NH_3 \quad \rightarrow \quad 7\ N_2 \quad + \quad 12\ H_2O$$

An overview of the entire system is given in *Figure 4*.

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[2] (Birkhold, Meingast , Wassermann, & Deutschmann, 2006)

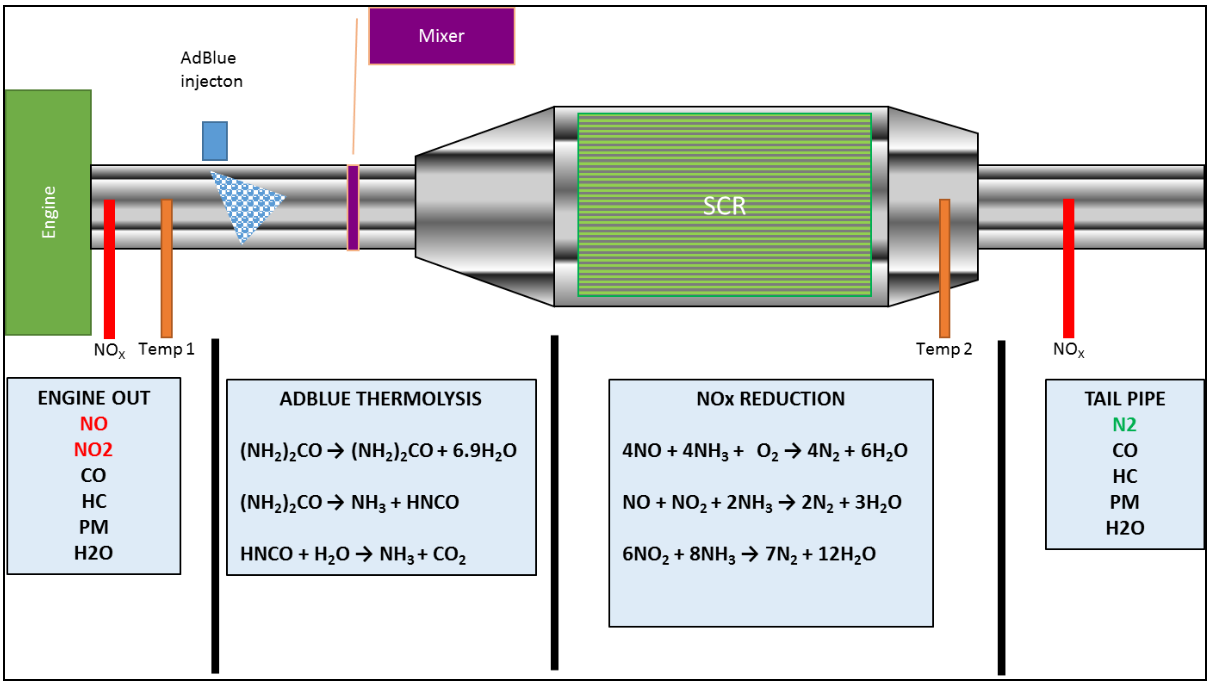

Figure 4: The working principles of NOx reduction using an SCR system

1.4 Emission limit values to be used for PROMINENT retrofit scenarios

The emission limits of the pilot systems were defined in WP1 of PROMINENT. A full substantiation of this decision can be found in the corresponding report: ‘D 1.2 List of best available greening technologies and concepts’. In chapter 5: ‘Best available greening technologies and concepts for the European inland fleet’ of the WP1 report, the best available greening technologies and concepts for the European inland fleet are identified and described. In this chapter limit values to be used within PROMINENT retrofit scenarios were proposed. These target values will be the objective for the pilot program in SWP 5.3. The values are stated in *Table 1*.

No	**Emission limits In gram per kWh**	**Reference**	**Diesel / Emission control technologies assumed: (or PROMINENT target)**
1	NOx < 1.8 PM: no INCREASE	NOx requirement of Latest proposal NRMM Stage V for IWP > 300 kW	Retrofit solution for SCR
2	NOx < 1.8 PM < 0.045	EPA Tier 4 marine diesel (for engine > 600 kW)	Target for LNG engines (dual-fuel)
3	NOx < 1.8 PM < 0.015 Particle Number limit: PN $<1x10^{12}$ per kWh	Latest proposal NRMM Stage V for IWP > 300 kW	Retrofit solution for SCR + DPF

Table 1: Proposed emission targets within PROMINENT

The following additional requirements are defined:

- A Not To Exceed requirement (NTE) for NOx:
  Above 25% engine power (for shipping also referred to as ‘load’). The NOx emissions in individual points in the engine map shall not exceed 150% of the limit value. Also the NOx per kg CO2 will not exceed 130% of the NOx per CO2 corresponding to the limit value in g/kWh and the E3 cycle fuel consumption.
- With application of SCR: average NH3 emission must be lower than 10 ppm.

The precise NTE area will be determined during the project. It will be based on the area of the engine map which can be reached with normal engine installations in inland ships with a broad range of operations (above 25% power).

The aging of the SCR system performance and the possible deterioration of the NOx conversion will be monitored during the PROMINENT project, both as E3 cycle performance as well as the real sailing emissions. The possible deteriorating will be evaluated in the light of normal deterioration factors for SCR systems.

2. Methodology used in ex-ante cost effectiveness analysis

2.1 Introduction

Within WP2, cost-benefit analyses are conducted for all technologies considered. However for after-treatment, the benefits are currently limited to discount on port dues in a few inland and sea ports. So, there are hardly any financial revenues. Therefore an analysis of costs and benefits from a vessel owner/investor perspective is not useful. Instead, a cost effectiveness analyses was conducted, in which the effectiveness of the proposed measure in terms of emission savings per unit of costs was assessed.

The calculations are based on the results of PROMINENT WP 1.1 as presented in the Deliverable 1.1. For the distinguished fleet families and their representative vessels the average cost structure has been defined in detail based on the current situation. Based on the cost structure of the vessel[3], a 'base line' cost estimation for the costs of transport has been estimated for various representative journeys taking into account the specific operational profile for the journeys[4].

By means of adapting the cost parameters for the vessels and the journeys, the economic performance is estimated in case of application of SCR and DPF. The adaptations in the cost structure concern the additional costs for the hardware and design and installation, repair and maintenance and cost of urea consumption. The cost estimation for after-treatment configurations have been also first calculated per vessel type and then calculated for the representative journeys based on the respective vessel type.

The range of different typical vessel types (representative for the fleet family) and the representative journeys present an overview of the various situations and the bandwidth that can be seen as regards the economic performance. The result of the cost benefit analyses is therefore quite different for the different operating conditions and vessels.

Besides illustrating the different outcomes for the range of representative vessels types and journeys also a sensitivity analysis have been made for the fuel price.

2.2 Vessel types and representative journeys

The costs are defined at the level of vessel types and for the general costs per representative journey. The following vessel types and journeys have been taken into account:

2.2.1 Vessel types, average in Europe according to fleet families

Division of fleet families is in line with the division used in the D1.1 report, except for the Danube barges, which were divided in the D1.1 report under the broader groups of push boats. The vessel types are in line with the RWS 2010 vessel categories, except for the push boats, which are categorised based on the installed engine power.

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[3] The general costs structures have been based on Rijkswaterstaat May 2015 Excel file which describes in detail the cost structure for Western European vessels, see the following link: http://www.rws.nl/zakelijk/werken-aan-infrastructuur/steunpunt-economische-expertise/kengetallen/overige-documenten/index.aspx
As regards the vessels on Danube, the cost structure was derived from the European research project "ECCONET" and were subsequently validated by the project partners Navrom, ProDanube and viadonau.

[4] Note: the representative journeys have been taken into account for which the operational profile was made available by DST. For some journeys specified in SWP 1.1, the profile could not be made available due to missing information on the waterway characteristics

Fleet family	Vessel type	Length (m)	Width (m)	Draught (m)	Max payload (t)	Operational hours/year	# engines	Installed kW	Fuel cons. (M^3)
Passenger vessels (hotel/cruise)	PAX 135m	135	11.5	2.0	-	4318	2.0	1492	438
Push boats <500 kW	PB <500 kW B04	85	8.2	2.7	1250	3360	1.0	400	82
Push boats 500-2000 kW	PushB2L 500-2000kW	190	11.4	3.0	5000 / 352 TEU	8064	2.0	1249	141
Push boats 500-2000 kW	PushBII-1, 500-2000kW	130	11.4	6.0	2800	4313	2.0	1249	178
Push boats >=2000 kW	Push B4 > 2000 kW	190	22.8	4.0	11200	8064	3.0	4080	1107
	Push B6 > 2000 kW	270	22.8	4.0	16800	8064	3.0	4080	2351
Motor vessel dry cargo >=110m length	MVS 110m	110	11.4	3.5	3043	4318	1.0	1527	311
	MVS 135m	135	11.4	3.3	3300 / 268 TEU	7898	2.0	1492	477
Motor vessel liquid cargo >=110m length	MTS 110m	110	11.4	3.5	2908	4318	1.1	1550	360
	MTS 135m (M11)	135	11.4	4.0	4290 (5320 m3)	7898	2.0	2347	357
	MTS 135M (M12)	135	17.0	3.8	6228	7898	2.0	2370	357
Motor vessel dry cargo 80-109m length	MVS 80m	80	8.2	2.7	1250	3499	1.0	700	111
	MVS 86m	86	9.5	2.9	1522	3971	1.1	756	155
	MVS 105m	105	9.5	3.0	2050	4013	1.1	1286	311
Motor vessel liquid cargo 80-109m length	MTS 86m	86	9.5	3.2	1680 (1918m3)	3971	1.0	1210	272
Motor vessels <80 m. length	MVS 67m	67	8.2	2.7	985	3778	1.2	445	81
	MVS 55m	55	7.2	2.6	653	3874	1.0	319	48
	MVS 50m	50	6.6	2.6	650	3830	1.0	300	34
	MVS 38,5m	39	5.1	2.5	400	3265	1.0	220	23
Coupled convoys	C3L/B	110 + 80	11.4	3.4	5500	8064	2.0	2351	558
Danube barges	Push Barge, 4 units, Danube	178	22.8	2.7	6400	8064	2.0	2000	1533
	Push Barge, 8/9 units, Danube	267	33.0	2.9	17400	8064	2.0	2000	1252

Table 2: Overview of vessel types with (average) operational hours, installed power and annual fuel consumption

2.2.2 Representative journeys

For each of the representative journeys annual fuel consumption was calculated based on the operational profiles and constant fuel consumption (0,22 kg/kWh) and multiplied by the number of trips performed in a year.

Trip No.	Port A	Port B	Type	Vessel type	Payload per trip (t)	Fuel consumption per year (M^3)
1	Rotterdam	Duisburg	Dry bulk	Push B4	11,200	3,939
2	Rotterdam	Antwerp	Container	C3L/B	4,420	531
3	Rotterdam	Karlsruhe	Liquid Bulk	MTS 135m	2,917	1,176
4	Amsterdam	Karlsruhe	Dry bulk	C3L/B	3,795	1,190
5	Rotterdam	Basel	Container	C3L/B	4,607	879
7	Amsterdam	Antwerp	Container	C3L/B	4,420	645
9	Amsterdam	Rotterdam	Liquid Bulk	MTS 135m	4,750	1,443
10	Antwerp	Mainz	Container	MVS 135m	3,179	733
12	Antwerp	Duisburg	Container	C3L/B	6,375	980
13	Rotterdam	Duisburg	Container	MVS 110m	2,465	311
14	Rotterdam	Ludwigshafen	Liquid Bulk	MTS 86m	1,210	240
16	Rotterdam	Strassbourg	Dry Bulk	MVS110m	2,039	432
18	Duisburg	Antwerp	General cargo	MVS 110m	2,039	643
22	Rotterdam	Herne	Dry Bulk	MVS 86m	1,096	184
23	Dusseldorf	Antwerp	Dry Bulk	MVS 110m	2,039	565
25	Rotterdam	Duisburg	Dry bulk	MVS 86m	1,237	265

Table 3: Overview of representative journeys in the Rhine / ARA area with (average) payload per trip and annual fuel consumption

Trip No.	Port A	Port B	Type	Vessel type	Payload (t)	Fuel consumption per year (M^3)
1	Bor district	Constanza	Dry bulk	Push 8/9	9,000	1,555
2	Bor district	Constanza	Liquid Bulk	Push 8/9	9,000	1,555
3	Constanza	Dunaújváros	Dry bulk	Push 8/9	9,000	1,391
4	Giurgiu	Constanza	Dry bulk	Push 8/9	9,000	954
5	Calafat	Constanza	Dry bulk	Push 8/9	9,000	1,557
6	Bratislava	Linz	Dry bulk	Push 4	4,400	1,533
7	Calafat	Constanza	Dry bulk	Push 8/9	9,000	1,557
8	Constanza	Dunaújváros	Dry bulk	Push 8/9	9,000	1,391
9	Giurgiu	Constanza	Dry bulk	Push 8/9	9,000	954
10	Giurgiu	Constanza	Dry bulk	Push 8/9	9,000	954

Table 4: Overview of representative journeys on the Danube with (average) payload per trip and annual fuel consumption

Trip No.	Port A	Port B	Type	Vessel type	Payload (t)	Fuel consumption per year (M^3)
7	Rotterdam	Hannover	Dry Bulk	MVS 86m	1,096	200
8	Duisburg	Wolfsburg	General goods	MVS 86m	1,096	125
16	Rotterdam	Oldenburg	Dry Bulk	MVS 80m	910	102
17	Rotterdam	Lingen	Liquid Bulk	MTS 86m	1,039	176

Table 5: Overview of representative journeys on the other waterways with (average) payload per trip and annual fuel consumption

Trip No.	Waterway	Port A	Port B	Vessel type	Fuel consumption per year (M^3)
1	ARA/Rhine	Amsterdam	Basel	PAX 135m	243
3	Danube	Passau	Budapest	PAX 135m	189

Table 6: Overview of representative passenger journeys with (average) annual fuel consumption

2.3 General costs calculation

The general costs are calculated based on the sources mentioned under paragraph 2.1. For each of the vessel types the base line annual costs of transport are calculated, including the following cost items:

The costs of capital include:

- Insurance costs per year;
- Depreciation per year: Based on the depreciation from the capital value of the vessel (see *Table 7*) and the residual value, depreciated linearly each year;
- Interest costs: The interest costs for the average book value, in which the interest costs of the borrowed capital and the opportunity costs of the equity are included. For both an interest or discount rate of 4% was used;

Besides, there are several other (operating) costs, such as:

- Repair and maintenance;
- Port Dues;
- Labour costs;
- Fuel costs, which are calculated based on a low, high and average price scenario (see paragraph 2.3.2);
- Other fixed costs.

2.3.1 Capital cost calculation

For the calculation of the costs of capital, such as the depreciation, interest and insurance cost, the capital value of a vessel are used as given in *Table 7*:

Fleet family	Vessel type	Capital value of vessel
Passenger vessels(hotel/cruise)	PAX 135m	€ 7,000,000
Push boat <500 kW	PB <500 kW B04	€ 300,000
Push boat 500-2000 kW	PushB2L 500-2000kW	€ 4,400,000
Push boat 500-2000 kW	PushBII-1, 500-2000kW	€ 1,400,000
Push boat >=2000 kW	Push B4 > 2000 kW	€ 9,300,000
	Push B6 > 2000 kW	€ 12,700,000
Motorvessel dry cargo >=110m length	MVS 110m	€ 2,457,200
	MVS 135m	€ 3,576,667
Motorvessel liquid cargo >=110m length	MTS 110m	€ 5,027,240
	MTS 135m (M11)	€ 9,065,668
	MTS 135M (M12)	€ 11,100,817
Motorvessel dry cargo 80-109m length	MVS 80m	€ 488,400
	MVS 86m	€ 937,500
	MVS 105m	€ 1,482,727
Motorvessel liquid cargo 80-109m length	MTS 86m	€ 2,178,750
Motorvessel <80 m. length	MVS 67m	€ 359,304
	MVS 55m	€ 338,200
	MVS 50m	€ 237,534
	MVS 38,5m	€ 124,000
Coupled convoy (mainly class Va + Europe II lighter)	C3L/B	€ 3,635,758
Danube barge	Push Barge, 4 units, Danube	€ 4,000,000
	Push Barge, 8/9 units, Danube	€ 6,000,000

Table 7: Capital value of vessel per vessel type

2.3.2 Fuel price calculation

As regards the sensitivity analyses, the following figure presents the development of the fuel price. The fuel price is calculated based on the figures of CBRB data[5] on average gasoil prices. It can be seen that the fuel price is volatile.

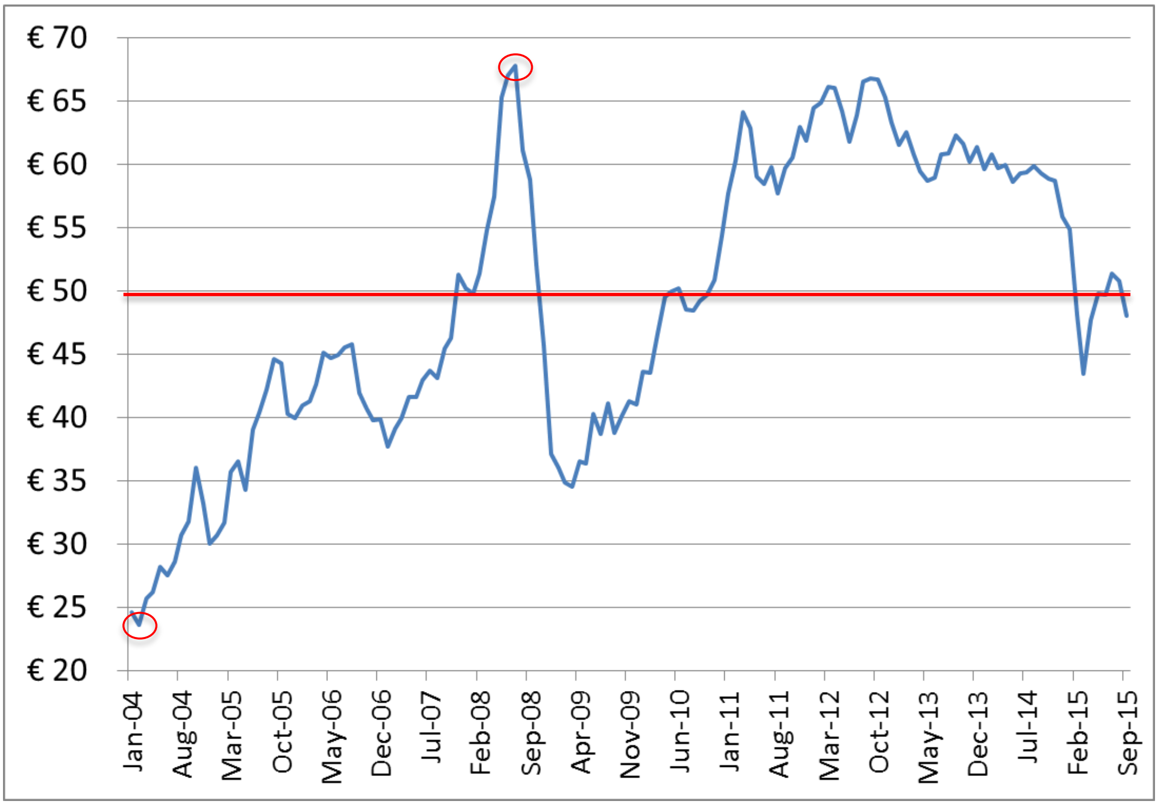

Figure 5: Development of the fuel price 2004-September 2015 with lowest, highest and average fuel price

To get a view on the bandwidth of the impact of the fuel prices, the following three values have been used:

- L: The lowest monthly average value seen since 2004: **23.65** EUR per 100 litre (Feb. 2004)
- M: The average fuel price between January 2004-September 2015: **49.25** EUR per 100 litre
- H: The highest monthly average value seen since 2004: **67.81** EUR per 100 litre (July 2008)

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[5] The Dutch sector organisation CBRB has a ‘Fuel Circular’, in which daily the average fuel price is set, based on the market prices of the major oil producers: http://www.cbrb.nl/publicaties/44-vervoervoorwaarden/256-abonnement-cbrb-brandstofcirculaire#EN

2.4 Calculation of cost and benefits for SCR and DPF

The calculation of the costs for SCR and DPF has been performed based on the vessel types, in line with the general cost calculations. Assumed are two options, one option with only SCR (SCR-only) and another option applying a DPF on the SCR configuration (SCR+DPF). These cost calculations have been used to calculate the annual costs of the application of the SCR-only and SCR+DPF options. With these annual cost calculations also the costs of the application of SCR-only and SCR+DPF on vessels on the selected representative journeys are made. The height of the different cost items has been determined based on expert knowledge of project partner Multronic.

2.4.1 Cost calculation for SCR

For SCR three types of costs are identified, the investment costs, the repair and maintenance costs and the costs of urea consumption. The investment costs of an SCR system consists of two elements, the fixed hardware, design and installation costs and the variable costs (consumables, repair and maintenance).

Investment costs

Fixed hardware, design and installation costs

Hardware, design and installation are determined as fixed costs per unit, including urea tank and compressor. These costs include most of the housing, which also scales with engine size and is for that reason also partly calculated under the variable hardware cost. Besides, it includes the steering package (control unit), the electric wiring, the design of the system and the costs of installing the housing and electric wiring into the ship. These costs are determined on €45,000 per unit/engine.

Variable hardware costs

The variable hardware costs are the costs related to the SCR system itself. The largest part of these costs is taken up by the costs of the SCR elements. Also the AdBlue (urea) injection system is a large cost item, which scales with the engine size. The hardware costs are calculated based on the installed power of the engine and are determined on €25 per kW. The lifetime of the system is determined on 30,000 hours, which is based on the target lifetime set in this project for the after-treatment systems. However, for some of the vessel types the engine hours of the system in 5 years exceed 30,000 hours of sailing time. In that case a second set of catalysts is needed to lengthen the lifetime to 60,000 hours. For these engines, the variable hardware costs are multiplied by a factor of 2.1 compared to the normal hardware costs, resulting in €52.50 per kW.

Repair and maintenance costs

The repair and maintenance costs are defined as costs per 1,000kWh and per 1,000 engine hours. These costs include a check-up of the system every 1,000 hours and - with regular intervals - the replacement of the pumps, filters and injectors. These costs are estimated on €2.00 per 1,000 kWh. For example: A motor tank vessel, 110 metres has around 1,943 sailing hours per year with an engine running on an average power of 731 kW, resulting in annual repair and maintenance costs for an SCR of: (1,943 x 731) / 1,000 x €2 = € 2,829.

Urea costs

For the use of SCR and NOx reduction urea is needed. The urea consumption depends on several factors, such as the fuel consumption and the amount of NOx emissions to be reduced. In these cost calculations the urea consumption is based on a certain percentage of the fuel consumption. For the urea consumption, it is estimated that 2 kg of AdBlue (a 32.5% urea solution) is needed to reduce NOx emissions by 1 kg.

It is assumed that CCNR Stage-II engines have engine-out NOx emissions of 7 g/kWh. In fact, depending on engine speed and installed power, the emission levels for CCNR Stage-II range from 6 to 11 g/kWh and, depending on power and displacement, for EU NRMM Stage-IIIa the emission levels of NOx and HC together range from 7.2 to around 8.7 g/kWh. For CCNR Stage-I and non-type approved engines, it is assumed that there is an average engine-out NOx emissions of 11.8 g/kWh. For CCNR Stage-I, the emission levels of NOx range from 9 g/kWh and higher, depending on engine speed and installed power, and is not regulated for non-type approved engines.

To reduce this to an emission level of 1.8 g NOx per kWh, taken into account an engineering safety margin, there is a ratio of 0.048 litres AdBlue for each kg fuel consumed for CCNR Stage-II engines and 0.09 litres AdBlue for each kg fuel consumed for CCNR Stage-I and non-type approved engines. Because of the NOx optimisation, it is assumed that there is a slightly higher fuel consumption for CCNR Stage-II compared to CCNR Stage-I and non-type approved engines. The price per litre AdBlue is assumed to be €0.28, based on the information of suppliers and ship-owners, with the AdBlue price ranging between €0.25 and €0.31 per litre (including discounts).

2.4.2 Cost calculation for DPF

Investment costs

The investment costs of the DPF are defined as the additional costs of adding a DPF system to an SCR system. Also for DPF the investment costs are calculated based on two elements, the (variable) hardware costs and the (fixed) hardware, design and installation costs. The former are dependent on the installed power of the engine and the latter are fixed costs per unit.

Variable hardware costs

The hardware costs are the costs related to the DPF system itself, which exist mainly of the costs of the filter elements. The hardware costs are calculated based on the installed power of the engine and are determined on €39 per kW. In line with the specifications set for the after-treatment configuration the lifetime of the system is determined on 30,000 hours. If the engine hours of the system in 5 years exceed 30,000 hours, a second set of filters is needed to lengthen the lifetime to 60,000 hours. For these engines, the hardware costs are multiplied by a factor of 2.1 compared to the normal hardware costs, resulting in €81.90 per kW.

Fixed hardware, design and installation costs

The design and installation costs are fixed costs for the design and installation of the unit(s), which include most of the housing (this cost also scales with engine size, so part of the cost is under the variable hardware cost), the active regeneration package, the design of the system and the costs of installing the housing into the ship. It is assumed that the installation takes place together with the installation of the SCR system, since both will share a single housing. These are determined at €15,200 per unit and for each engine a unit is needed. It is assumed that the fixed hardware, design and installation costs for medium speed engines are 50% higher than for high speed engines. Medium speed engines have lower back-pressure requirements than high speed engines. In order to meet these requirements, a larger volume of filter elements is needed.

Operating costs

The only operating cost item which is taken into account is the cost for repairing and maintaining the DPF.

Repair and maintenance costs

The repair and maintenance costs are based as costs per 1,000kWh and – also calculated - per 1,000 engine hours. These costs include a check-up of the system every 1,000 hours and a cleaning of the filter elements every 3,000 hours. These costs are estimated on €2.34 per 1,000kWh.

2.4.3 Calculation of the benefits in port dues

In the report of Deliverable 1.2 it was concluded that the only financial benefit of the use of after-treatment can currently be achieved by the discount on the port dues. The discount on the port dues for the sea ports Amsterdam, Rotterdam and Antwerp has been included in calculating the (net) annual costs of the application of after-treatment. These ports all have a particular differentiation policy for the port dues based on a bonus for cleaner inland vessels and – in the case of the Port of Rotterdam – also a malus for more polluting inland vessels. Currently, there are also similar incentive schemes for inland ports and it is expected to be used in more (inland) ports in the future. However, for the benefit calculations only these three ports are relevant. [6] For the Rhine/ARA journeys – in which ports grant discount on port dues for 'cleaner vessels' – net costs will be calculated including these benefits in port dues.

Port dues Rotterdam

For the port dues in Rotterdam, the basic tariff is determined for inland vessels complying to CCNR Stage-II standards, whereas vessels with CCNR Stage-I and non-type approved engines pay a surcharge of 10%. Vessels with lower emissions and/or Green Award certification get a discount on their port dues.

Rotterdam Port Dues	Discount/surcharge	Tariff per tonne
Basic Tariff (based on annual tariff, complied to CCNR-II standards)	0%	€ 3.196
Tariff if not complied to CCNR-II standards	+ 10%	€ 3.5156
Tariff if complied to CCNR-II standards and Green Award certified	-/- 15%	€ 2.7166
Tariff if emissions are 60% lower than CCNR-II standards	-/- 30%	€ 2.2372

Assumed is that an inland vessel equipped with SCR and DPF emits at least 60% less NOx and PM than necessary for CCNR Stage-II engines, which results in a discount on the port dues with 30% compared to CCNR Stage-II and 36,4% compared to CCNR Stage-I.

Port dues Port of Antwerp

For the Port of Antwerp the basic tariff is for all vessels. If a vessel can comply with CCNR-II standards, it is granted a discount on its port dues.

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[6] Some Dutch inland ports provide incentives based on Green Award certification: http://www.greenaward.org/greenaward/file.php?id=1404&hash=ff2f4a63104129a0a467230f4f0020dc

Antwerp Port Dues	Discount/surcharge	Tariff per tonne
Basic Tariff (based on annual tariff)	0%	€ 3.15
Tariff if complied to CCNR-II standards	-/- 7%	€ 2.9295
Tariff if diesel-electric (with CCNR-II engine), LNG or hydrogen powered	-/- 15%	€ 2.6775

Assumed is that an inland vessel equipped with SCR and DPF can comply (at least) with CCNR Stage-II standard. However, only diesel-electric, LNG and hydrogen powered vessels can get a 15% discount. So, for after-treatment the discount on the port dues is 7% compared to CCNR-I and there is no discount compared to CCNR-II engines.

Port dues Port of Amsterdam

To get a discount on the port dues in Amsterdam, Green Award certification is needed.

Amsterdam Port Dues	Discount/surcharge	Tariff per tonne
Basic Tariff (based on annual tariff)	0%	€ 3.2446
Tariff if Green Award (bronze) certified	-/- 5%	€ 3.0824
Tariff if Green Award (silver) certified	-/- 10%	€ 2.9201
Tariff if Green Award (gold) certified	-/- 15%	€ 2.7579

It is assumed that with after-treatment a vessel owner can achieve a gold certification and gets a 15% discount compared to the normal port dues.

2.4.4 Calculation of the annual costs per vessel type

Based on the cost calculation with the identified cost items, the annual costs have been calculated for each of the vessel types. There has been calculated based on six options, depending on the choice to apply only SCR or also DPF and the engines on which they are applied:

- SCR-Only:
  - Applied on a CCNR-I or non-type approved engine;
  - Applied on a CCNR-II or EU NRMM Stage-IIIa approved engine.
- SCR+DPF:
  - Applied on a CCNR-I or non-type approved medium-speed engine;
  - Applied on a CCNR-I or non-type approved high-speed engine;
  - Applied on a CCNR-II or EU NRMM Stage-IIIa approved medium-speed engine;
  - Applied on a CCNR-II or EU NRMM Stage-IIIa approved high-speed engine.

Annual cost calculation

For the annual costs the following cost items are included:

- Depreciation costs, resulting from the investment costs divided by the depreciation time;
- Interest costs, The interest costs for the average book value, in which the interest costs of the borrowed capital and the opportunity costs of the equity are included. For both an interest or discount rate of 4% was used;
- Total maintenance cost per year, which is based on the repair and maintenance costs;
- Urea cost per year.

As the benefits achieved by the discount on the port dues are not sufficient to cover additional annual costs, in almost all the cases the net present value and internal rate of return will be negative and therefore there has been decided to express the costs and benefits in two other ways:

- The annual costs for the 6 options will be expressed in percentage cost increase compared to the base line costs of transport;
- The costs are also expressed in costs for the SCR per kilogram NOx reduction and the additional costs for the DPF-option per kilogram PM reduction.

2.4.5 Calculation of the annual costs for representative journeys

In Deliverable 1.2 a selection of representative journeys was identified, based on the volume of the cargo flows. These representative journeys were divided in three sailing areas, Rhine/ARA (Amsterdam-Rotterdam-Antwerp), Danube and other waterways. Besides, a selection of representative passenger journeys was identified. For many of these representative journeys operational profiles were defined. Based on these operational profiles, in the overview of these representative journeys the sailing hours, the number of roundtrips and the fuel consumption were determined and included. A second step in the analysis of the costs and benefits of SCR and DPF is to calculate the costs and the effect of these technologies specific for these representative journeys. For this the annual costs of depreciation and interest were used from the relevant vessel type, for the urea costs and the costs of repair and maintenance a correction was made based on the journey specific fuel consumption and kWh.

In the calculations for the different vessel types the calculations have been made for six options. For the representative journeys the calculations have been made for only the most common engine installed in the specific vessel type operating mostly on the particular representative journey. For this selection, data from Deliverable 1.2 were used, in which the most common vessel type was selected for each of the representative journeys and an analysis of the construction year and engine speed of the engines were performed. The calculations are therefore made for the option of applying only SCR and of applying SCR and DPF for the most common engine type.

The annual cost calculations are in line with the calculations made for the vessel types. As effects are taken into account:

- The benefit of the discount on the port dues for the Rhine/ARA journeys and what percentage of the annual costs of these two options it covers;
- The (net) annual costs for SCR and SCR+DPF expressed as percentage of cost increase compared to the base line costs of transport;
- The costs for SCR and SCR+DPF expressed as an amount per tonnes cargo transported;
- The costs are also expressed per kg emission reduction, for the SCR-only per kg NOx reduction and for the additional costs of applying DPF per kg PM reduction.

3. Ex-ante cost effectiveness analysis

In this chapter the outcomes of the annual cost calculations and the effects of the application of SCR and SCR+DPF are given. These calculations have been made according to the methodology described in chapter 2. An overview of the costs are given in Annexes A1-A5. In paragraph 3.1 the calculation for the vessel types are given and in paragraphs 3.2-3.5 the outcomes for respectively Rhine/ARA, Danube, other waterways and passenger journeys are given.

3.1 Calculations for the vessel types

As a base-line, also to calculate the effect of the application of SCR and SCR+DPF, in *Table 8* the total annual costs of transport are given per vessel type. A more detailed overview of the cost calculation for each of the vessel types can be found in Annex A1.

Fleet family	**Vessel type**	**Total annual costs**		
		Low	Medium	High
Passenger vessels (hotel/cruise)	PAX 135m	€ 3,021,202.90	€ 3,133,456.36	€ 3,214,840.12
Push boats <500 kW	PB <500 kW B04	€ 189,185.99	€ 210,262.04	€ 225,542.18
Push boats 500-2000 kW	PushB2L 500-2000kW	€ 1,260,709.26	€ 1,296,900.28	€ 1,323,138.78
Push boats 500-2000 kW	PushBII-1, 500-2000kW	€ 616,199.39	€ 661,843.92	€ 694,936.21
Push boats >=2000 kW	Push B4 > 2000 kW	€ 2,482,482.94	€ 2,765,964.61	€ 2,971,488.83
	Push B6 > 2000 kW	€ 3,372,506.46	€ 3,974,267.13	€ 4,410,543.62
Motor vessel dry cargo >=110m length	MVS 110m	€ 526,920.97	€ 606,497.53	€ 664,190.53
	MVS 135m	€ 992,738.60	€ 1,114,924.29	€ 1,203,508.90
Motor vessel liquid cargo >=110m length	MTS 110m	€ 840,683.54	€ 932,745.35	€ 999,490.16
	MTS 135m (M11)	€ 1,486,215.36	€ 1,577,502.06	€ 1,643,684.92
	MTS 135M (M12)	€ 1,658,790.47	€ 1,750,077.17	€ 1,816,260.03
Motor vessel dry cargo 80-109m length	MVS 80m	€ 206,752.30	€ 235,226.82	€ 255,870.84
	MVS 86m	€ 291,641.18	€ 331,300.18	€ 360,052.95
	MVS 105m	€ 407,004.42	€ 486,540.51	€ 544,204.18
Motor vessel liquid cargo 80-109m length	MTS 86m	€ 440,545.38	€ 510,198.37	€ 560,696.80
Motor vessels <80 m. length	MVS 67m	€ 177,666.10	€ 198,323.76	€ 213,300.56
	MVS 55m	€ 170,666.67	€ 182,863.13	€ 191,705.56
	MVS 50m	€ 158,463.53	€ 167,128.61	€ 173,410.80
	MVS 38,5m	€ 105,410.74	€ 111,215.79	€ 115,424.46
Coupled convoys	C3L/B	€ 1,168,449.60	€ 1,311,297.60	€ 1,414,862.40
Danube barges	Push Barge, 4 units, Danube	€ 1,289,201.70	€ 1,681,634.44	€ 1,966,148.18
	Push Barge, 8/9 units, Danube	€ 1,603,025.66	€ 1,923,517.28	€ 2,155,873.71

Table 8: Total annual costs per vessel type, based on fixed costs, labour costs and fuel costs (with low-average-high fuel price scenarios)

3.1.1 Annual cost calculations for SCR-only

For each of the vessel types the annual costs are calculated for the configuration with SCR only. The annual costs are calculated for CCNR-I (and non-type approved) as well as CCNR-II (and EU NRMM Stage-IIIA) with the main difference the higher urea consumption for engines with higher NOx emissions before after-treatment. The annual costs are calculated based on the cost calculations in chapter 2.3.4, including depreciation, interest, repair and maintenance and urea costs. The total annual costs are given in *Table 9* and can be found in more detail in Annex A2.

Vessel type	Annual costs SCR-only	
	CCNR-I	CCNR-II
PAX 135m	€ 27,506.06	€ 23,226.05
PB <500 kW B04	€ 6,130.71	€ 5,327.12
PushB2L 500-2000kW	€ 20,558.97	€ 19,179.07
PushBII-1, 500-2000kW	€ 19,240.05	€ 17,499.71
Push B4 > 2000 kW	€ 81,137.91	€ 70,329.29
Push B6 > 2000 kW	€ 116,970.11	€ 94,026.11
MVS 110m	€ 16,009.08	€ 12,974.98
MVS 135m	€ 30,042.48	€ 25,383.76
MTS 110m	€ 17,706.00	€ 14,195.86
MTS 135m (M11)	€ 29,298.54	€ 25,817.95
MTS 135M (M12)	€ 29,372.10	€ 25,891.51
MVS 80m	€ 7,663.11	€ 6,577.43
MVS 86m	€ 9,694.73	€ 8,182.61
MVS 105m	€ 15,720.62	€ 12,688.06
MTS 86m	€ 13,629.02	€ 10,973.29
MVS 67m	€ 7,093.05	€ 6,305.41
MVS 55m	€ 5,168.03	€ 4,703.00
MVS 50m	€ 4,639.50	€ 4,309.12
MVS 38,5m	€ 4,521.50	€ 4,300.17
C3L/B	€ 47,050.99	€ 41,604.46
Push Barge, 4 units, Danube	€ 68,554.64	€ 53,411.64
Push Barge, 8/9 units, Danube	€ 60,462.88	€ 48,095.91

Table 9: Overview of the annual costs for SCR-only for each of the vessel types

Heavily depending on the engine and operational characteristics, the annual costs of applying an SCR on a vessel with CCNR Stage-II engines can differ between € 4,300 (for a small dry-cargo motor vessel of 38.5m) and € 94,027 (for a push boat with 6 barges). For application on a vessel with CCNR Stage-I or non-type approved engines these costs can be even 5-28% higher, ranging from € 4,521 to € 116,970. As can be seen in *Figure 6*, these annual costs exist from the four cost items, depreciation costs, interest costs, repair and maintenance costs and urea costs. The latter is higher for CCNR Stage-I approved engines.

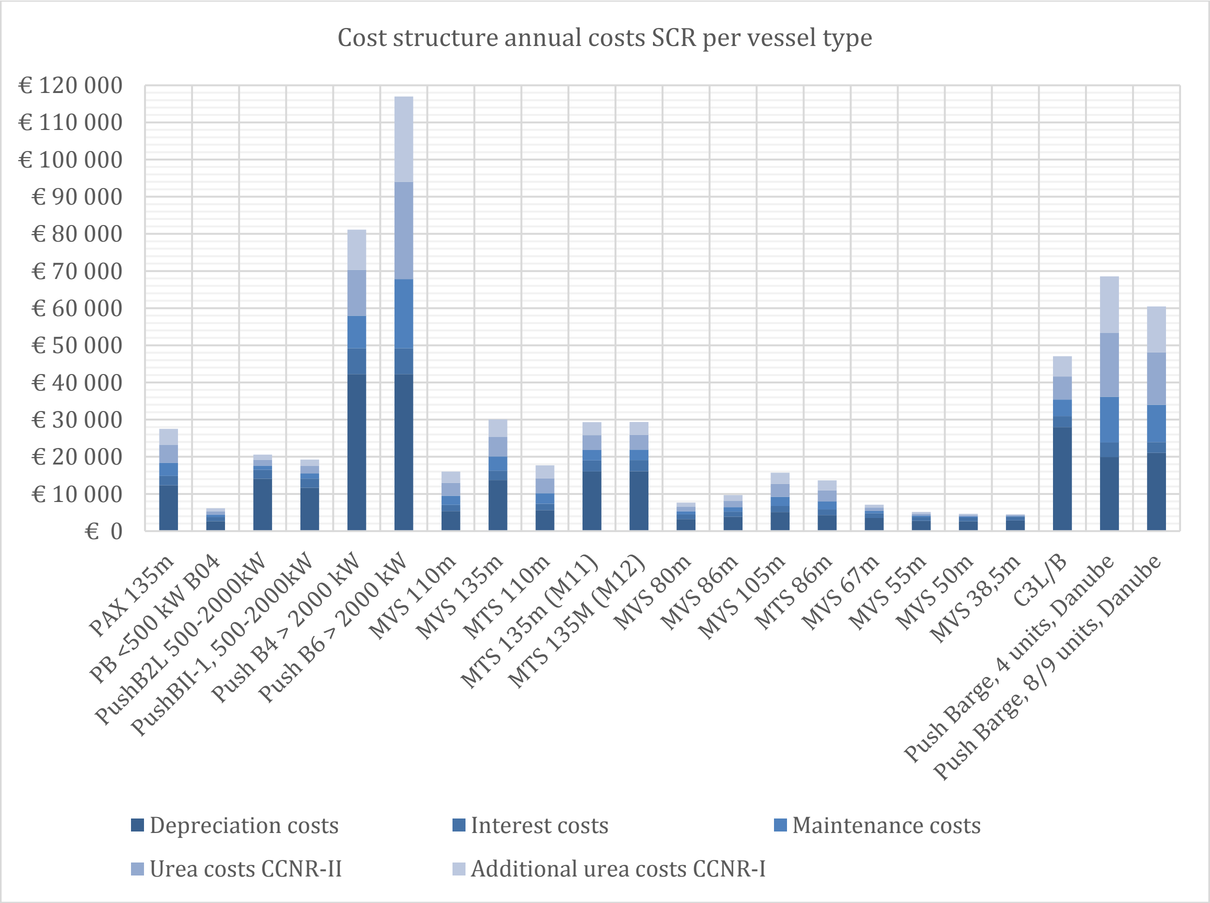

Figure 6: Cost structure annual costs SCR per vessel type

Most important cost element are the capital costs, for CCNR Stage-I engines the depreciation costs are on average 46% of the total annual costs and the interest costs are on average 12% of the total annual costs (for CCNR Stage-II engines these costs have a relatively higher share, respectively on average 55% and 16%). The operating costs are lower, for CCNR Stage-I engines the urea costs are on average 30% of the total annual costs, while for CCNR Stage-II engines these costs are only 19% of the total annual costs of an SCR.

Cost increase as percentage of the base line costs of transport

In *Table 10* the annual cost increase by the application of SCR is given as a percentage of the general (base line) annual costs (of transport). These annual costs are based on the costs with an average fuel price scenario. This cost increase shows the relative impact on the operational costs of a ship-owning company.

Vessel type	Annual cost increase	
	CCNR-I	CCNR-II
PAX 135m	0.9%	0.7%
PB <500 kW B04	2.9%	2.5%
PushB2L 500-2000kW	1.6%	1.5%
PushBII-1, 500-2000kW	2.9%	2.6%
Push B4 > 2000 kW	2.9%	2.5%
Push B6 > 2000 kW	2.9%	2.4%
MVS 110m	2.6%	2.1%
MVS 135m	2.7%	2.3%
MTS 110m	1.9%	1.5%
MTS 135m (M11)	1.9%	1.6%
MTS 135M (M12)	1.7%	1.5%
MVS 80m	3.3%	2.8%
MVS 86m	2.9%	2.5%
MVS 105m	3.2%	2.6%
MTS 86m	2.7%	2.2%
MVS 67m	3.6%	3.2%
MVS 55m	2.8%	2.6%
MVS 50m	2.8%	2.6%
MVS 38,5m	4.1%	3.9%
C3L/B	3.6%	3.2%
Push Barge, 4 units, Danube	4.1%	3.2%
Push Barge, 8/9 units, Danube	3.1%	2.5%

Table 10: Annual cost increase SCR-only as percentage of general costs

This shows an increase of costs compared to the general costs by 0.9% (for a passenger vessel of 135m) up to 4.1% (for a Danube push boat with 4 barges and a motor vessel of 38.5m) when applied on CCNR Stage-I or non-type approved engines and ranging from 0.7% to 3.9% for CCNR Stage-II engines.

Costs per kg NOx-reduction

To show the value for money and the environmental benefits of the application of SCR, in *Table 11* the costs per kg NOx-reduction is given. This table shows that unless there are higher annual costs for the application of SCR on a CCNR Stage-I engine (because of higher urea consumption), the costs per kg NOx-reduction are relatively lower than on a CCNR Stage-II engine.

Vessel type	Costs per kg NOx-reduction for SCR	
	CCNR-I	CCNR-II
PAX 135m	€ 1.59	€ 2.58
PB <500 kW B04	€ 1.88	€ 3.15
PushB2L 500-2000kW	€ 3.68	€ 6.60
PushBII-1, 500-2000kW	€ 2.73	€ 4.78
Push B4 > 2000 kW	€ 1.85	€ 3.09
Push B6 > 2000 kW	€ 1.26	€ 1.95
MVS 110m	€ 1.30	€ 2.03
MVS 135m	€ 1.59	€ 2.59
MTS 110m	€ 1.25	€ 1.92
MTS 135m (M11)	€ 2.08	€ 3.52
MTS 135M (M12)	€ 2.08	€ 3.53
MVS 80m	€ 1.74	€ 2.88
MVS 86m	€ 1.58	€ 2.57
MVS 105m	€ 1.28	€ 1.99
MTS 86m	€ 1.27	€ 1.96
MVS 67m	€ 2.22	€ 3.80
MVS 55m	€ 2.74	€ 4.80
MVS 50m	€ 3.47	€ 6.19
MVS 38,5m	€ 5.04	€ 9.23
C3L/B	€ 2.13	€ 3.63
Push Barge, 4 units, Danube	€ 1.12	€ 1.68
Push Barge, 8/9 units, Danube	€ 1.21	€ 1.85

Table 11: Costs for SCR-only per kg NOx-reduction

3.1.2 Annual cost calculations for SCR-DPF

The same calculations have also been made for the application of SCR in combination with DPF. In *Table 12* the annual costs of the application of SCR-DPF on four different types of engines are given.

Vessel type	Annual costs			
	CCNR-I, Medium speed	CCNR-I, High speed	CCNR-II, Medium speed	CCNR-II, High speed
PAX 135m	€ 47,081.88	€ 41,908.41	€ 42,801.87	€ 37,628.40
PB <500 kW B04	€ 10,048.80	€ 8,996.58	€ 9,245.21	€ 8,192.99
PushB2L 500-2000kW	€ 38,003.08	€ 32,624.20	€ 36,623.19	€ 31,244.31
PushBII-1, 500-2000kW	€ 34,692.78	€ 30,091.54	€ 32,952.44	€ 28,351.20
Push B4 > 2000 kW	€ 171,674.08	€ 144,909.16	€ 160,865.46	€ 134,100.54
Push B6 > 2000 kW	€ 219,004.82	€ 192,239.90	€ 196,060.82	€ 169,295.89
MVS 110m	€ 28,388.06	€ 25,220.03	€ 25,353.96	€ 22,185.92
MVS 135m	€ 51,457.54	€ 45,790.60	€ 46,798.83	€ 41,131.88
MTS 110m	€ 30,773.69	€ 27,526.44	€ 27,263.55	€ 24,016.30
MTS 135m (M11)	€ 55,996.51	€ 48,196.50	€ 52,515.92	€ 44,715.91
MTS 135M (M12)	€ 56,242.22	€ 48,384.83	€ 52,761.63	€ 44,904.24
MVS 80m	€ 13,238.38	€ 11,722.86	€ 12,152.70	€ 10,637.18
MVS 86m	€ 16,442.82	€ 14,671.05	€ 14,930.70	€ 13,158.92
MVS 105m	€ 26,906.85	€ 24,135.91	€ 23,874.29	€ 21,103.35
MTS 86m	€ 23,342.23	€ 20,943.29	€ 20,686.50	€ 18,287.55
MVS 67m	€ 11,791.34	€ 10,474.01	€ 11,003.70	€ 9,686.37
MVS 55m	€ 8,577.41	€ 7,587.83	€ 8,112.39	€ 7,122.80
MVS 50m	€ 7,768.57	€ 6,829.90	€ 7,438.19	€ 6,499.51
MVS 38,5m	€ 7,463.31	€ 6,552.61	€ 7,241.97	€ 6,331.28
C3L/B	€ 90,332.76	€ 77,625.74	€ 84,886.23	€ 72,179.21
Push Barge, 4 units, Danube	€ 118,519.00	€ 106,646.99	€ 103,376.00	€ 91,503.99
Push Barge, 8/9 units, Danube	€ 100,966.65	€ 91,371.39	€ 88,599.68	€ 79,004.41

Table 12: Annual costs for the application of SCR-DPF

The costs for applying SCR+DPF are higher for CCNR Stage-I and non-type approved medium-speed engines than for CCNR Stage-II approved high-speed engines, which can be 18-30% higher in annual costs, because of the higher urea consumption and the higher fixed costs for the application of DPF. The (absolute) annual costs are also much higher for e.g. the large push boats compared to small motor vessels, due to several factors (e.g. engine size, urea consumption and engine hours). The cost structure of the annual costs of SCR per vessel type are given in *Figure 6*. *Figure 7* shows the additional costs for applying a DPF on an SCR system, with the depreciation costs and the interest costs (and for both also the 50% additional costs for applying it on a medium-speed engine) and the maintenance costs.

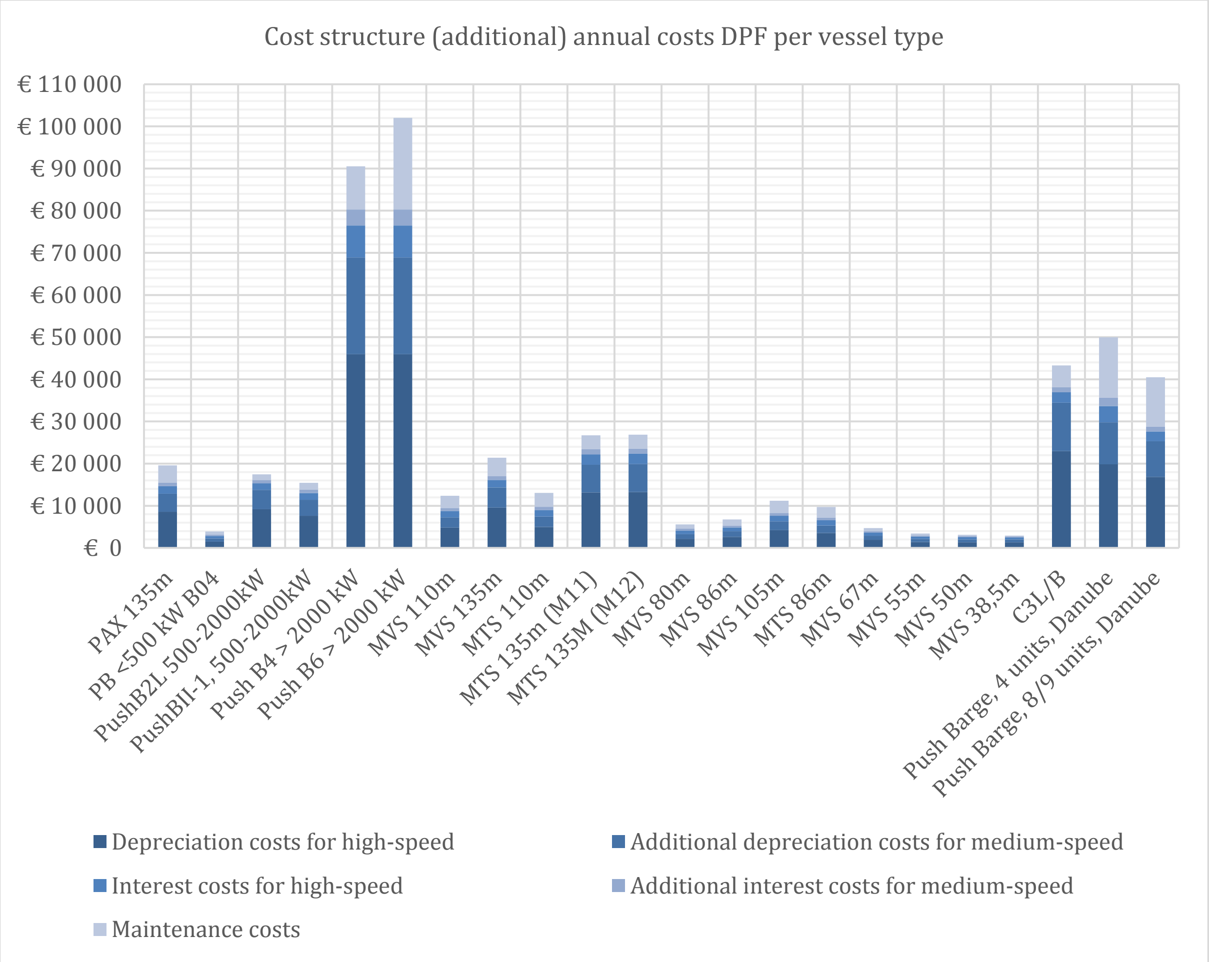

Figure 7: Cost structure of the additional annual costs of DPF per vessel type

The majority of the additional annual costs of DPF exists from the depreciation costs (on average 60% for high-speed and 65% for medium-speed engines). On average 16-17% are formed by the interest costs. To get a better insight into the relative heights of these costs, the costs have also been calculated as cost increase compared to the general costs and the costs expressed per kg emission reduction.

Cost increase as percentage of the base line costs of transport

For an insight into the relative costs of the application of SCR+DPF, in *Table 13* the annual cost increase compared to the base-line annual costs are given.

Vessel type	Annual cost increase			
	CCNR-I, Medium speed	CCNR-I, High speed	CCNR-II, Medium speed	CCNR-II, High speed
PAX 135m	1.5%	1.3%	1.4%	1.2%
PB <500 kW B04	4.8%	4.3%	4.4%	3.9%
PushB2L 500-2000kW	2.9%	2.5%	2.8%	2.4%
PushBII-1, 500-2000kW	5.2%	4.5%	5.0%	4.3%
Push B4 > 2000 kW	6.2%	5.2%	5.8%	4.8%
Push B6 > 2000 kW	5.5%	4.8%	4.9%	4.3%
MVS 110m	4.7%	4.2%	4.2%	3.7%
MVS 135m	4.6%	4.1%	4.2%	3.7%
MTS 110m	3.3%	3.0%	2.9%	2.6%
MTS 135m (M11)	3.5%	3.1%	3.3%	2.8%
MTS 135M (M12)	3.2%	2.8%	3.0%	2.6%
MVS 80m	5.6%	5.0%	5.2%	4.5%
MVS 86m	5.0%	4.4%	4.5%	4.0%
MVS 105m	5.5%	5.0%	4.9%	4.3%
MTS 86m	4.6%	4.1%	4.1%	3.6%
MVS 67m	5.9%	5.3%	5.5%	4.9%
MVS 55m	4.7%	4.1%	4.4%	3.9%
MVS 50m	4.6%	4.1%	4.5%	3.9%
MVS 38,5m	6.7%	5.9%	6.5%	5.7%
C3L/B	6.9%	5.9%	6.5%	5.5%
Push Barge, 4 units, Danube	7.0%	6.3%	6.1%	5.4%
Push Barge, 8/9 units, Danube	5.2%	4.8%	4.6%	4.1%

Table 13: Annual cost increase SCR+DPF as percentage of total annual costs (based on average)

As can be seen in the table, the cost increase for applying SCR+DPF on a CCNR Stage-II high-speed engine can range from 1.2% for a passenger vessel up to 5.7% for a dry-cargo motor vessel of 38.5m and even 1.5%-7% for application on a CCNR Stage-I/non-type approved medium-speed engine.

Costs per kg NOx and PM-reduction

In *Table 11* the costs of the applying SCR is given per kg NOx reduction. The additional costs of applying DPF on an SCR system (the difference between the costs of SCR+DPF compared to SCR-only) are calculated per kg PM-reduction. For this, an engine-out PM emission of 0.2 g/kWh is assumed for both CCNR Stage-I as well as CCNR Stage-II and reducing it to 0,015 g/kWh (in line with the emission targets set in *Table 1*).

Vessel type	**Additional costs per kg PM-reduction for DPF**			
	CCNR-I, Medium speed	**CCNR-I, High speed**	**CCNR-II, Medium speed**	**CCNR-II, High speed**
PAX 135m	€ 61.06	€ 44.92	€ 61.06	€ 44.92
PB <500 kW B04	€ 65.09	€ 47.61	€ 65.09	€ 47.61
PushB2L 500-2000kW	€ 168.76	€ 116.72	€ 168.76	€ 116.72
PushBII-1, 500-2000kW	€ 118.53	€ 83.24	€ 118.53	€ 83.24
Push B4 > 2000 kW	€ 111.82	€ 78.76	€ 111.82	€ 78.76
Push B6 > 2000 kW	€ 59.37	€ 43.79	€ 59.37	€ 43.79
MVS 110m	€ 54.46	€ 40.53	€ 54.46	€ 40.53
MVS 135m	€ 61.36	€ 45.13	€ 61.36	€ 45.13
MTS 110m	€ 49.70	€ 37.35	€ 49.70	€ 37.35
MTS 135m (M11)	€ 102.40	€ 72.48	€ 102.40	€ 72.48
MTS 135M (M12)	€ 103.06	€ 72.92	€ 103.06	€ 72.92
MVS 80m	€ 68.55	€ 49.92	€ 68.55	€ 49.92
MVS 86m	€ 59.57	€ 43.93	€ 59.57	€ 43.93
MVS 105m	€ 49.24	€ 37.04	€ 49.24	€ 37.04
MTS 86m	€ 48.82	€ 36.77	€ 48.82	€ 36.77
MVS 67m	€ 79.63	€ 57.30	€ 79.63	€ 57.30
MVS 55m	€ 97.87	€ 69.46	€ 97.87	€ 69.46
MVS 50m	€ 126.43	€ 88.50	€ 126.43	€ 88.50
MVS 38,5m	€ 177.43	€ 122.50	€ 177.43	€ 122.50
C3L/B	€ 106.08	€ 74.94	€ 106.08	€ 74.94
Push Barge, 4 units, Danube	€ 44.05	€ 33.58	€ 44.05	€ 33.58
Push Barge, 8/9 units, Danube	€ 43.72	€ 33.36	€ 43.72	€ 33.36

Table 14: Additional costs for DPF per kg PM-reduction

3.2 Rhine/ARA journeys

In Deliverable 1.1 (PROMINENT, 2015) operational profiles are elaborated for 18 of the 25 Rhine/ARA journeys. These journeys are given in Table 15 with the most common used engine. In the cost calculations for urea consumption, a distinction in engine types has been made between CCNR-II and EU NRMM Stage-IIIA engines on the one hand and CCNR-I and non-type approved engines on the other. The engine type is based on the construction years of the engines for the specific vessel type (table 6 in the D1.1 report). The engine speed (rpm) is based on the majority of the engines for the specific vessel type (table 5 in the D1.1 report). The majority of most of the vessel types have a CCNR Stage-I or non-type approved high speed engine, except for the larger push boats (which have mostly medium-speed engines) and the larger motor tank vessels (which have in majority relatively new engines).

	Selected representative journeys Rhine / ARA						**Most common engine**	
	Port A	**Port B**	**Type**	**Vessel type**	**Commodity**	**mln tkm**	**Type**	**Speed**
1	Rotterdam	Duisburg	Dry bulk	Push B4	Ore	4074	CCR1	Medium
2	Rotterdam	Antwerp	Container	C3L/B	Containers	3067	CCR1	High
3	Rotterdam	Karlsruhe	Liquid Bulk	MTS 135m	Crude oil	2478	CCR2	High
4	Amsterdam	Karlsruhe	Dry bulk	C3L/B	Coal	2219	CCR1	High
5	Rotterdam	Basel	Container	C3L/B	Containers	1094	CCR1	High
7	Amsterdam	Antwerp	Container	C3L/B	Containers	983	CCR1	High
9	Amsterdam	Rotterdam	Liquid Bulk	MTS 135m	Oil	968	CCR2	High
10	Antwerp	Mainz	Container	MVS 135m	Containers	827	CCR1	High
12	Antwerp	Duisburg	Container	C3L/B	Containers	677	CCR1	High
13	Rotterdam	Duisburg	Container	MVS 110m	Containers	620	CCR1	High
14	Rotterdam	Ludwigshafen	Liquid Bulk	MTS 86m	Chemicals	571	CCR1	High
16	Rotterdam	Strassbourg	Dry Bulk	MVS110m	Agribulk	254	CCR1	High
18	Duisburg	Antwerp	General cargo	MVS 110m	Metal products	181	CCR1	High
22	Rotterdam	Herne	Dry Bulk	MVS 86m	Metal (scrap)	43	CCR1	High
23	Dusseldorf	Antwerp	Dry Bulk	MVS 110m	Agribulk	40	CCR1	High
25	Rotterdam	Duisburg	Dry bulk	MVS 86m	Agribulk	14	CCR1	High

Table 15: Selected representative journeys Rhine / ARA with most common engine

In *Table 16* the total (base-line) costs of transport are given with a differentiation based on low, average and high fuel cost scenarios. For journeys 3 and 9 - operated mainly by the larger motor tank vessels - a correction has been made based on the discount on the port dues for the most common engines (CCNR-II or EU NRMM Stage-IIIA type approved).

	Port A	Port B	Total costs (low)	Total cost (average)	Total costs (high)
1	Rotterdam	Duisburg	€ 3,134,295.97	€ 4,142,796.18	€ 4,873,958.83
2	Rotterdam	Antwerp	€ 1,166,362.68	€ 1,302,263.46	€ 1,400,791.53
3	Rotterdam	Karlsruhe	€ 1,661,282.59	€ 1,962,410.42	€ 2,180,728.10
4	Amsterdam	Karlsruhe	€ 1,320,359.25	€ 1,624,874.53	€ 1,845,648.10
5	Rotterdam	Basel	€ 1,249,570.80	€ 1,474,511.02	€ 1,637,592.68
7	Amsterdam	Antwerp	€ 1,191,958.85	€ 1,357,185.53	€ 1,476,974.87
9	Amsterdam	Rotterdam	€ 1,740,759.54	€ 2,110,242.55	€ 2,378,117.73
10	Antwerp	Mainz	€ 1,046,779.39	€ 1,234,375.55	€ 1,370,382.76
12	Antwerp	Duisburg	€ 1,285,040.33	€ 1,535,963.66	€ 1,717,883.07
13	Rotterdam	Duisburg	€ 532,027.27	€ 611,534.25	€ 669,176.81
14	Rotterdam	Ludwigshafen	€ 435,312.74	€ 496,797.66	€ 541,374.22
16	Rotterdam	Strassbourg	€ 561,888.20	€ 672,498.71	€ 752,691.32
18	Duisburg	Antwerp	€ 609,991.61	€ 774,699.49	€ 894,112.70
22	Rotterdam	Herne	€ 420,913.85	€ 467,947.97	€ 502,047.71
23	Dusseldorf	Antwerp	€ 592,168.70	€ 736,760.66	€ 841,589.84
25	Rotterdam	Duisburg	€ 441,015.37	€ 508,814.11	€ 557,968.20

Table 16: Total annual costs per representative journey (with low, average and high fuel price)

Annual costs SCR and SCR+DPF

In Table 17 the annual cost for the use of an SCR only and SCR + DPF are given based on the relevant vessel type operating on the representative journey.

	Port A	Port B	SCR only	SCR+DPF
1	Rotterdam	Duisburg	€ 162,696.70	€ 278,188.69
2	Rotterdam	Antwerp	€ 46,260.16	€ 76,417.22
3	Rotterdam	Karlsruhe	€ 41,283.62	€ 67,393.18
4	Amsterdam	Karlsruhe	€ 65,232.16	€ 101,273.97
5	Rotterdam	Basel	€ 56,278.61	€ 89,543.20
7	Amsterdam	Antwerp	€ 49,559.82	€ 80,740.37
9	Amsterdam	Rotterdam	€ 46,337.09	€ 74,832.29
10	Antwerp	Mainz	€ 37,394.44	€ 55,275.54
12	Antwerp	Duisburg	€ 59,202.16	€ 93,373.57
13	Rotterdam	Duisburg	€ 15,996.16	€ 25,107.06
14	Rotterdam	Ludwigshafen	€ 12,705.51	€ 19,649.27
16	Rotterdam	Strassbourg	€ 19,495.83	€ 29,692.27
18	Duisburg	Antwerp	€ 25,582.71	€ 37,667.17
22	Rotterdam	Herne	€ 10,522.02	€ 15,707.08
23	Dusseldorf	Antwerp	€ 23,319.33	€ 34,701.73
25	Rotterdam	Duisburg	€ 12,858.39	€ 18,768.15

Table 17: Annual costs for SCR only and SCR+DPF per representative journey

These costs are without the benefit of the discount on the port dues, that in one or both of the ports of these journeys can be achieved for a vessel with low air pollutant emissions. The benefits in terms of lower port dues are given in Table 18, based on the regulation in the particular port and taken as a discount on the calculated port dues for the representative journeys.

	Port A	Port B	Benefit on port dues Port A	Benefit on port dues Port B	Average annual benefit on port dues
1	Rotterdam	Duisburg	36.4%	0.0%	€ 14,318.08
2	Rotterdam	Antwerp	36.4%	7.0%	€ 8,273.93
3	Rotterdam	Karlsruhe	30.0%	0.0%	€ 4,113.25
4	Amsterdam	Karlsruhe	15.0%	0.0%	€ 2,676.80
5	Rotterdam	Basel	36.4%	0.0%	€ 7,268.98
7	Amsterdam	Antwerp	15.0%	7.0%	€ 3,903.69
9	Amsterdam	Rotterdam	15.0%	30.0%	€ 9,580.71
10	Antwerp	Mainz	7.0%	0.0%	€ 727.65
12	Antwerp	Duisburg	7.0%	0.0%	€ 1,793.55
13	Rotterdam	Duisburg	36.4%	0.0%	€ 3,800.68
14	Rotterdam	Ludwigshafen	36.4%	0.0%	€ 2,147.71
16	Rotterdam	Strassbourg	36.4%	0.0%	€ 3,890.17
18	Duisburg	Antwerp	0.0%	7.0%	€ 665.16
22	Rotterdam	Herne	36.4%	0.0%	€ 1,945.72
23	Dusseldorf	Antwerp	0.0%	7.0%	€ 670.98
25	Rotterdam	Duisburg	36.4%	0.0%	€ 2,196.29

Table 18: Benefit by the discount on the port dues per representative journey

On average almost 14% discount on the port dues can be achieved if applying SCR or SCR+DPF compared to the normal situation, resulting in the net annual costs given in Table 19.

	Net annual cost and percentage covered by discount on port dues					
	Port A	Port B	SCR only	SCR only, % covered by port dues	SCR+DPF	SCR+DPF, % covered by port dues
1	Rotterdam	Duisburg	€ 148,378.62	9%	€ 263,870.61	5%
2	Rotterdam	Antwerp	€ 37,986.23	18%	€ 68,143.29	11%
3	Rotterdam	Karlsruhe	€ 37,170.37	10%	€ 63,279.93	6%
4	Amsterdam	Karlsruhe	€ 62,555.37	4%	€ 98,597.17	3%
5	Rotterdam	Basel	€ 49,009.63	13%	€ 82,274.22	8%
7	Amsterdam	Antwerp	€ 45,656.13	8%	€ 76,836.68	5%
9	Amsterdam	Rotterdam	€ 36,756.38	21%	€ 65,251.58	13%
10	Antwerp	Mainz	€ 36,666.79	2%	€ 54,547.89	1%
12	Antwerp	Duisburg	€ 57,408.61	3%	€ 91,580.02	2%
13	Rotterdam	Duisburg	€ 12,195.47	24%	€ 21,306.38	15%
14	Rotterdam	Ludwigshafen	€ 10,557.80	17%	€ 17,501.55	11%
16	Rotterdam	Strassbourg	€ 15,605.66	20%	€ 25,802.10	13%
18	Duisburg	Antwerp	€ 24,917.55	3%	€ 37,002.02	2%
22	Rotterdam	Herne	€ 8,576.29	18%	€ 13,761.36	12%
23	Dusseldorf	Antwerp	€ 22,648.34	3%	€ 34,030.75	2%
25	Rotterdam	Duisburg	€ 10,662.10	17%	€ 16,571.86	12%

Table 19: Net annual costs for SCR-only and SCR+DPF (after discount on the port dues) and percentage of annual costs covered by discount on port dues

For SCR-only and SCR+DPF on average respectively 12% and 8% of the costs can be covered by the discount on the port dues. For journey 13 (Rotterdam-Duisburg, motor vessel 110 m with containers) even respectively 24% and 15% of the annual costs of applying after-treatment can be covered by the discount on the port dues.

Effects of the application of SCR and SCR+DPF

Based on the net annual costs (in which the discount on the port dues is included), the effects of the application of SCR and SCR+DPF are calculated. In *Table 20* the increase of the annual costs compared to the base line costs of transport are given. For the base line costs of transport, the average costs are used for the representative journeys, as is given in *Table 16*.

	Selected representative journeys Rhine / ARA		Increase in annual costs (%)	
	Port A	Port B	SCR only	SCR+DPF
1	Rotterdam	Duisburg	3.6%	6.4%
2	Rotterdam	Antwerp	2.9%	5.2%
3	Rotterdam	Karlsruhe	1.9%	3.2%
4	Amsterdam	Karlsruhe	3.8%	6.1%
5	Rotterdam	Basel	3.3%	5.6%
7	Amsterdam	Antwerp	3.4%	5.7%
9	Amsterdam	Rotterdam	1.7%	3.1%
10	Antwerp	Mainz	3.0%	4.4%
12	Antwerp	Duisburg	3.7%	6.0%
13	Rotterdam	Duisburg	2.0%	3.5%
14	Rotterdam	Ludwigshafen	2.1%	3.5%
16	Rotterdam	Strassbourg	2.3%	3.8%
18	Duisburg	Antwerp	3.2%	4.8%
22	Rotterdam	Herne	1.8%	2.9%
23	Dusseldorf	Antwerp	3.1%	4.6%
25	Rotterdam	Duisburg	2.1%	3.3%

Table 20: Annual cost increase SCR-only and SCR+DPF as percentage of total annual costs (based on average)

The increase in annual costs by applying only SCR is at least 1.7% (for journey 9, Amsterdam-Rotterdam, motor tank vessel of 135m with oil) and can go up to 3.8% (for journey 4, Amsterdam-Karlsruhe, coupled convoys with coal) and respectively 3.1% and 6.4% (for journey 1, Rotterdam-Duisburg, pusher with 4 barges with ore) if SCR+DPF is applied. For the representative journeys also the extra costs per tonne transported are calculated. This is given in Table 21, based on dividing the annual costs of SCR and SCR+DPF by the tonnes carried during a year (which is calculated by the average payload carried multiplied by the number of trips performed within a year).

	Selected representative journeys Rhine / ARA		Total (base line) costs per tonne	Total extra cost per tonne (including discount on port dues)	
	Port A	Port B	Average	SCR only	SCR+DPF
1	Rotterdam	Duisburg	€ 2.06	€ 0.07	€ 0.13
2	Rotterdam	Antwerp	€ 2.78	€ 0.08	€ 0.15
3	Rotterdam	Karlsruhe	€ 11.41	€ 0.22	€ 0.37
4	Amsterdam	Karlsruhe	€ 7.54	€ 0.29	€ 0.46
5	Rotterdam	Basel	€ 9.53	€ 0.32	€ 0.53
7	Amsterdam	Antwerp	€ 2.86	€ 0.10	€ 0.16
9	Amsterdam	Rotterdam	€ 1.52	€ 0.03	€ 0.05
10	Antwerp	Mainz	€ 7.18	€ 0.21	€ 0.32
12	Antwerp	Duisburg	€ 2.78	€ 0.10	€ 0.17
13	Rotterdam	Duisburg	€ 4.55	€ 0.09	€ 0.16
14	Rotterdam	Ludwigshafen	€ 15.67	€ 0.33	€ 0.55
16	Rotterdam	Strasbourg	€ 13.25	€ 0.31	€ 0.51
18	Duisburg	Antwerp	€ 5.66	€ 0.18	€ 0.27
22	Rotterdam	Herne	€ 7.86	€ 0.14	€ 0.23
23	Dusseldorf	Antwerp	€ 6.13	€ 0.19	€ 0.28
25	Rotterdam	Duisburg	€ 6.23	€ 0.13	€ 0.20

Table 21: Costs per tonne for the representative journeys including extra costs per tonne for SCR-only and SCR+DPF

The extra costs of applying SCR and SCR+DPF can go up to respectively € 0.33 and € 0.55 per tonne transported. This is for journey 14 (Rotterdam-Ludwigshafen, motor tank vessel 86m with chemicals), which has also the highest base line costs per tonne.

To get insight into the height of the costs relatively to the environmental benefits achieved by applying SCR and SCR+DPF, Table 22 shows the costs for SCR per kg NOx reduced and the additional costs for DPF per kg PM reduced. Important is to take into account that the environmental benefits of a kg NOx and a kg PM reduced are not the same.

	Selected representative journeys Rhine / ARA		Cost per kg NOx and PM reduction	
	Port A	**Port B**	**SCR Costs/kg NOx reduction**	**DPF Costs/kg PM reduction**
1	Rotterdam	Duisburg	€ 0.99	€ 41.50
2	Rotterdam	Antwerp	€ 1.87	€ 80.42
3	Rotterdam	Karlsruhe	€ 1.59	€ 31.42
4	Amsterdam	Karlsruhe	€ 1.38	€ 42.90
5	Rotterdam	Basel	€ 1.46	€ 53.60
7	Amsterdam	Antwerp	€ 1.85	€ 68.39
9	Amsterdam	Rotterdam	€ 1.28	€ 27.95
10	Antwerp	Mainz	€ 1.31	€ 34.54
12	Antwerp	Duisburg	€ 1.53	€ 49.36
13	Rotterdam	Duisburg	€ 1.03	€ 41.53
14	Rotterdam	Ludwigshafen	€ 1.15	€ 40.93
16	Rotterdam	Strasbourg	€ 0.95	€ 33.41
18	Duisburg	Antwerp	€ 1.01	€ 26.59
22	Rotterdam	Herne	€ 1.22	€ 39.95
23	Dusseldorf	Antwerp	€ 1.05	€ 28.53
25	Rotterdam	Duisburg	€ 1.05	€ 31.59

Table 22: Costs for SCR per kg NOx reduction and additional costs for DPF per kg PM-reduction

The costs for SCR per kg NOx reduction are in general lower than those shown in the calculation per vessel types. These range from € 0.95 (journey 16, Rotterdam-Strasbourg, a motor vessel 110m with agribulk) up to €1.87 (journey 2, Rotterdam-Antwerp, coupled convoy with containers). The additional costs for DPF per kg PM reduction range between €26.59 and € 80.42.

3.3 Danube journeys

In line with the vessel types identified for the representative journeys in Deliverable 1.1, there have been two vessel types used for the Danube, a push boat with 4 barges and a push boat with 8/9 barges. The push boat with 4 barges is used on the journey between Bratislava and Linz, for the other 9 journeys the push boat with 8/9 barges is used. As the analysis of the construction year and speed of the engines in Deliverable 1.1 were made for the Western European fleet, the most common engine has been defined based on the engine information of the push boats of NAVROM. An overview is included in Annex A4 of Deliverable 1.1, all of the push boats are equipped with high speed engines.

	Selected representative journeys Danube						**Most common engine**	
	Port A	**Port B**	**Type**	**Vessel type**	**Commodity**	**mln tkm**	**Type**	**Speed**
1	Bor district	Constanza	Dry bulk	Push 8/9	Agribulk	972	CCR1	High
2	Bor district	Constanza	Liquid Bulk	Push 8/9	Petroleum products	725	CCR1	High
3	Constanza	Dunaújváros	Dry bulk	Push 8/9	Coal	682	CCR1	High
4	Giurgiu	Constanza	Dry bulk	Push 8/9	Building mat. / minerals	537	CCR1	High
5	Calafat	Constanza	Dry bulk	Push 8/9	Building mat. / minerals	337	CCR1	High
6	Bratislava	Linz	Dry bulk	Push 4	Ores	271	CCR1	High
7	Calafat	Constanza	Dry bulk	Push 8/9	Agribulk	237	CCR1	High
8	Constanza	Dunaújváros	Dry bulk	Push 8/9	Agribulk	216	CCR1	High
9	Giurgiu	Constanza	Dry bulk	Push 8/9	Agribulk	143	CCR1	High
10	Giurgiu	Constanza	Dry bulk	Push 8/9	Ores	118	CCR1	High

Table 23: Selected representative journeys Danube with most common engine

For each of these representative journeys the total general costs per year are calculated, based on the cost calculation performed for the two relevant vessel types. Also for these journeys fuel costs were calculated with the low, average and high fuel price scenarios. This can range up to almost € 700,000 cost differences between the low and high fuel price scenarios. The total costs are given in Table 24 and the further costs specification can be found in Annex A4.

	Port A	**Port B**	**Total costs (low)**	**Total costs (average)**	**Total costs (high)**
1	Bor district	Constanza	€ 1,674,781.53	€ 2,072,945.48	€ 2,361,614.34
2	Bor district	Constanza	€ 1,674,781.53	€ 2,072,945.48	€ 2,361,614.34
3	Constanza	Dunaújváros	€ 1,635,969.03	€ 1,992,120.29	€ 2,250,329.95
4	Giurgiu	Constanza	€ 1,532,660.74	€ 1,776,985.68	€ 1,954,121.26
5	Calafat	Constanza	€ 1,675,086.86	€ 2,073,581.30	€ 2,362,489.77
6	Bratislava	Linz	€ 1,289,201.70	€ 1,681,634.44	€ 1,966,148.18
7	Calafat	Constanza	€ 1,675,086.86	€ 2,073,581.30	€ 2,362,489.77
8	Constanza	Dunaújváros	€ 1,635,969.03	€ 1,992,120.29	€ 2,250,329.95
9	Giurgiu	Constanza	€ 1,532,660.74	€ 1,776,985.68	€ 1,954,121.26
10	Giurgiu	Constanza	€ 1,532,660.74	€ 1,776,985.68	€ 1,954,121.26

Table 24: Total annual costs per representative journey (with low, average and high fuel price)

Annual costs SCR and SCR+DPF

In *Table 25* the annual cost for the use of an SCR only and SCR + DPF are given based on the relevant vessel type operating on the representative journey and with a correction based on the calculated fuel consumption and kWh.

	Port A	Port B	SCR only	SCR+DPF
1	Bor district	Constanza	€ 68,747.10	€ 101,833.77
2	Bor district	Constanza	€ 68,747.10	€ 101,833.77
3	Constanza	Dunaújváros	€ 64,019.96	€ 95,640.36
4	Giurgiu	Constanza	€ 51,437.59	€ 79,155.20
5	Calafat	Constanza	€ 68,784.29	€ 101,882.50
6	Bratislava	Linz	€ 67,997.21	€ 105,437.36
7	Calafat	Constanza	€ 68,784.29	€ 101,882.50
8	Constanza	Dunaújváros	€ 64,019.96	€ 95,640.36
9	Giurgiu	Constanza	€ 51,437.59	€ 79,155.20
10	Giurgiu	Constanza	€ 51,437.59	€ 79,155.20

Table 25: Annual costs for SCR only and SCR+DPF per representative journey

Effects of the application of SCR and SCR+DPF

As there are no benefits known on the port dues for vessels with low-emission engines, these annual costs are also used in calculating the effects. In *Table 26* the increase of the annual costs compared to the base line costs of transport are given. For the base line costs of transport, the average costs are used for the representative journeys, as is given in *Table 24*.

	Port A	Port B	SCR only	SCR+DPF
1	Bor district	Constanza	3.3%	4.9%
2	Bor district	Constanza	3.3%	4.9%
3	Constanza	Dunaújváros	3.2%	4.8%
4	Giurgiu	Constanza	2.9%	4.5%
5	Calafat	Constanza	3.3%	4.9%
6	Bratislava	Linz	4.0%	6.3%
7	Calafat	Constanza	3.3%	4.9%
8	Constanza	Dunaújváros	3.2%	4.8%
9	Giurgiu	Constanza	2.9%	4.5%
10	Giurgiu	Constanza	2.9%	4.5%

Table 26: Annual cost increase SCR-only and SCR+DPF as percentage of total annual costs (based on average)

The table shows that the cost increase is between 2.9% (Giurgiu-Constanta) and 4% (Bratislava-Linz) for SCR-only and between 4.5% and 6.3% for the application of SCR+DPF.

The total extra costs of the application SCR and SCR+DPF are also calculated per tonne cargo transported. These costs are given in *Table 27*, together with the average total costs of transport per tonne.

	Port A	Port B	Total costs per tonne (avg)	SCR only	SCR+DPF
1	Bor district	Constanza	€ 4.87	€ 0.16	€ 0.24
2	Bor district	Constanza	€ 3.65	€ 0.12	€ 0.18
3	Constanza	Dunaújváros	€ 9.13	€ 0.29	€ 0.44
4	Giurgiu	Constanza	€ 2.36	€ 0.07	€ 0.11
5	Calafat	Constanza	€ 4.45	€ 0.15	€ 0.22
6	Bratislava	Linz	€ 2.61	€ 0.11	€ 0.16
7	Calafat	Constanza	€ 4.45	€ 0.15	€ 0.22
8	Constanza	Dunaújváros	€ 9.13	€ 0.29	€ 0.44
9	Giurgiu	Constanza	€ 2.36	€ 0.07	€ 0.11
10	Giurgiu	Constanza	€ 2.36	€ 0.07	€ 0.11

Table 27: Costs per tonne for the representative journeys including extra costs per tonne for SCR-only and SCR+DPF

The extra costs for applying SCR range between € 0.07 and € 0.29 per tonne transported and for SCR+DPF between € 0.11 and € 0.44. To get insight into the height of the costs relatively to the environmental benefits achieved by applying SCR and SCR+DPF, *Table 28* shows the costs for SCR per kg NOx reduced and the additional costs for DPF per kg PM reduced.

	Port A	Port B	SCR Costs/kg NOx reduction	DPF Costs/kg PM reduction
1	Bor district	Constanza	€ 1.16	€ 30.12
2	Bor district	Constanza	€ 1.16	€ 30.12
3	Constanza	Dunaújváros	€ 1.21	€ 32.18
4	Giurgiu	Constanza	€ 1.41	€ 41.11
5	Calafat	Constanza	€ 1.16	€ 30.10
6	Bratislava	Linz	€ 1.16	€ 34.58
7	Calafat	Constanza	€ 1.16	€ 30.10
8	Constanza	Dunaújváros	€ 1.21	€ 32.18
9	Giurgiu	Constanza	€ 1.41	€ 41.11
10	Giurgiu	Constanza	€ 1.41	€ 41.11

Table 28: Costs for SCR per kg NOx reduction and additional costs for DPF per kg PM-reduction

Although the annual costs and the costs per tonne for applying SCR and SCR+DPF are the lowest for the journey Giurgiu-Constanta, the costs per NOx and PM reduction are the highest for this journey compared to the other Danube journeys. The costs per NOx and PM reduction are the lowest for the journeys between Calafat/Bor district and Constanta.

3.4 Journeys on other waterways

In Deliverable 1.1 for the other waterways for four representative journeys the operational profiles were elaborated. These journeys are given in *Table 29* with the most common engines used in these particular vessel types.

	Selected representative journeys Other Waterways							Most common engine	
	Port A	Port B	Type	Vessel type	CEMT Class	Commo-dity	mln tkm	Type	Speed
7	Rotterdam	Hannover	Dry Bulk	MVS 86m	IV	Agribulk		CCR1	High
8	Duisburg	Wolfsburg	General goods	MVS 86m	IV	Steel coils		CCR1	High
16	Rotterdam	Oldenburg	Dry Bulk	MVS 80m	III / IVa	Animal Fodder	335	CCR1	High
17	Rotterdam	Lingen	Liquid Bulk	MTS 86m	IV	Oil		CCR1	High

Table 29: Selected representative journeys other waterways with most common engine

The base line costs of transport were not calculated for these journeys, except for the fuel costs, which were based on the operational profiles. An overview of these journeys can be found in Annex A5. The annual costs of the application of SCR and SCR+DPF on vessel types operating on these journeys has been calculated and are given in *Table 30*.

	Selected representative journeys Other Waterways		Annual cost	
	Port A	Port B	SCR only	SCR+DPF
7	Rotterdam	Hannover	€ 10,983.50	€ 16,311.71
8	Duisburg	Wolfsburg	€ 8,819.05	€ 13,475.89
16	Rotterdam	Oldenburg	€ 7,382.32	€ 11,320.61
17	Rotterdam	Lingen	€ 10,847.09	€ 17,214.39

Table 30: Annual costs for SCR only and SCR+DPF per representative journey

To give an impression what these extra costs mean for the transport price, these extra costs are also calculated per tonne transported and given in *Table 31*.

	Selected representative journeys Other Waterways		Total extra costs per tonne	
	Port A	Port B	SCR only	SCR+DPF
7	Rotterdam	Hannover	€ 0.32	€ 0.48
8	Duisburg	Wolfsburg	€ 0.23	€ 0.35
16	Rotterdam	Oldenburg	€ 0.27	€ 0.41
17	Rotterdam	Lingen	€ 0.23	€ 0.37

Table 31: Extra costs per tonne for SCR-only and SCR+DPF for the representative journeys

These extra costs are between 23 and 27 eurocent per tonne for the application of only SCR and between 35 and 48 eurocent for applying SCR+DPF. Also for the four representative journeys on the other waterways the costs are compared with the environmental benefits of reducing NOx and PM emissions. In *Table 32* the costs per kg NOx and PM reduction are given.

	Selected representative journeys Other Waterways		Costs per kg NOx and PM reduction	
	Port A	**Port B**	**SCR Costs/kg NOx reduction**	**DPF Costs/kg PM reduction**
7	Rotterdam	Hannover	€ 1.44	€ 37.76
8	Duisburg	Wolfsburg	€ 1.85	€ 52.91
16	Rotterdam	Oldenburg	€ 1.90	€ 54.91
17	Rotterdam	Lingen	€ 1.62	€ 51.32

Table 32: Costs for SCR per kg NOx reduction and additional costs for DPF per kg PM-reduction

3.5 Passenger journeys

For the representative passenger journeys two journeys are selected, representing the main sailing areas Rhine/ARA and (Upper) Danube. These journeys can be seen in *Table 33* with the most common engine for passenger vessels. A more detailed overview is included in Annex A5.

	Waterway	Selected representative journeys					Most common engine	
		Port A	Port B	Vessel type	CEMT Class	Commodity	Type	Speed
1	ARA/Rhine	Amsterdam	Basel	PAX 135m	VI	Passengers	CCR1	High
3	Danube	Passau	Budapest	PAX 135m	VI	Passengers	CCR1	High

Table 33: Selected representative passenger journeys with most common engine

For these journeys only the fuel costs have been calculated, based on the operational profiles. The normal cost structure of passenger vessels can be found in paragraph 3.1.

	Waterway	Selected representative journeys		Annual cost	
		Port A	Port B	SCR only	SCR+DPF
1	ARA/Rhine	Amsterdam	Basel	€ 27,506.06	€ 41,908.41
3	Danube	Passau	Budapest	€ 27,506.06	€ 41,908.41

Table 34: Annual costs for SCR only and SCR+DPF per representative journey

For the freight transport journeys, the costs were calculated per tonne transported. As this is not possible for passenger journeys and for example the average number of passengers is not known, for the passenger journeys these annual costs are calculated per trip.

	Waterway	Selected representative journeys		Total extra costs per trip	
		Port A	Port B	SCR only	SCR+DPF
1	ARA/Rhine	Amsterdam	Basel	€ 2,223.16	€ 3,387.22
3	Danube	Passau	Budapest	€ 1,821.85	€ 2,775.78

Table 35: Extra costs per trip for SCR-only and SCR+DPF for the representative journeys

These costs have also been calculated per kg NOx reduction for the application of SCR and per kg PM reduction for the additional costs of applying DPF.

	Waterway	Selected representative journeys		Costs per kg NOx and PM reduction	
		Port A	Port B	SCR Costs/kg NOx reduction	DPF Costs/kg PM reduction
1	ARA/Rhine	Amsterdam	Basel	€ 2.97	€ 84.03
3	Danube	Passau	Budapest	€ 3.82	€ 108.16

Table 36: Costs for SCR per kg NOx reduction and additional costs for DPF per kg PM-reduction

Conclusions and recommendations

This analysis shows as a first calculation of the costs and benefits of the application some figures about the economic feasibility of the application of after-treatment. As already concluded in Deliverable 1.2, with the application of SCR and DPF it is possible to achieve a major reduction of air pollutant emissions. However, this reduction comes with a price, as there are no benefits covering the entire costs of the application.

Annual costs SCR and SCR+DPF: Highly dependent on vessel type and engine type

In this analysis the annual costs were calculated for 22 different vessel types, these absolute costs are influenced by a number of factors, such as the fuel consumption, the number and size of the engines (in installed power), the power used in normal conditions and the engine hours. This results in annual costs of applying SCR of maximum around 30,000 euro for the regular motor cargo vessels with CCNR Stage-I engines, which mostly depends on the size of the vessel (e.g. for a 38.5 metre motor vessel, the annual costs amount € 4,521). At the other side, for the coupled convoys and especially the larger pushed convoys, these costs can range from around € 47,000 to around € 117,000. For vessels with CCNR Stage-II approved engines, the annual costs of applying SCR can be 5-22% lower than with CCNR Stage-I or non-type approved engines.

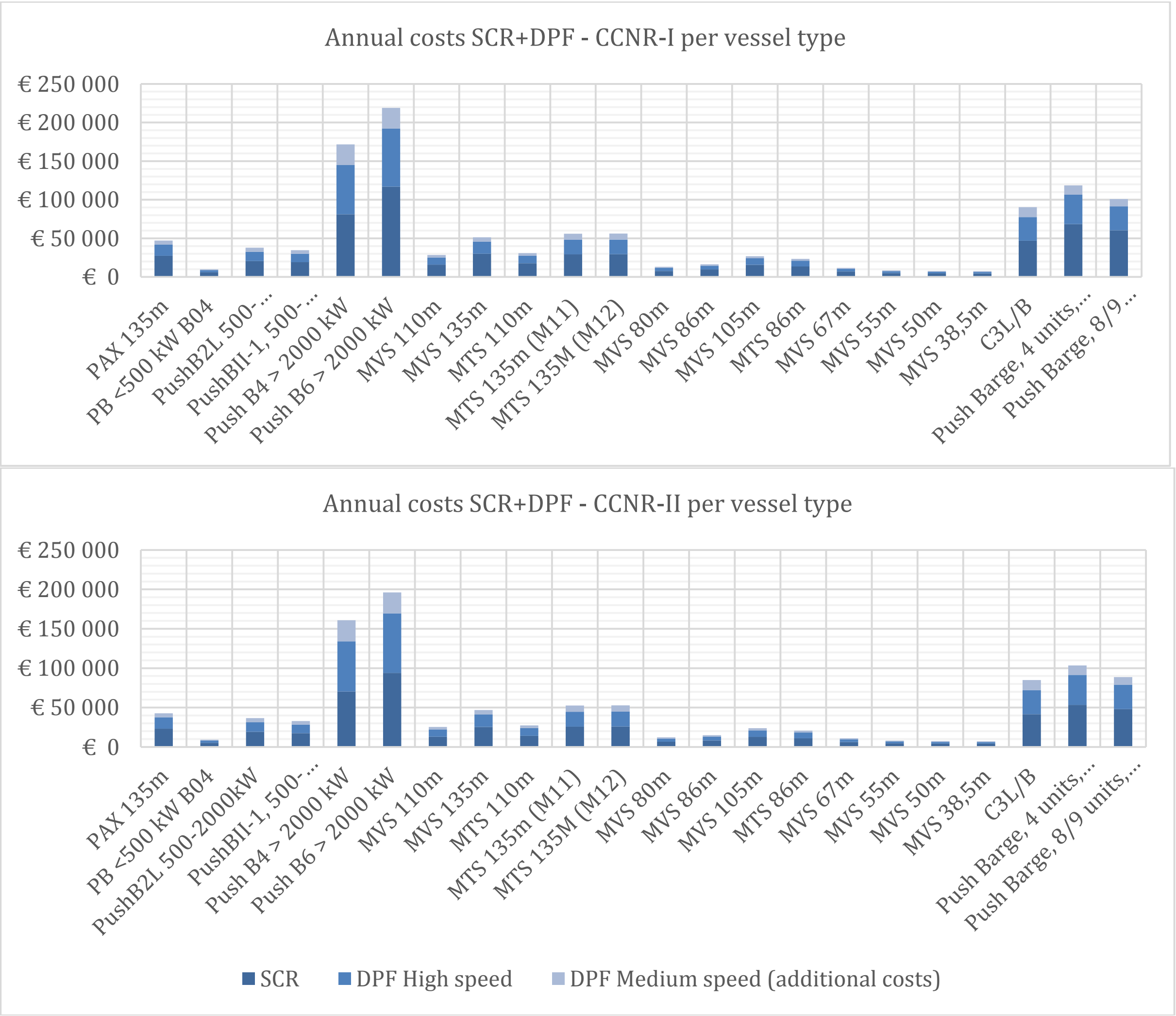

Figure 8: Annual costs SCR+DPF per vessel type for CCNR Stage-I and CCNR Stage-II engines (with the costs of SCR in dark blue, of DPF for high speed in medium blue and DPF for medium speed in light blue)

For the application of SCR and DPF, the annual costs can be 45% to 91% higher for high-speed engines than the annual costs for the application of only SCR. Due to the higher investment costs for the filter, this is even higher for the medium-speed engines (between 64% and 129%). The annual costs can go up to € 219,000 for a pusher with 6 barges and medium-speed CCNR Stage-I engines, which is according to the report of D1.1 the most common engine used in this fleet family.

Relative cost increase of applying SCR and SCR+DPF compared to base line costs

There are major differences between vessel types and engine types in absolute annual costs for the application. To show the business case in relation with the general costs a ship-owning company has in operating a vessel, the relative cost increase of the application of SCR and SCR+DPF has also been calculated. For application of SCR this cost increase is on average around 2.4% (for CCNR Stage-II engines) and 2.8% (for CCNR Stage-I engines).

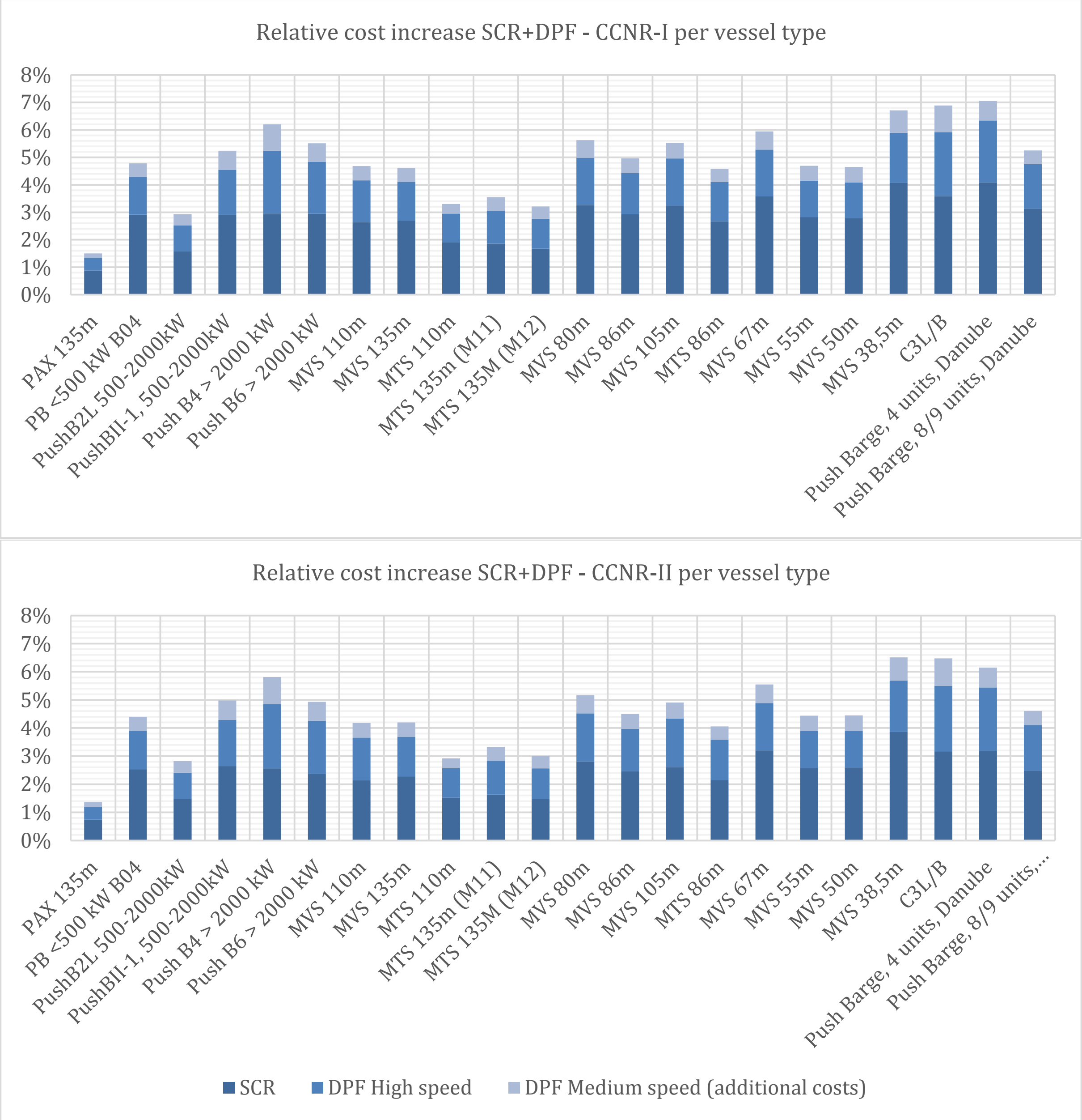

Figure 9: Relative cost increase SCR+DPF per vessel type for CCNR Stage-I and CCNR Stage-II engines (with the costs of SCR in dark blue, of DPF for high speed in medium blue and DPF for medium speed in light blue)

For SCR+DPF this is on average around 3.9% (for CCNR Stage-II, high speed) to 4.9% (for CCNR Stage-I, medium speed). For some vessel types, like passenger vessels, this is even much lower (1.3% for applying SCR+DPF on a CCNR Stage-I high speed engine, the most common engine). The cost increase for the larger motor tank vessels is also relatively low, especially taking into account that many of these vessels have CCNR Stage-II engines. At the other side, for the Danube push boats with four barges, this can be around 6.3% for SCR-DPF on the most common engine (CCNR Stage-I high speed engine). In lesser extent, this counts also for the coupled convoys, the other push boats with high installed power, but also for some smaller vessel types (e.g. motor vessel 38.5m).

The same conclusions can be seen in the outcomes for the representative journeys. Because of the high relative costs for the Danube push boats, this is also relatively high for the Danube journeys. On the Rhine journeys most of the ship-owning companies can benefit from the discount on the port dues, which covers in the most positive situation (journey 13, motor vessel 110 m with containers, between Rotterdam and Duisburg) for 15% (SCR+DPF) and 24% (SCR-only) of the extra annual costs, resulting in a net annual cost increase of 2% (SCR+DPF) and 3.5% (SCR-only). For journey 9 (motor tank vessel, 135m, between Amsterdam and Rotterdam with oil) this cost increase is the lowest with respectively 1.7% and 3.1%.

Relative costs SCR and SCR+DPF per tonne cargo transported

Journey 9 of the Rhine journeys has also the most positive business case, if expressed as costs per tonne cargo transported, € 0.03 and € 0.05 for respectively SCR-only and SCR+DPF. Although the annual costs for applying it on a push boat, the costs per tonne cargo transported is also relatively low for journey 1 of the Rhine journeys (push boat Rotterdam-Duisburg). Due to the high payload carried, this is respectively € 0.07 and € 0.13. Although the discount on the port dues reduces the net annual costs of applying SCR and SCR+DPF for the Rhine journeys, there is not a big difference between the average costs per tonne cargo transported for the Rhine and Danube journeys. For the Danube journeys these costs are between € 0.07 and € 0.29 for SCR and between € 0.11 and € 0.44 for SCR+DPF. For the journeys on the other waterways these costs are higher (between € 0.23 and € 0.32 for SCR and between € 0.35 and € 0.48 for SCR+DPF), because of the low average payload.

Relative costs SCR and SCR+DPF compared to environmental benefits

As SCR and DPF is effective in reducing NOx and PM emissions, making it possible to achieve emission levels proposed for new emission standards (EU NRMM Stage-V). For that reason, the choice have been made to express the annual costs of applying SCR and – in combination with – DPF as costs per kg NOx and PM reduction. This shows that although the annual costs of applying SCR on a CCNR Stage-I engine is higher than on a CCNR Stage-II engine, the costs per kg NOx-reduction are lower. For the CCNR Stage-I engines these costs range from € 1.12 (a Danube push boat with 4 barges) to € 5.04 (MVS 38.5m) and respectively € 1.68 to € 9.23 for the same vessel types with CCNR Stage-II engines. These costs are lower for some of the Rhine/ARA journeys, because of the discount on the port dues, ranging from € 0.99 to € 1.87 for SCR-only. For the Danube journeys these costs are between € 1.16 and € 1.41 per kg NOx reduction, for the journeys on the other waterways between € 1.44 and € 1.90 and relatively high for the passenger journeys (€ 2,97 and € 3.82).

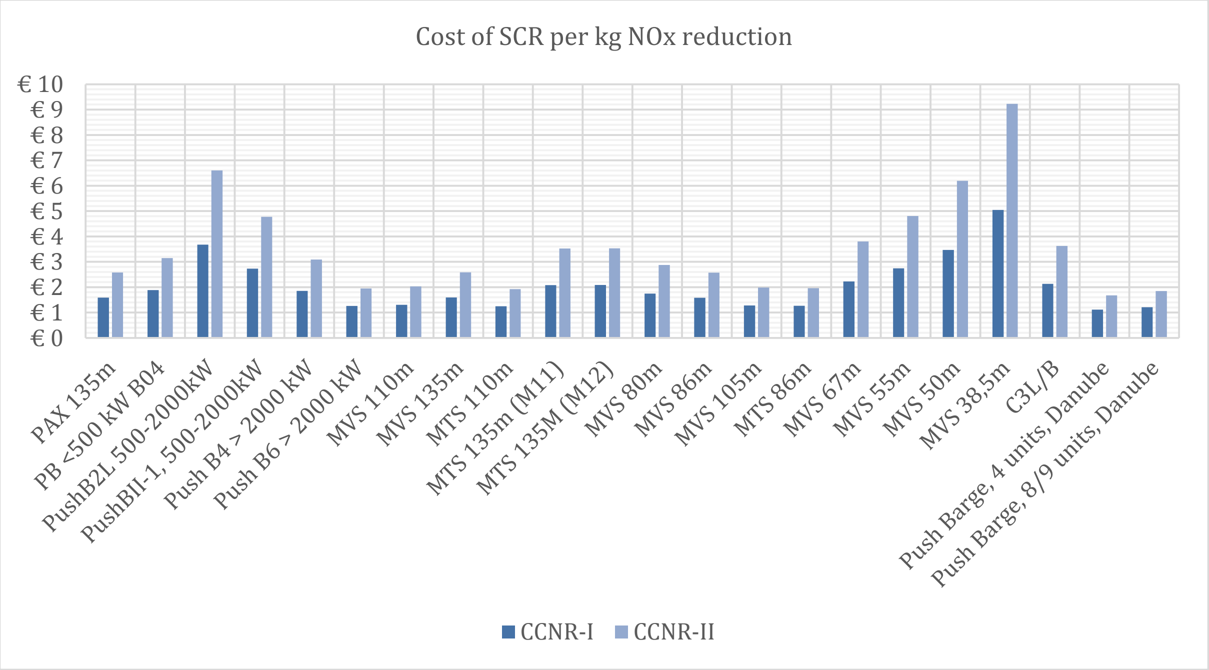

Figure 10: Costs of SCR per kg NOx reduction for CCNR Stage-I (dark blue) and CCNR Stage-II (medium blue)

For the additional costs for applying a DPF on an SCR system, the costs are calculated per kg PM emissions. This ranges from € 33.36 (Danube push boat with 8/9 barges) to € 122.50 (MVS 38.5m) for high-speed engines and € 43.72 to € 177.43 for the same vessel types with medium-speed engines. The costs compared to the emission reduction are relatively high for the smaller motor cargo vessels (38.5m and 50m) and the push boats with 500-2,000kW installed power. The most positive case compared to the emission reduction is for the Danube push boats, the medium large motor cargo vessels (105m and 110m) and motor tank vessels (86m and 110m) and the passenger vessels.

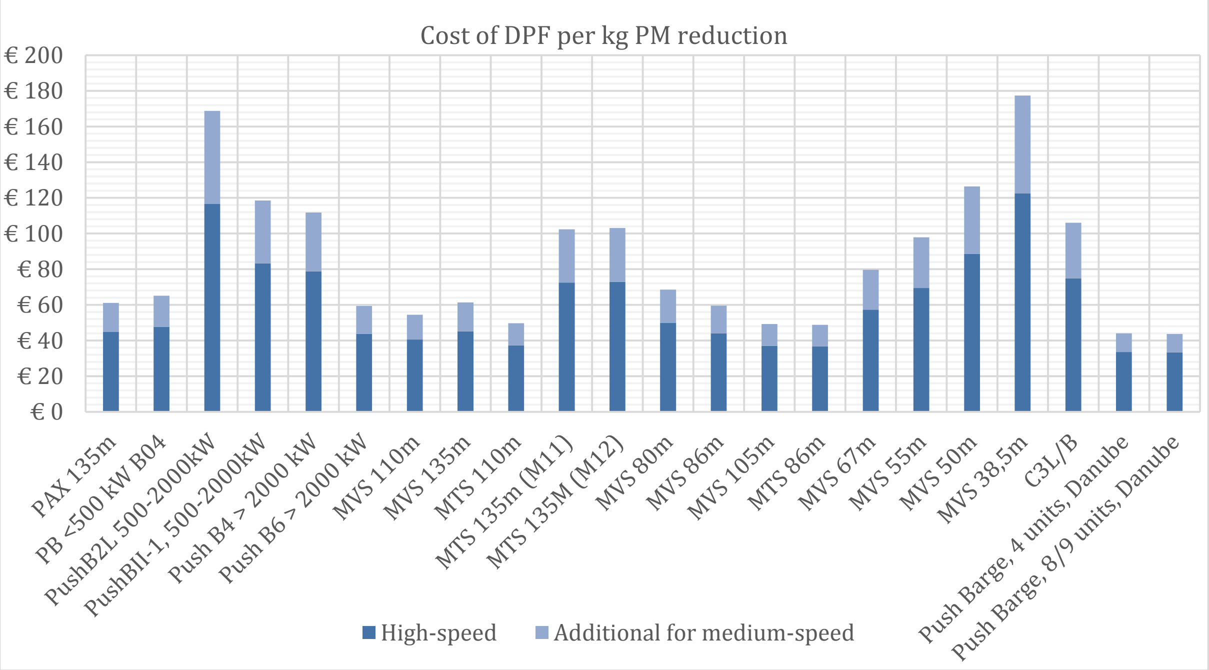

Figure 11: Costs of DPF per kg PM reduction for high-speed (medium blue) and additional costs for medium-speed engines light blue)

Recommendation: Comparing costs per units of emission reduction with external cost reduction
Before drawing conclusions on the application of only SCR or also DPF based on the costs per kilogram NOx and PM emission, it is important to notice that one kilogram of NOx and one kilogram of PM are not equal in external costs. To get a good insight into the effects of SCR and SCR+DPF, the costs of SCR/SCR+DPF per kg NOx or PM reduction could be compared with the external costs of a kg NOx or PM. There are several methodologies for calculating the external costs of transport, for example Handbook on estimation of external costs in the transport sector (CE Delft et al., 2008) and its update for 2008 (CE Delft et al., 2011). Taking 2008 as base year the external costs per tonnes are given in *Table 37* for the countries of the representative journeys.

Pollutant	**PM2.5 (exhaust)**			**PM10 (non-exhaust)**			**NOx**
Region type	**Metropolitan**	**Urban**	**Non-urban**	**Metropolitan**	**Urban**	**Non-urban**	
Source	**HEATCO**	**UBA/ HEATCO**	**HEATCO**	**HEATCO**	**UBA/ HEATCO**	**HEATCO**	**NEEDS**
Country							
Austria	€ 482,200	€ 155,900	€ 80,700	€ 192,900	€ 62,400	€ 32,300	€ 13,600
Belgium	€ 483,400	€ 156,000	€ 104,400	€ 193,400	€ 62,400	€ 41,700	€ 8,700
Bulgaria	€ 70,500	€ 22,700	€ 18,100	€ 28,200	€ 9,100	€ 7,200	€ 7,100
France	€ 438,600	€ 141,200	€ 87,700	€ 175,500	€ 56,500	€ 35,100	€ 10,500
Germany	€ 430,300	€ 138,800	€ 83,900	€ 172,100	€ 55,500	€ 33,600	€ 12,700
Hungary	€ 288,900	€ 93,000	€ 74,100	€ 115,600	€ 37,200	€ 29,600	€ 12,400
Netherlands	€ 485,000	€ 156,500	€ 94,800	€ 194,000	€ 62,600	€ 37,900	€ 8,800
Romania	€ 49,100	€ 15,800	€ 12,600	€ 19,700	€ 6,300	€ 5,000	€ 9,700
Slovakia	€ 293,900	€ 94,100	€ 79,400	€ 117,600	€ 37,600	€ 31,700	€ 11,000
Switzerland	€ 498,700	€ 160,500	€ 82,400	€ 199,500	€ 64,200	€ 33,000	€ 19,300

Table 37: External costs in €/tonne (CE Delft et al., 2011)

This shows that it is possible in many cases to achieve higher environmental benefits – measured in the reduction of external costs - than the costs for the application of SCR. Depending on the regular operating area mainly of the vessel (more densely populated regions or non-urban regions), this is also possible in some cases for the application DPF. Thus implying that the measure could be feasible from a societal perspective.

Recommendation: Validation of these calculations needed during the pilots
As this analysis shows a first calculation for the costs, benefit and effects of applying after-treatment on inland waterway vessel, the data should be validated during the activities in the PROMINENT project. The pilots will provide a valuable insight into not only the technical, but also the economic feasibility of applying after-treatment. In the pilots also the operational profile of the different vessel types and during the different journeys will be validated. The pilots and the validation among suppliers, end-users and other experts will be the basis of updating these data for the ex-post cost benefit analysis, which will be performed in WP6.

Possible fuel reduction by fuel optimisation of CCNR Stage-II engines
One potential benefit is not taken into consideration in this analysis, which is the possibility to improve the fuel consumption and PM emissions of a CCNR Stage-II and EU NRMM Stage III-a approved engines by allowing higher engine out NOx emissions. This is referred to as NOx-BSFC and NOx-PM trade-offs. The urea consumption for the CCNR II engine will usually increase up to the level of a CCNR I engine. But the fuel consumption reduction can be more or less equal to the urea consumption. This could mean a substantial annual benefit. However, this cannot be done without

obstacles, as the engine setting then needs to be changed and the original type approval is not valid any more.

Focus on the stimulation of environmental benefits in the policy recommendations

As this ex-ante cost effectiveness analysis shows that there is currently not yet a positive business case for the application of after-treatment, and that for assessing the effectiveness in reducing NOx and PM emissions, it is important to also take the external cost reduction into account. It will be an interesting focal point for the policy recommendations, if there is a possibility to monetise this environmental benefit of the application of SCR and SCR+DPF. One of the options is a discount on the port dues, which is already provided in some of the ports and included in this analysis under the representative journeys in the Rhine/ARA region.

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Annexes

A1. General costs per vessel type

A2. Costs for SCR/SCR+DPF per vessel type

A3. Costs Rhine/ARA journeys

A4. Costs Danube journeys

A5. Costs journeys other waterways and passenger vessels