Green Deal Validation study EMIGREEN

DPF and SCR technology for maritime applications

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Mobility & Built Environment
www.tno.nl
+31 88 866 00 00
info@tno.nl

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Author(s)	Thomas Frateur, Ruud Verbeek
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Contents

1 Introduction

1.1 General

1.1.1 Green deal

Firm objectives have been set by the IMO for reduction of emissions in the shipping industry, and the Dutch Green Deal aims to go one step further. The IMO agreements mean that the transport performance by seagoing vessels must improve to such an extent that CO_2 emissions per tonne-kilometre will be reduced by an average of 40-60% by 2030. The Green Deal aims for an absolute reduction of 70-100% in 2050 compared to 2008, regardless of market growth.

These ambitious goals call for solutions that can be applied today, because ships that are put into service today will most likely still be operational in 2050. The potential of available sustainable maritime solutions is great and is constantly expanding, but none of the available solutions is suitable for all ship types and in all operational conditions. The decision to opt for a sustainable solution also depends on the business case in which the ship must be able to operate. Currently there is a lack of objective information on the match between sustainable solutions and type of business case.

In addition to direct CO_2 emissions, the emissions of the greenhouse gases CH_4 and N_2O and air-polluting emissions such as NO_x, NH_3, SO_x and particulate matter are of great importance. The emissions of NO_x, SO_x and particulate matter from shipping are relatively high and are decreasing slowly due to insufficiently effective emission legislation and slow fleet renewal.

The diversity of available sustainable maritime solutions makes it difficult to determine which solution is most suitable for application on a ship as this depends on many factors. For example, each solution differs in the required space on board, the layout of the ship and integration with other systems, as well as for the costs and earning capacity of the ship itself. There is a large array of available sustainable solutions for various ship types, for various operational conditions and lengths of shipping routes. It is therefore important that the effects of these solutions are made transparent in an independent manner, and that through validation reliable information is collected so that these solutions can be weighed against each other (ref. NL Green Deal art.12 paragraph 3: “Knowledge institutions will work with the industry to provide independent insight into and validate the effects of the sustainable maritime solutions so that comparison of these solutions is possible and it is easier for shipowners and financiers to compare.”).

The results of the performed validations provide reliable information for all parties in the maritime chain, making it easier to choose sustainable solutions.

1.1.2 Validation process

Transparency towards all parties in the maritime chain (from ship owners, ship operators and other logistics operators, shippers, financiers, suppliers, shipyards, to government) is important in the implementation of these validations.

The sector itself is investigating which sustainable maritime solutions have the greatest potential to accelerate the energy transition. The technologies with the greatest potential are then validated at independent knowledge institutions. We call this form a cluster study; the sector is represented in this by KVNR and NMT, the knowledge institutions involved are MARIN and TNO, possibly supplemented by an external party if this is necessary for the implementation of a concrete validation case.

Transparency is achieved by making the results public through reports that present an overview of how the various sustainable maritime solutions, grouped by theme, perform in terms of social impact, technical impact and economic impact.

1.1.3 Green deal validation

The green deal validation program of the Ministry of Infrastructure and Water management (I&W) offers the opportunity to independently review reduction measures. The marine sector, represented by KVNR and NMT, plays an important role in putting forward the key solutions for GHG and pollutant reductions which can be implemented or scaled up in the near future. KVNR and NMT consult the sector (technology providers and ship owners) to identify the most important techniques to validate. Thereafter, the contacts are handed over to the knowledge institute that is most knowledgeable, which can also be both, making it a joint validation project.

The validation needs to include the following aspects:

- **Environmental impact**: impact on reduction of GHG and pollutant emissions
  This is the core of the validation: the provider claims an emission reduction technique, which is validated by an independent study.
- **Applicability** to the maritime fleet (categories)
  Related to the 6 reference ships identified in the Green Deal (See Table 4.1).
  Identifying possible opportunities and obstacles.
- **Technical impacts and Safety aspects;**
- **Economic aspects;**
- **Scalability and future proofness;**
  An expert opinion.

1.2 Technology specific introduction

The technologies under consideration in this validation are the diesel particulate filter (DPF) and selective catalytic reduction (SCR) technology for maritime applications.

The DPF is a filter technology designed to capture and remove particulate matter (PM) from the exhaust gases of diesel engines. They consist of a large housing with filter elements that trap particles as the exhaust gases pass through. To ensure filter loading does not result in clogging of the exhaust stack and that the filter remains effective, either active or passive regeneration is applied during use. In maritime applications, filters are capable of removing up to 97% [1]of organic particulate matter from the exhaust stack emissions.

Figure 1.1: A used wall-flow diesel particulate filter (DPF) filter elements taken out of the filter housing onboard a marine vessel.

The SCR is a catalytic technology designed to reduce nitrogen oxides (NO_x) emissions in the exhaust gasses of diesel engines. The SCR system works by injecting a reductant commonly known as AdBlue or Diesel Exhaust Fluid (DEF) into the exhaust gas stream. The reductant, often a urea-based solution, reacts with NO_x in in the catalyst to form mainly nitrogen (N_2) and water (H_2O). SCR systems can significantly reduce the NO_x emissions from the tailpipe of maritime vessels with typical conversion efficiencies up to 80% at higher engine loads [2].

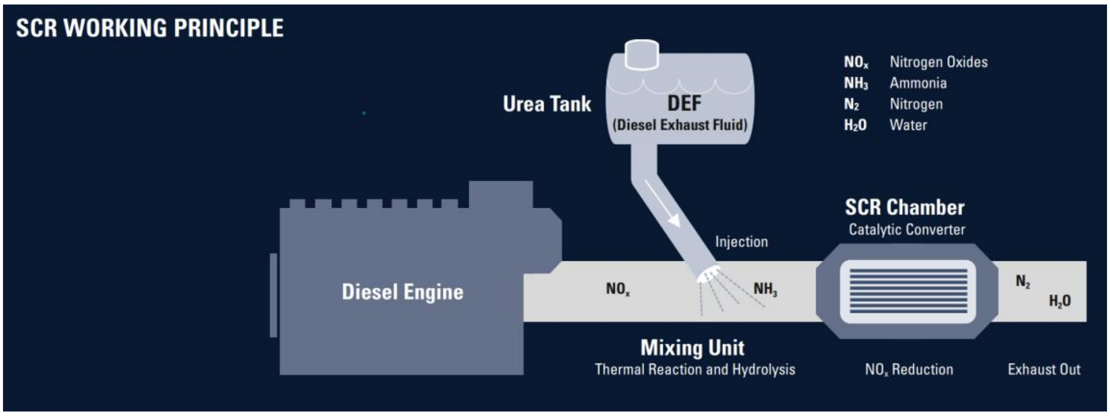

Figure 1.2: Schematic overview of a selective catalytic reduction (SCR) system in an exhaust stack [3].

1.2.1 Research questions

The validation described in this report is carried out based on a pollutant emissions reduction claim by Emigreen regarding their DPF systems. The DPF technology is claimed to reduce particulate matter emissions from sea going vessels to levels at or below the particle number (PN) and particle mass (PM) Stage V limit for inland shipping engines (IWP).

The IWP Stage V limit values for CO, HC, NO_x, PM and PN emissions are more stringent or even an addition to the limit values required by IMO Tier III regulation and are applied to sea going vessels for a voluntary ULEv (Ultra Low Emission vessel) label from Bureau Veritas (see Section 2.2.2). Next to a DPF system to achieve the required particulate emission reduction, ULEv's require the use of a well-tuned SCR system onboard the vessel to achieve the required NO_x reduction.

As the DPF technology in this validation is proposed to work together with an SCR system for vessels with an ULEv notation, also validation of the SCR system to achieve NO_x emissions below the current regulatory limit values is relevant.

The research question posed in this study is therefore whether marine DPF and SCR systems are a suitable option for pollutant emissions reduction for the Dutch reference ship categories with respect to the voluntary ULEv label limit values.

More in detail, the research questions are:

- Are there regulatory hurdles associated with the use these systems?
- What are the technical and operational risks?
- What are the expected impacts of these systems on pollutant emissions?
- What are the maintenance and monitoring requirements for these systems?
- What are the costs for these systems?
- How future proof are these systems?

2 Technical, regulatory and risk aspects

2.1 Technology types and standards

2.1.1 Diesel Particulate Filter

The diesel particulate filter (DPF) is an emission aftertreatment device developed in the early 1980s for diesel road vehicles. Only between 2000 and 2010, the DPF started to be used more frequently on both light duty vehicles (LDV) and heavy duty vehicles (HDV) due to different new regulations for the on-road sector [4]. Around this time, the DPF also started to be developed for marine diesel engines [5].

DPF systems usually are categorised as a wall flow filter or a partial flow filter. In a wall flow filter, all exhaust gas is routed through a porous filter surface, resulting in a very high filtering efficiency over 95% [6] [1]. Filter elements are usually designed with a honeycomb structure with alternating capped off channels to force the walls of the structure. Passing all exhaust gas through a porous surface however means that potential clogging of the filter could lead to a complete blockage of the exhaust stack.

Partial flow filters, also called particle oxidation catalysts, allow a portion of the exhaust gas to bypass the filter media to reduce backpressure in the system. However, these types of filters have a much lower filtering efficiency compared to wall flow filters. Unless otherwise specified, the use of DPF will refer to wall flow filters in the remainder of this report.

DPFs usually rely on depth filtration when they are new. In depth filtration, particles are trapped in the porous structure of the filter medium upon passing the filter. When the pores of the filter medium become saturated, particulates form a cake layer on the filter surface and filtration occurs based on the surface filtration principle. This later mechanism has a higher filtering efficiency compared to depth filtration, but also causes higher backpressures in the exhaust stack.

Due to the high filtering efficiency of DPF systems, filters can become overloaded, causing obstructions to the exhaust gas flow. To ensure continuous operation of the filter, regular regenerations are needed to prevent soot buildup. Removal of particulates in the filter is usually achieved with thermal regeneration. Thermal regeneration oxidises carbon particulates with oxygen or nitrogen dioxide at high temperatures to carbon dioxide [7]. The temperatures needed to regenerate can be achieved either through continuous passive regeneration, or with periodic active regeneration events. In the first case, high temperatures in the DPF are reached with the heat in the exhaust gas during normal operation. In these passive systems, the DPF often incorporates catalytic materials to decrease the oxidation temperature of carbon as exhaust gas temperatures usually don't reach the required temperature for oxidation without a catalyst.

It is good to note that catalytic elements in the DPF can cause high sulphate particle emissions due to catalytic oxidation of sulphur dioxides [8]. DPFs with catalytic elements should therefore always be operated with ultra-low sulphur fuels.

With active regeneration strategies, the catalyst is heated to the required temperature for carbon oxidation either by active engine management or a standalone fuel based or electric heater in the DPF. The advantage of standalone heater systems is that regeneration can be achieved during low load conditions or even during engine shut off.

While thermal regeneration oxidizes carbon particulates, inorganic ash contents in the DPF are not removed during the combustion process [9]. Accumulation of inorganic material in the DPF can cause clogging over longer periods of time. Low frequency cleaning with air or water is therefore necessary to ensure continuous operation of the filter. Furthermore, filter elements should be checked for cracks and possible leaks on the mounting seals to ensure high filtration rates are achieved. Traces of black soot downstream of the DPF usually indicate defects in the DPF causing blow by (unfiltered exhaust gas).

2.1.2 Selective Catalytic Reduction system

The selective catalytic reduction system (SCR) is an emission aftertreatment device developed in the late 1970s for thermal power plants. The first SCR applications for maritime engines were commissioned around 1990. Around the mid-1990s, SCR technology was further developed for automotive applications [10]. The system uses a catalyst to convert nitrogen oxides (NO_x) emissions to nitrogen (N_2) and water (H_2O) through a reaction with ammonia (NH_3).

The SCR usually consists of a metal or ceramic monolithic honeycomb structure with an applied wash coat containing catalytic materials such as vanadium, tungsten and titanium oxides to increase the surface area and provide a medium for the catalytic reaction to occur on [11]. A urea injection nozzle is placed upstream of the catalyst to atomize urea in the exhaust gas stream. Urea is a non-toxic substitute for aqueous ammonia and needs to be mixed with hot exhaust gases to start the process of hydrolysis and thermal decomposition to pure ammonia [12]. Within the catalyst, the decomposed ammonia reacts with NO_x and oxygen (O_2).

The typical reaction process in the SCR is as follows [13]:

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

Injection of urea can either be controlled with an open or closed feedback loop. Injection needs to be dosed to ensure sufficient reduction efficiency of the SCR while minimising NH_3 slip from the catalyst. In open loop control, urea injection rates are based on a pre-determined injection map without real-time feedback. In closed loop control, injection rates are adjusted based on feedback from NO_x sensors in the exhaust stack. Closed loop control allows for more critical injection rates and therefore higher reduction efficiencies, however, the dependency on sensor data can make the system more costly and less robust. Too high injection rates or faulty catalyst elements can result in unreacted NH_3 to escape from the catalyst. Similar to NO_x, NH_3 emissions to the environment cause acidification and eutrophication and have adverse health effects [14].

SCR systems on maritime engines can achieve very high reduction ratio's up to 90% [15]. With the addition of an SCR system, the NO_x-Fuel trade-off [13] in the engine tune can be shifted further towards lower fuel consumption where the higher NO_x emissions are reduced by the SCR system.

The added benefit is that this can also lead to lower particle mass (PM) emissions. The SCR system however is not well suited to operate at low engine power conditions. The low temperatures of the exhaust gas at low load are not sufficient for catalyst light off (~200°C) or to sustain the decomposition of ammonia typically occurring at temperatures above 250°C [12] [15]. At low load conditions, this results in higher NO_x emissions from the exhaust stack. Good placement of the SCR or alternative DEF strategies can improve low load performance in practice.

Next to reduction of NO_x emissions, it should be noted that the SCR system can also play a role in the reduction of particulate emissions due to catalytic cracking and partial oxidation of long chain hydrocarbons that constitute the organic fraction of diesel particulates [16]. In contrast, the SCR can also generate particulate matter in the form of urea particles, sulphates and nitrates (see Paragraph 2.3).

2.1.3 SCR and DPF interaction

Both SCR and DPF systems can be used in the same exhaust stack to reduce both NO_x and particulate emissions. The order in which both systems are installed in the exhaust stack influences efficiencies and possible side effects of both systems. Both SCR-DPF and DPF-SCR architectures are possible in maritime applications. In automotive applications, also combined technologies exist with for example SCR wash coats applied on top of DPF substrates. These combined technologies in relation to maritime applications are not discussed in this report.

2.1.3.1 DPF upstream of SCR

Installation of a DPF with catalytic elements upstream of the SCR can increase the NO_2 levels and potentially oxidize carbon monoxide (CO) emissions in the exhaust gas stream towards the SCR, leading to a faster reduction reaction in the SCR [17]. Furthermore, the DPF is exposed to higher temperature exhaust gasses, resulting in higher efficiency for passive regeneration while preventing clogging of the SCR due to high soot loading. However, in case of an active regeneration strategy of the DPF, the SCR can be exposed to high temperatures causing potential durability problems and the production of ammonium sulphate and nitrate particles downstream of the DPF.

2.1.3.2 SCR upstream of DPF

Installation of the SCR upstream of the DPF improves the heat-up time of the SCR due to its proximity to hotter exhaust gases, hence increasing its efficiency at lower loads and cold starts. Furthermore, potential urea, sulphate or nitrate particle formation in the SCR can be captured by the DPF system, increasing the total particulate filtering efficiency in the system. However, in this configuration the SCR is exposed to potentially higher soot loading which might lead to blocking of the SCR catalyst. Furthermore, potential higher CO levels originating from thermal decomposition of urea cannot be oxidized in the DPF.

2.2 Regulatory framework (pollutants, safety) and effect on the technology

2.2.1 MARPOL Annex VI

Pollutant emissions of ship engines are controlled via IMO MARPOL Annex VI regulations.

Fuel sulphur content (FSC) and emissions of SO_x and PM are treated in regulation 14 of MARPOL Annex VI. Different limits apply in different ocean areas. The regulation requires that the FSC of marine fuel in Sulphur Emission Control Areas (SECAs) does not exceed 0.1% m/m. Of the seas close to Europe, the Baltic Sea, the North Sea and the English Channel are SECA areas. Further SECAS exist in the coastal areas of the United States of America and China. From 1st of January 2020 a world-wide limit on maximum FSC of 0.5% is enforced outside SECAs. This is a significant reduction from the previously allowed FSC of 3.5%. The FSC requirements can be met by using fuel fulfilling these requirements. Alternatively it can be met by using a SO_x scrubber such that the SO_x is removed from the engine exhaust gasses. Note that regulation regarding PM emissions does not require the use of exhaust gas aftertreatment systems.

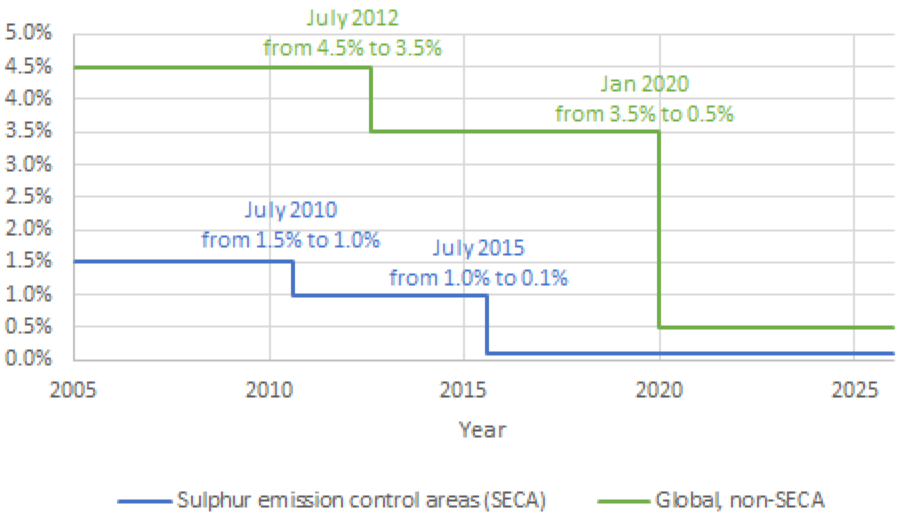

Figure 2.1: Fuel Sulphur Content (FSC) requirements for sea ships (% by weight).

The NO_x pollutant emissions of ship engines are regulated via IMO MARPOL Annex VI regulation 13. In particular, these are described by the IMO NO_x technical code ((MEPC.177(58) and MEPC.251.(66)) and apply to diesel engines with more than 130 kW power output. The maximum NO_x emissions are quite dependent on the maximum engine speed. The lower this maximum engine speed, the higher the limit value of specific NO_x emissions expressed in g/kWh (gram per unit of engine work). An overview of the (logarithmic) functions of the Tier I, II and III limit value and year of enforcement is presented in Table 2.1. Tier III engines require the use of exhaust gas aftertreatment systems to comply with the posed NO_x limit values.

Table 2.1: IMO MARPOL NO_x requirements dependent on the maximum engine speed.

Tier	Ship keel laying date on or after	Total weighted cycle emission limit (g/kWh)		
		n = engine's rated speed (rpm)		
		n < 130	n = 130 – 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$	7.7
III	1 January 2016 (USA) 1 January 2021 (Europe)	3.4	$9 \cdot n^{(-0.2)}$	2.0

The NO_x emissions of the engine are calculated as a weighted average during the applicable ISO test cycle. In practise, these are 4 to 5 engine load and/or speed points in the full range of the engine.

In order to proof NO_x compliance of the powertrain onboard a sea going vessel, the EIAPP (Engine International Air Pollution Prevention) Certificate needs to be valid. This also requires mandatory periodic surveys when the vessel is in operation. The EIAPP certificate is usually issued by a classification society on behalf of the flag state.

Other pollutant emissions such as particle number (PN), particle mass (PM) or ammonia (NH_3) are currently not regulated under IMO.

2.2.2 ULEv notation requirements (voluntary)

Current aftertreatment systems allow for pollutant emission reductions below the NO_x limit values in IMO Tier III regulation. To offer a pathway for vessel owners/operators to prove they exceed existing MARPOL requirements, Bureau Veritas (BV) developed the voluntary 'Ultra-Low Emission vessel' (ULEv) notation by adopting the European Commission's Stage V policy limit values of inland waterway engines (IWP) for the maritime industry.[1] The applicable limit values for all included pollutant emissions are shown in Table 2.2. Note that next to NO_x emissions, also limits are posed on carbon monoxide (CO), hydrocarbons (HC), particle mass (PM) and particle number (PN) emissions.

Table 2.2: Stage V emission limit values applicable for ULEv notation [18].

Net Power [kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PM [g/kWh]	PN [1/kWh]
≥ 300	3.50	0.19	1.80	0.015	10^{12}

To receive the voluntary ULEv notation, relevant documentation for engine and aftertreatment system specifications need to be supplied to Bureau Veritas. After receiving the required documentation, a conformity check is performed based on emission measurements to ensure compliance with the emission limits and a surveyor conducts an onboard inspection to ensure compliance with relevant documentation and installation instructions [19].

[1] https://marine-offshore.bureauveritas.com/sustainability/ultra-low-emission-vessels

2.3 Potential risks of the technology (technical and operational)

For both SCR and DPF systems, technical and operational risks can be identified. The most important risks of each technology are discussed here.

For DPF systems, the main risk is potential blocking of the exhaust stack when soot loading accumulates over time without proper regeneration or cleaning. Increased soot loading causes high back pressure on the engine outlet side, causing lower fuel efficiency and potentially stalling the engine in the worst case. Regular regenerations can prevent buildup of organic particulate matter and keep de system operating within pre-defined safe backpressure limits. However, accumulation of inorganic particles in the DPF can occur due to for example engine wear products and lubricant consumption [20] as these particles are not removed during regeneration. Additional cleaning is necessary to keep the DPF in good working order. For DPF systems with catalytic elements, poisoning of the catalytic surface is an additional concern. Therefore running on high sulphur fuels should be avoided with these types of systems.

The SCR system is less prone to clogging compared to the DPF due to its more open structure. The catalytic elements in the SCR are however prone to poisoning[2] and fouling[3] when exposed to different elements. When ammonia is present in the SCR at low temperatures, it can form ammonium nitrate due to a reaction with NO_2, resulting in fouling of the catalyst. Similar fouling can occur on the formation of ammonia-sulphur salts, fly ash and other particulate matter [21]. Exposure to poisons such as sulphur, phosphorus, alkali metals and heavy metals can poison the active elements in the catalytic wash coat [22]. These poisons are often present in the fuel or lubricating oils from natural oil sources or as additives. Different catalyst elements have different sensitivities to poisoning elements, therefore the impact of elements in the fuel is dependent on the exact catalyst design. In general, the use of high sulphur fuels should be avoided with catalytic elements to prevent sulphate formation and fouling.

The lifetime of the catalyst is mostly dependant on its exposure to poisoning elements from fuel and oil additives. When the catalyst starts to degrade, conversion efficiency of the SCR starts to reduce leading to high exhaust stack NO_x emissions. In open loop systems, this also has the potential to lead to high ammonia slip, as the injected urea cannot be fully reacted with NO_x in the SCR catalyst. Next to poisoning, the SCR system should be guarded against thermal shock (temperatures above ~450°C) and mechanical impacts.

2.4 Impact on maintenance and reliability of operations

Both exhaust gas aftertreatment systems require regular maintenance to ensure reliable operation.

[2] Poisoning: chemisorption between the active elements in the catalyst wash coat and the poison element leading to deactivation of catalytic elements.

[3] Fouling: the encapsulation of active elements in the catalyst wash coat by a fouling layer of a different element, leading to reduced active catalytic surface area.

For DPF systems, monitoring of the pressure differential over the filter offers good insight in the current filter loading. Regeneration is often an automated process which can run while the engine is in normal operation. Additional manual regenerations can be required when the pressure differential over the filter cannot be sufficiently reduced with the automated regeneration events. Especially on DPF systems with a standalone regeneration heater, performing regeneration with the main engine shut-off can result in higher regeneration temperatures and therefore a more efficient regeneration. When regeneration cannot bring the backpressure in the system back to normal levels, the DPF elements require manual cleaning. This can be performed with in-situ vacuum cleaning of the elements, or with specialised pressured air or water cleaning of the elements outside of the DPF housing. Emigreen indicates that their maritime DPF installations only require cleaning every 3000 to 4000 engine running hours [23].

To ensure continued operation in SCR systems, the proper control of urea injection is of high importance. In both open- and closed loop systems, monitoring of NO_x and possibly NH_3 emissions offers the required insight to keep the SCR system operational and to make timely adjustments to the system. Adjustments might be needed on the urea injection system, to the NO_x sensors in a closed control loop, or to the actual catalytic elements. From discussions with onboard chief engineers, replacement of catalytic elements is advised every 2 to 5 years in the manufacturers maintenance instructions to keep the SCR in good running order. In addition, regular sensor calibrations are needed in a closed loop control system and for monitoring purposes. During the validation measurements discussed in Paragraph 3.2, SCR elements of approximately 4 years old were already found to result in elevated NO_x emissions, possibly due to ageing effects of the catalyst.

3 Environmental impact

3.1 Validation approach

The validation of the environmental impact of DPF and SCR systems on maritime diesel engines is based on an on-board measurements of two trailing suction hopper dredgers with an ULEv notation. Both vessels are equipped with Emigreen DPF systems and a MAN and Caterpillar SCR system respectively. Relevant properties of both ships are shown in Table 3.1. The environmental impact of both exhaust gas aftertreatment systems is assessed in two parts, in Section 3.2 the effect on pollutant emissions is discussed. In Section 3.3, the impact on greenhouse gas well to wake emissions is discussed.

Table 3.1: Validation vessel properties.

Property	Vessel 1	Vessel 2
Build year	2019	2019
Vessel type	Trailing suction hopper dredger (Dredging)	Trailing suction hopper dredger (Dredging)
Main generators	3 x CAT 3512E (1700kW at 1800RPM)	3 x MAN 8L27/38 (2640kW at 750RPM)
Total installed diesel power	5510 kW	7700 kW
Aftertreatment system	SCR + DPF	SCR + DPF
Main engine IMO emission standard	Tier III and ULEv (Stage V)	Tier III and ULEv (Stage V)

3.2 Pollutant emissions

The impact on pollutant emissions for the DPF and SCR technologies is evaluated based on on-board measurements. The exhaust stack pollutant emissions were measured on the two trailing suction hopper dredgers mentioned in Table 3.1. On each vessel, measurements were performed on two of the three main generator engines onboard equipped with both SCR and DPF exhaust gas aftertreatment systems. In total, three engines[4] were measured while running on low sulphur (10 ppm) marine gasoil (MGO) instead of the regular 1000 ppm MGO. One engine was measured while running on hydrotreated vegetable oil (HVO). The detailed validation measurement approach and measurement results can be found in TNO 2025 R11145 [24] and TNO 2025 R11146 [25].

3.2.1 Diesel Particulate Filter

The DPF systems on all 4 measured engines were non-catalytic filters of the wall-flow type with a diesel burner for an active regeneration strategy. Regenerations are performed every 4 hours, or when the backpressure in the system exceeds the set threshold. Visual inspections of the filter are performed when regenerations can not reduce backpressure in the system to normal levels.

[4] Two engines onboard Vessel 1, one engine onboard Vessel 2.

When regeneration cannot sufficiently reduce the backpressure in the exhaust system, the DPF elements are also cleaned in-situ or outside of the DPF housing using a specialised pressurised air cleaner. Cleaning of DPF elements using one of both methods is performed approximately every 6 months.

During the validation measurements, particle emissions of the DPF equipped engines are evaluated on both the E2 (sailing) and D2 (auxiliary) emission cycles with additional measurements being performed during regeneration of the DPF.

Measurements show low particle number (PN) emissions under all measured conditions with average emission values of 7.8×10^{10} #/kWh and 4.0×10^{10} #/kWh for the E2 cycle, and 1.1×10^{10} #/kWh and 6×10^{11} #/kWh for the D2 cycle between both measured vessels. Therefore PN emissions on all measured DPF equipped engines fall well below the Stage V limit value for inland ships of 10×10^{12} #/kWh applicable to ULEv vessels. During active regeneration, PN concentration in the exhaust stack did not increase compared to measurements on the same engine load point with no active regeneration. Furthermore, particulate emissions were observed to remain relatively constant between different engine load points on all measured engines. As such, measured values on the respective E2 and D2 cycle without regeneration are representative for the emissions during normal operation. The flat operational profile of the filter is also in line with the high filtering efficiency of the DPF described in literature and is an additional indication that no cracks or other leaks exist in the system.

Particle mass (PM) emission measurements show average values of 3 mg/kWh to 11 mg/kWh on the E2 cycle, and 4 mg/kWh to 11 mg/kWh for the D2 cycle between both measured vessels. Measured PM emissions are below the Stage V limit value for inland ships of 15 mg/kWh applicable to ULEv vessels.

For both PN and PM emissions, no difference in emissions between MGO and HVO operation was observed from measurements after the DPF. Measurements during the validation study were compared to measurements performed at commissioning of both vessels. Changes in particulate emissions between initial measurements and measurements performed during this validation study are very insignificant, hence no deterioration of the DPF systems is observed over the course of approximately four years.

It should be noted that one of the measured vessels was equipped with a DPF bypass valve in the exhaust stack to bypass the DPF when sailing on heavy fuel oils. Measured particulate emission levels are only valid when a DPF bypass is not active.

3.2.2 SCR system

The SCR systems on both vessels were mounted immediately after the engine and were part of the Tier III certification of the engine. After certification, the SCR installation of both vessels was calibrated to also comply with the Stage V limit value for inland ships of 1.8 g/kWh applicable to ULEv vessels. On both vessels, the SCR installations were equipped with OEM NO_x sensors up- and downstream of the SCR for monitoring purposes. The injection strategy the SCR systems onboard both vessels is unknown, but an open loop control is assumed due to the observed constant urea injection setpoints at various engine loads.

NO_x emissions of the SCR equipped engines are evaluated on both the E2 (sailing) and D2 (auxiliary) emission cycles.

On vessel 1, the SCR elements were not replaced since commissioning of the vessel 4 years prior to the validation measurement campaign. Furthermore, the SCR systems were not always used in Stage V mode. Measurements onboard this vessel showed average NO_x emissions of 2.3 g/kWh and 2.0 g/kWh for the E2 and D2 cycle respectively, therefore exceeding the Stage V limit value for inland vessels applicable for ULEv vessels of 1.8 g/kWh. On the E2 cycle, the measured NO_x emissions also exceeded the TIER III emission limit of 2.01 g/kWh. The OEM monitoring system displayed several warnings about reduced catalyst efficiency after starting the validation measurement campaign. NO_x emissions were seen to fluctuate heavily due to instable urea injection. Next to high NO_x emissions, also high ammonia (NH_3) emissions were observed from the measurements. Replacement of the SCR elements and re-calibrating of the SCR software by the OEM brought the NO_x emissions back below the applicable Stage V limit value[5].

On vessel 2, the SCR elements were replaced every two years according to the OEM maintenance interval. All tested SCR systems were replaced within a few months before the validation campaign. Measurements onboard this vessel showed average NO_x emissions of 0.5 g/kWh and 0.8 g/kWh for the E2 and D2 cycles respectively. For both cycles, emissions were below the Stage V limit value of 1.8 g/kWh for inland vessels applicable for ULEv vessels, and below the Tier III limit value of 2.39 g/kWh. While NO_x emissions are low, measurements showed NH_3 slip up to 27 mg/Nm^3 on some engine load points. While NH_3 slip can be an indicator for reduced catalyst efficiency or faulty urea injection control, it is important to note that slip can also be caused by a temporary problem relating to urea crystal formation and release in the exhaust stack.

Measurements on both vessels show that SCR systems are capable to reduce NO_x emissions well below the Stage V limit value of 1.8 g/kWh applicable to ULEv vessels. It is however important to perform timely maintenance or replacements on the systems to ensure continued operation. Defects or ageing of the catalysts can significantly affect the system performance to a level where NO_x emissions increase beyond the regulatory limit values. Monitoring of SCR performance and degradation is crucial to ensure NO_x emissions are reduced to low levels. In addition, the problem of NH_3 slip requires extra attention as, similar to NO_x, NH_3 has a large potential for acidification upon deposition in the environment. Additional sensors to monitor NH_3 emissions could be employed to ensure timely detection of urea based SCR problems.

3.3 Well to Wake GHG emission

Effects on the GHG emissions of both the DPF and SCR exhaust gas aftertreatment systems is limited in relation to their effect on pollutant emissions.

For the DPF system, both regenerations and backpressure in the system can cause additional fuel consumption and the related CO_2 emissions. A good balance in the amount of regenerations and the backpressure in the exhaust system can keep the additional fuel use from the DPF within 5%. The typical backpressure of a clean, well-functioning DPF filter is around 40 mbar.

In contrast to the DPF, the SCR system can sightly reduce the fuel consumption of the diesel engine as the engine tune can be optimized for better fuel economy with higher engine-out NO_x emissions. This effect is highly dependent on the exact engine specifications and is therefore not quantified in this report.

[5] Based on NO_x sensor measurements

4 Applicability

4.1 Dutch fleet categories

Aftertreatment systems can generally be installed on all ship types, although sometimes an extra box or room has to be installed on one of the ship decks. EMIGREEN has confirmed that on all Dutch reference ship types DPF and SCR systems can be installed. On all ship types, maybe with the exception of the TUG, this has already been done. An overview of the Dutch green deal reference ships is given in Table 4.1.

Table 4.1: The six Dutch reference ships used for the Green Deal validation projects.

Nb	Vessel type	Length (m)	DWT	Total max power (kW)	Engine type	Main fuel type
1	General Cargo	112	9200	4290	Medium Speed	MGO
2	TUG	32	285	5000	High Speed	Diesel ULSFO
3	Offshore supply	82	2900	6000	High Speed	MGO
4	Crew Tender	25	20	2100	High Speed	Diesel ULSFO
5	Dredging	125	21000	12000	Medium Speed	MGO
6	Super yacht	100	460	13000	High Speed	Diesel ULSFO

4.2 Operational aspects

Aftertreatment systems do require periodic maintenance. Inorganic dust or particles like metals and silicon will accumulate within the DPF system over time. In contrary to organic particles, the inorganic particles cannot be regenerated by heating (and converted to gaseous components such as CO_2 and water). So these inorganic components needs to be removed by periodically vacuuming the individual DPF filter elements.

Also SCR systems and sensors and analysers used for monitoring and control do need maintenance such as period replacement or cleaning. Information on maintenance costs and costs of consumables such as urea and fuel can be found in section 5.2. More details on maintenance aspects is found in section 2.4.

DPF systems can operate on all engine load points and do not require specific temperature windows to operate at its full efficiency. In contrast, the SCR system requires exhaust gas temperatures above 200°C to operate. For vessels that see a significant share of low load operation, the SCR system might be only operational for a very limited amount of time.

5 Economic aspects

5.1 Description of instruments

5.1.1 IMO

The IMO regulations are primarily focused on NO_x and SO_x reduction as explained in Section 2.2. Particle mass (PM) reduction is indirectly addressed via the limitation on Fuel Sulphur Content (FSC) in the Emission Control Areas. Lower FSC lowers both the gaseous SO_x emissions and the PM emissions, because a part of the sulphur in the fuel ends up as sulphate part of the PM emissions. In addition to this, the IMO MEPC and NGO's give a recommendation to reduce Black Carbon emissions on artic routes [26] [27]. The latter source is submitted by FOEI, WWF, Pacific Environment and CSC. Black carbon is a part of the PM emissions. Other parts consist of hydrocarbons, inorganic components and sulphate with adsorbed water. The current recommendations for BC reduction on artic routes are not going further than using relatively clean (diesel) fuels and avoiding Heavy Fuel Oils. DPF systems would however reduce BC emissions by more than 95%.

The NO_x pollutant emissions of ship engines are regulated via IMO MARPOL Annex VI regulation 13. The most stringent level is Tier III which is only applied to emissions control areas (ECA's). The grand majority of the ships, that comply with Tier III are using SCR systems to reduce the NO_x emissions below the required level. A small portion uses Exhaust Gas Recirculation (EGR). A large part of the ships sailing on LNG do not need SCR, but also then SCR systems are often installed, since the engines can also run on diesel fuel. The SCR is needed to meet the Tier III requirements.

5.1.2 External costs - MKI

National policies can also stimulate the use of DPF and SCR systems. For example the Dutch agency Rijkswaterstaat (RWS) and Port authorities are responsible for (among others) the development and maintenance of the shipping channels and sea shores (such as dunes). RWS has ambitious goals for the reduction of pollutants and GHG emissions for their construction activities. They aim for 75% PM reduction between 2016 and 2030, and for 60% NO_x reduction between 2018 and 2030[6]. For their maritime activities, they set goals for NO_x emissions via a requirement to adhere to at least Tier III standards in 2030 (with a gradual phase out for the years up to 2030. No PM requirements have been set for waterborne construction activities.

RWS and several port authorities (such as Port of Rotterdam) also use the MKI (**Milieu-Kosten-Indicator**) as a financial incentive for the contracted work. The MKI is based on 'shadow costs' via Life Cycle Analysis. The lower the impact on the environment, the lower the environmental costs (MKI), the higher a "discount" can be given to a price for a contracted work tender. NO_x, SO_x, methane (NH_3) and to a lesser extend PM are accounted for in this MKI. The application of this MKI incentive is already in place for more than a decade.

[6] These are the goals of the "Schoon en Emissieloos Bouwen" (Clean and Emission-free Construction) covenant.

Recently, a new set of specific MKI factors have been set up for marine contracting. In the table below the MKI value for the different pollutant emissions are given. It should be noted that MKI costs are much lower than 'external costs' due to damage. These damage costs are listed in the EU Handbook on the external cost of Transport [28]. For example for NO_x on the North sea, the damage costs are 10.7 €/kg compared to 3.278 €/kg for the MKI shadow costs. For PM emissions this difference is much higher, namely 34.4 €/kg for the damage costs, where the MKI shadow costs are only 0.0738 €/kg.

Table 5.1: Environmental costs, MKI, for pollutant emissions.

EUR per kg emission reduction	NO_x	PM	SO_x
Climate change	-	-	-
Photochemical oxidation	-	-	0.096
Acidification	2	-	4.8
Eutrophication	1.17	-	-
Human toxicity	0.108	0.0738	0.0086
Total (EUR/kg)	3.278	0.0738	4.9046

5.2 Costs and benefits for end users

The investment costs and the costs for consumables and maintenance for DPF and SCR system are listed in Table 5.2. Costs are based on information given by EMIGREEN and on the EMERGE and PROMINENT projects [29] [30].

Table 5.2: Investment and operational costs for DPF, SCR and combined systems for a new build ship.

	DPF	SCR	DPF + SCR
Investment costs EUR/kW engine power	67 - 96	45 - 68	112 - 131
Urea consumption EUR/MWh mechanical work		2.8	2.8
Maintenance costs EUR/MWh mechanical work	3	0.9	3.9
Fuel penalty for active DPF regeneration (max)	5%		5%

Based on these costs specification, the total annual costs for an DPF + SCR system is calculated for new-build Dutch reference ships. The results are presented in the table below. The investment costs for refitting this system to an existing ship has been estimated to be about 20% higher. It should also be noted that the investment costs in an SCR system is already necessary to comply with IMO Tier III requirements. It is expected, that in many cases, Tier III SCR systems can be re-calibrated to the somewhat more stringent ULEv NO_x requirements. This will lead to a 10-15% higher urea consumption. The SCR system accounts for about 45% to 49% of the total costs of the system, the DPF system accounts for the rest.

Table 5.3: Annual costs estimation for a combined DPF plus SCR system for a new build ship. Annual CAPEX costs is set to 12% of investment costs (depreciation in 8 years). Combined system investment: EUR 131 per kW engine power.

Ship type	Total engine power	Fuel ton/year	Investment cost SCR+DPF	Mech energy	Total OPEX + CAPEX	Share SCR in costs	Share DPF in costs
	kW	ton/year	EUR	MWh/year	EUR/year		
General Cargo	4290	3407	562,000	17033	188,700	48%	52%
TUG	5000	3732	655,000	17771	205,500	48%	52%
Offshore supply	6000	3344	786,000	15925	208,000	47%	53%
Crew tender	2100	1190	275,100	5664	73,500	47%	53%
Dredger	12000	12283	1,572,000	61416	625,900	49%	51%
Super yacht	13000	3150	1,703,000	14998	311,500	45%	55%

The specifications and the annual emissions of NO_x, PM and other emissions are given in the Green deal report *'Vervolgstappen validatie methodieken t.b.v. transistie naar emissieloze scheepvaart'* [31]. The emissions reduction for the ULEv ships is calculated and presented in the table below. Furthermore, the MKI-value of these emissions is presented. The table shows that the value represented in MKI may be significant, but is almost exclusively linked to NO_x emissions.

Table 5.4: Total annual emission reduction for Dutch reference ships equipped with ULEv DPF plus SCR system.

	NO_x reduction (to 1.8 g/kWh)	PM reduction (90%)	MKI value NOx	MKI value PM	Total MKI value
	ton/year		EUR/year		
General Cargo	139	3.9	454,900	300	455,200
TUG	122	4.2	398,400	300	398,700
Offshore supply	103	3.8	337,800	300	338,100
Crew tender	39	1.4	127,000	100	127,100
Dredger	500	14.0	1,640,300	1,000	1,641,300
Super yacht	97	3.6	318,100	300	318,400

Consequently the total annual costs and benefits (MKI value) can be compared. This is presented in Figure 5.1. The benefits are generally 60% to 140% higher than the investment plus operational costs. However, almost all of the benefits are associated to NO_x reduction, while only half of the costs are linked to NO_x. There is hardly any compensation for PM reduction under the current MKI methodology. A second notion is that the MKI benefits only occur in certain contracts, for instance in dredging contracts by Rijkswaterstaat or Port of Rotterdam. General cargo vessels or super yachts will therefore not have these benefits.

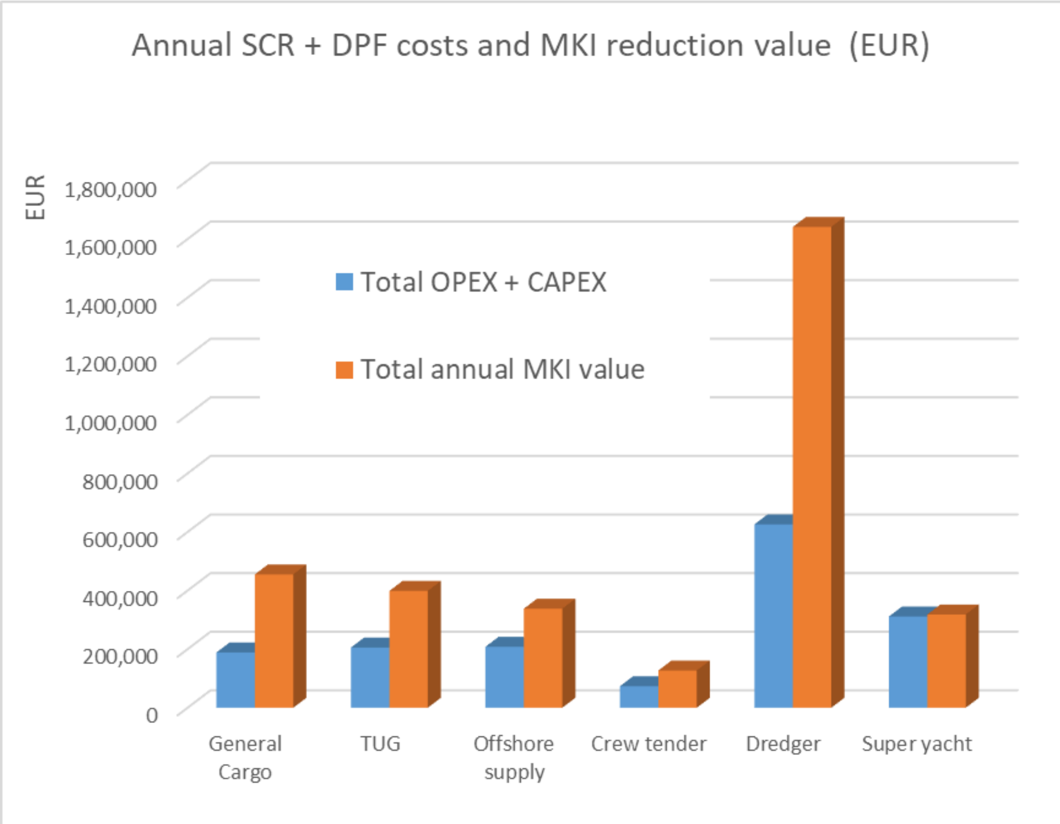

Figure 5.1: Comparison of annual costs of DPF plus SCR system and the MKI value of the emissions reduction for NO_x and PM.

6 Scalability and future proofness

Particulate Matter (PM) and NO_x emissions of sea ships have an impact on the air quality over land. Moreover PM and NO_x emissions from other sources such as households, industry and land-based mobility are on a long-term reduction path due to more stringent requirements and faster product renewal rates in many cases (see Figure 6.1 for NO_x emissions). For sea shipping, the requirements have been less stringent in the past low. Currently, emissions of seagoing vessels therefore have a significant share in the total emissions of the Netherlands.

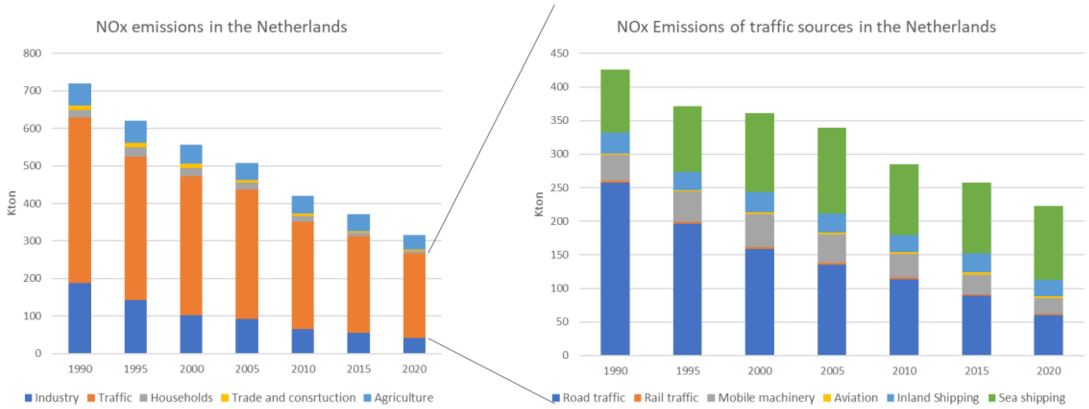

Figure 6.1: NO_x emissions of different sources in the Netherlands between 1990 and 2020 in the Netherlands
Source: emissieregistratie.nl

6.1 DPF systems

According to the Dutch emissions inventory, sea ships are by far the largest PM emission source of mobility. For 2020 this was about 45% [32]. Up to 2030 some reduction is foreseen, but this is lower than for other transport modalities.
The current market demand for DPF is primarily related to customer demand for lower emissions such as for dredger work outsourced by Rijkswaterstaat, the government agency for infrastructure maintenance and expansion. However, the value associated to PM emissions under MKI does not cover costs of a DPF system. Owners of luxury yachts sometimes require the installation of DPFs.

The European requirements for lowering PM emissions in the Netherlands can primarily be achieved by measures from the other main emissions sources like households, industry and land-based mobility. Also the planned installation of shore power for ships contribute to this. Specific measures for sea vessels when sailing, are not (yet) necessary.

The transition to sustainable fuels like biodiesel and sustainable methanol, ammonia or methane may somewhat affect the application of DPF systems, since these sustainable fuels generally have lower PM emissions.

The need for further PM reduction via a DPF becomes lower, however the precise PM emission levels for these new fuels are not always readily available.

A positive market demand for DPF systems may come in the future from legislation for sailing on artic routes. The black carbon part of PM emissions is known to increase the heat adsorption of ice and snow and in that way contributes to global warming. The IMO works regulations to control these BC emissions.

6.2 SCR systems

Sea ships are by far the largest contributor to NO_x emissions of mobile sources according to the Dutch Emission inventory. The contribution of sea ships is around 50%, similar to the share with PM emissions.

SCR systems are currently the dominant technology to meet the Tier III NO_x requirements for sea vessels. About 90% of the Tier III ships are equipped with SCR systems. Also about 50% of the ships with LNG as fuel have SCR systems installed (mainly as a requirement for dual fuel).

The SCR systems evaluated for this validation were tuned to meet the voluntary 'Stage V inland shipping' requirements. This is about 10-30% more stringent than Tier III depending on the engine size.

The high level of nitrogen deposition (deposition of NH_3 and NO_x) in the Netherlands and several other countries in Europe, is a large problem. Due to that, permits for expansion of economic activities or for new activities such as 'work on sea' are not easily granted. This will likely remain the case for many years to come. So, it is very likely that low NO_x emissions will remain very valuable in the future. Also for work contracted by RWS, low NO_x emissions are set via Tier III requirements and through use of the MKI system. In this respect there is a demand for SCR systems with lower NO_x emissions than Tier III and Stage V. Much lower NO_x emissions can be achieved with optimally designed SCR systems.

For the transition to more sustainable fuels, SCR systems will likely remain important. For biodiesel engine out NO_x emissions are similar to fossil diesel. Also new fuels like sustainable methanol, ammonia and methane (LNG or liquid methane), SCR system generally remain necessary to meet IMO Tier III levels in case of a dual fuel system. Certain LNG engine types can do without, but if they want to run on diesel as well, the SCR system is still needed.

7 Conclusions

TNO has investigated the Emigreen Diesel Particulate Filter (DPF) and OEM SCR catalyst systems in the context of the Green Deal validation program.

The validation include the following elements:

- Environmental impact;
- Practical application and scalability;
- Economic aspects;
- Future proofness.

The investigations, which included emissions measurements on two dredger vessels with an ULEv notation, lead to the conclusions below.

Environmental impact
The measured DPF systems significantly reduce particle number (PN) and particle mass (PM) emissions from the exhaust stack. All measured systems reduced particulate emissions to levels well below the limit values for Stage V inland vessel engines applicable to the voluntary ULEv label. Filtered particulate matter emissions are kept stable across the entire engine load range. With an active regeneration strategy and regular in-situ and external cleaning of the DPF elements, no deterioration of the system performance is observed over a period of approximately 4 years.

The measured SCR systems on-board one of the measured vessels was capable to reduce NO_x emissions from the tailpipe to levels below the limit value for Stage V inland vessel engines applicable to the voluntary ULEv label and the limit values for Tier III marine engines. The SCR systems on-board this vessel were recently replaced according to the maintenance schedule. Although NO_x emissions were reduced, NH_3 slip was measured partially offsetting the reduced NO_x emissions based on its acidification potential. Measurements on-board the second vessel showed highly dynamic NO_x emission levels exceeding the limit value for Stage V inland vessel engines applicable to the voluntary ULEv label and significant NH_3 slip. SCR elements on-board this vessel were not replaced since commissioning of the vessel in 2019. After replacement of the SCR elements and calibration of the control strategy, emissions from this vessel also were at levels below the limit value for Stage V inland vessel engines applicable to the voluntary ULEv label and the limit values for Tier III marine engines. Measurements during this validation show the importance of timely maintenance and monitoring of emissions to ensure the continuous proper operation of SCR systems. Possible over injection of urea fluid should be avoided to prevent NH_3 slip from the catalyst. Additional monitoring on this pollutant could be necessary to safeguard this.

Practical application and scalability
Both DPF and SCR exhaust gas aftertreatment systems can be installed on all Dutch reference ships. As described above, especially the SCR system requires monitoring and regular maintenance to ensure continuous operation while the DPF system relies on automated regeneration and periodic cleaning events.

Note that SCR systems will not work at low exhaust gas temperatures, they therefore are only operational when the engine is under load. Both exhaust gas aftertreatment systems have proven to be capable in reducing particulate and NO_x pollutant emissions to levels well below the acting limit values for marine vessels. This makes them a good option with respect to future regulatory updates.

Economic impact
Investment and operational costs of both aftertreatment systems are substantial. The investment costs for a combined SCR and DPF system on a new build vessel are expected to be around €112 to €131 per kW installed engine power. National policies and public contract requirements currently play a significant role in encouraging the use SCR systems, and to a much lesser extend the use of DPF systems. The MKI (Milieu-Kosten-Indicator) can serve as a financial incentive to reward lower emissions with higher contract prices for dredgers, especially for sensitive projects such as those near Natura 2000 sites. The results show that the discount of MKI may outweigh the investment and operational costs. However, the benefits are almost exclusively associated to NO_x reduction, and are only relevant for certain government contracts.

Future proofness
Aftertreatment systems will remain important in the future. IMO MARPOL legislation for NO_x emissions will likely become more stringent in the future with respect to low load and real life emissions performance. This is due to the limited effectiveness of the current Tier III legislation. Use of a DPF system is less relevant under the current legislative framework. The importance of aftertreatment systems will remain with the transition to sustainable fuels, especially for the SCR NO_x reduction part. The Diesel Particulate Filter becomes less important, since the PM emissions are substantially lower with sustainable fuels like methane, methanol and ammonia. Also for biodiesel PM emissions generally lower. Methanol and methane (LNG) have lower NO_x emissions, but generally not enough to meet the Tier III legislation without aftertreatment.

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Signature

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Fieke Beemster Research manager SUMS	Thomas Frateur Author

Mobility & Built Environment

Anna van Buerenplein 1
2595 DA Den Haag
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