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Progress in the implementation of the 2022–2023 workplan**Draft guidance document on technical measures for
reduction of air pollutant emissions from shipping***Summary*

The present document is submitted by the Task Force on Techno-economic Issues for consideration by the Working Group on Strategies and Review. It presents updated information on the effective means to reduce emissions from maritime shipping. The document was prepared by the Task Force in accordance with its revised mandate (Executive Body decision 2018/7, annex, para. 2 (c)).^a It is expected that a final draft of the document will be forwarded by the Working Group to the Executive Body for adoption at its forty-third session (Geneva, 11–14 December 2023).

^a All Executive Body decisions referred to in the present document are available at <https://unece.org/decisions>.



I. Introduction

1. The objective of the present document is to provide Parties to the Convention on Long-range Transboundary Air Pollution and other stakeholders with the most up-to-date information on effective measures to reduce maritime shipping air pollutant emissions and related impacts on human health and environment.
2. The guidance document presents pollution control techniques applicable to ships, both during navigation and at berth, to limit their atmospheric emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOCs), particulate matter (PM), total suspended particles (TSP), PM₁₀ and PM_{2.5}, including black carbon (BC) and polyaromatic hydrocarbons (PAH)). In addition, where relevant, this guidance also provides information on the co-benefits for reduction of greenhouse gas emissions. Further analysis and complementary information are provided in the associated background informal technical report.¹
3. The recommended techniques are presented in the present document as guidance in possible implementation of air pollutant emission reduction techniques for the shipping sector, although the list of all existing and/or promising future measures is not exhaustive. In general, all techniques assessed provide measurable emission reductions, over a reference technology, at a cost that is proportional to the achieved reductions, and they are technically implementable under certain specific conditions, depending on the techniques.

II. Definitions

4. See below for a list of definitions of terms used in the present document:
 - (a) “PM” is used here to refer to TSP, since no specific range of particle sizes is considered. Nevertheless, the differences between TSP and PM can be rather marginal, as the fractions of PM_{2.5} and PM₁₀ in TSP in marine fuel combustion are very large. According to the European Monitoring and Evaluation Programme/European Environment Agency air pollutant emissions inventory guidebook², the granulometry is 100 per cent for PM₁₀ (meaning all the PM fraction measured is of an aerodynamic diameter of 10 µm or less) and 90–93 per cent for PM_{2.5}. In addition, the measurement techniques for ship engines often follow the standards established in International Organization for Standardization (ISO) 8178, where dilution of the exhaust gases is realized before measurement is carried out, in order to include the volatile PM fractions or condensables;
 - (b) Pollutant emission reduction techniques are referred as “best available techniques” (BATs) and are categorized as primary techniques, acting directly at the source, i.e. fuel switch or a modification/optimization of the combustion technology and process, and secondary techniques, which are exhaust gas treatment technologies;
 - (c) Emission control areas (ECAs) are geographically limited coastal areas where air quality matters are more sensitive, therefore stringent emission levels are imposed to ships navigating in these waters. So far, sulfur and nitrogen ECAs, respectively named SECAs and NECAs, are in place and require emission limit values for sea-going ship sulfur dioxide (SO₂) and NO_x emissions. The current NECAs and SECAs are implemented in the Baltic Sea, the North Sea, the North American coastal waters and the Caribbean Sea. In addition, the Mediterranean Sea was established as a SECA in December 2022, in force

¹ Grégoire Bongrand and Nadine Allemand, “Background informal technical document on maritime shipping emissions, reduction techniques and determination of their costs”, available as an informal document for the fifty-eighth session of the Working Group on Strategies and Review (Geneva, 14–17 December 2020), see https://unece.org/fileadmin/DAM/env/documents/2020/AIR/WGSR/TFTEI_informal_doc_on_shipping_emissions-final-december2020.pdf.

² European Environmental Agency (EEA) Report No 13/2019, “EMEP/EEA air pollutant emission inventory guidebook 2019. Technical guidance to prepare national emission inventories.” (September 2019)

from May 1st, 2025, and North East Atlantic and Canadian ECAs implementation are under discussion.

III. Background information

5. International ship transport deals with about 80 per cent of world global trade volumes and constitutes an active and growing economic sector. The amount of international seaborne freight is in constant increase, and was the highest ever observed in 2019 (11 megatonnes (Mt)), which is almost double than the amount of 2000 (5.9 Mt), and almost reached its pre-crisis level in 2021.³ Meanwhile, the number of passengers also increased before the COVID-19 pandemic. Therefore, the ship fleet increased year on year, as did associated fuel consumption, except when economic or sanitary crises occurred.⁴

6. As a consequence of this intensive activity, shipping transport is a significant pollutant emission source. Emissions from shipping transport mostly result from fuel combustion in the main and auxiliary engines during cruising, but also when vessels are at berth or manoeuvring in port areas. In addition, some significant fugitive emissions of volatile organic bulk liquid cargoes (mainly VOCs), during loading and unloading operations, and related to the use of refrigerants or air conditioning (hydrofluorocarbons (HFCs)) have to be considered.

7. Although regarded as a relatively clean modal transport due to its low greenhouse gas (GHG) emission rate per tonne of transported goods compared to other types of transport, shipping transport was still responsible for about 2.9 per cent of all anthropogenic carbon dioxide (CO₂) emissions in 2018. Despite a significant reduction in the sulfur content of marine fuel oil in 2020, following the implementation of International Maritime Organization (IMO) rules, marine shipping is the largest source of SO₂ per tonne-km among the various transport modes. As compared to large trucks, maritime shipping NO_x emissions per tonne-km are slightly lower, but the PM₁₀ emission rate is higher. In addition, growing interest in tackling ship pollutant emissions in harbours is observed, due to their proximity to densely populated areas. In fact, while at berth, emission rates can be higher than in the cruise phase, because engines operate at low loads. Indeed, emissions in harbours are estimated from a few percent up to 20–30 per cent of the total ship emissions of SO₂, NO_x and PM depending upon vessel type.⁵

IV. Legislative framework

8. In order to limit the negative impact of maritime shipping on air quality and human health, IMO, through the International Convention for the Prevention of Pollution from Ships (MARPOL Convention, adopted in 1973), introduced several regulations with progressively more stringent constraints. The MARPOL Convention covers pollution from shipping transport in the oceans and some specific areas such as the Mediterranean Sea or the Baltic Sea, as well as vessels operating in the waters of the United States of America. Throughout the years, diverse protocols have been adopted and, in 1997, MARPOL annex VI “Regulations for the Prevention of Air Pollution from Ships” was introduced, entering into force in 2005.

9. Following the initial implementation of MARPOL annex VI, the IMO Marine Environment Protection Committee adopted amendments thereto. In 2015, fuel sulfur content was limited to 0.1 weight per cent in SECAs and to 0.5 weight per cent outside SECAs, effective since 2020. Concerning NO_x emissions, emission limit values (ELVs) were introduced for diesel engines with a nominal power output higher than 130 kW, for

³ UNCTAD, “Review of maritime transport 2022” (2022) available at : <https://unctad.org/publication/review-maritime-transport-2022>

⁴ International Maritime Organization (IMO), *Fourth IMO Greenhouse Gas Study: 2020* (London, 2020).

⁵ *ibid.*

ships constructed after 1 January 2000, or engines that underwent a major conversion after the same date. The NO_x ELVs are defined by use of tiers and they vary depending on the rated engine speed. Tier I and II ELVs are applied depending on the ship construction date or the date of major engine conversion (before or after 1 January 2011), whereas tier III is applicable for ships constructed after 1 January 2016, when operating in NECAs.

10. Regulations are essential drivers in order to achieve emission abatement and improve air quality along coastlines, as well as inland. An important fact to bear in mind is that around 70 per cent of shipping emissions are generated less than 400 km offshore and such emissions can be transported hundreds of km onshore. A 2007 study revealed that shipping was responsible for nearly 60,000 premature annual deaths near the coastlines of Europe and East and South Asia.⁶ Another study reported that approximately 4,000 and 8,000 premature deaths could be avoided, respectively, by 2030 and 2050, if additional NECAs and associated tier III NO_x standards were applied in the European Union. One recent study⁷ analysed the impact of the IMO 2020 global sulfur cap policy and the implementation of SECAs and NECAs in the Mediterranean Sea and revealed that over 6,000 premature deaths in the Mediterranean Area due to PM_{2.5} could be avoided and at least €17 billion could be saved annually in health-care costs, while the additional investment for such measure implementations in the Mediterranean Sea would be no more than €5 billion per year.

11. No specific rules are established in port areas by international regulations but regional or local regulatory authorities may define some rules. In the European Union region, a fuel sulfur content limit of 0.1 weight per cent, for ships at berth, is established by Directive 2012/33/EU.⁸ In California (United States of America), the Ocean-going Vessel Fuel Regulation established a fuel sulfur content limit of 0.1 weight per cent for main, auxiliary and boiler engines, for vessels within 24 nautical miles of the Californian coastline, as of 2014. In addition, in six Californian ports (Los Angeles, Long Beach, Oakland, San Diego, San Francisco and Hueneme), the Californian Ocean-going Vessels at Berth Regulation establishes the use of onshore power supply or of alternative control techniques achieving similar emission reductions (at least 85–90 per cent for PM and NO_x).

V. Best available techniques for ships: primary techniques

A. Fuel switch

Low-sulfur fuels

12. SO₂ emissions from fuel combustion are directly proportional to the fuel sulfur content. Since 2020, significant progress has been made through the MARPOL annex VI regulation, which brought down the sulfur cap from 3.5 weight per cent to 0.5 weight per cent. In the specific seawaters defined as SECAs, the sulfur content limit is established at 0.1 weight per cent. Thus, these rules limit the use of heavy fuel oil (without post-treatment of exhaust gases) and, furthermore, discussions are ongoing at IMO, to consider the ban of heavy fuel oils in the Arctic. For instance, switching from a 0.5 weight per cent marine fuel to marine diesel oil, with 0.1 weight per cent, would lead to an 80 per cent SO₂ emission reduction. Nowadays, in some highly distillate marine fuels, such as ultra-low sulfur fuel oil, sulfur content may be reduced to as little as 0.001 weight per cent.

⁶ James Corbett and others, “Mortality from shipping emissions: a global assessment”, *Environmental Science and Technology*, vol 41, No. 24 (December 2007), pp. 8512–8518.

⁷ Laurence Rouil and others, “ECAMED: A technical feasibility study for the implementation of an Emission Control Area (ECA) in the Mediterranean Sea – Synthesis report” (Paris, French National Institute for Industrial Environment and Risks, 2019).

⁸ Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulfur content of marine fuels, *Official Journal of the European Union*, L 327 (2012), pp. 1–13.

13. In addition to SO₂ emission reductions, switching from residual fuel oils to lower sulfur distillate fuels makes it possible to achieve PM emission reductions of 50–90 per cent,⁹ due to lower ash contents. Jointly, BC emission reductions of 0–80 per cent, depending on the engine characteristics and fuel used, with average reductions of about 30 per cent, are achievable when switching to light marine fuels.¹⁰

14. In terms of investments, switching to lower-sulfur fuel oils only induces changes in operating costs related to fuel prices. At the end of 2022, since the IMO 2020 sulfur cap implementation, the global average bunker prices of marine medium gas oil and very low sulfur fuel oil (VLSFO) – a mixture of various residual and distillate fuels – are about €1,126 per tonne and €754 per tonne (exchange rate of 0.98 €/€), respectively. In comparison, higher sulfur-content fuels, such as intermediate fuel oil 380, have average global prices of around €532 per tonne.

Liquefied natural gas

15. The switch from marine fuel oils to liquified natural gas (LNG) for ship diesel engines makes it possible to considerably reduce emissions of SO₂, NO_x, PM and BC. Compared to other oil products, LNG combustion barely generates SO₂ emissions and reductions of 90–100 per cent are achieved. In addition, NO_x and PM emission reductions are also obtained when switching to LNG, varying from approximately 64–90 per cent for NO_x and from 60–98 per cent for PM, depending on the engine characteristics and fuels used.¹¹ Furthermore, BC emission reductions of 75–90 per cent are achievable when replacing typical marine fuels by LNG. Nevertheless, the majority of ship engines running on LNG are dual-fuel engines (81 per cent of all installed or ordered LNG engines), as LNG has a high ignition temperature, therefore the environmental benefits related to LNG engine application are more moderate as conventional fuel or distillate oils are also used.

16. Anticipating the implementation of SECAs, NECAs and the IMO 2020 sulfur cap, as well as the willingness of the sector to carry out decarbonization, the interest in LNG engines has grown and the global share of delivered LNG-powered ships increased from 1.4 per cent to 13.5 per cent between 2010 and 2018. However, retrofitting LNG engines implies costly conversions, and an additional space of approximately 3–4 per cent of container capacity is required for the installation of the engine.¹²

17. Compared to other ship types, the initial investment for newly built LNG-powered ship is 10–20 per cent higher, which corresponds to approximately €1 million–€4 million, mostly due to the LNG storage tank, the fuel piping system and additional safety measures.¹³ Depending on engine size and whether the installation refers to a newly built ship or to retrofitting, capital investments for LNG engines vary from €219–€1,603 per kW nominal power.¹⁴ In terms of operational costs, fuel savings of about 5–10 per cent are

⁹ Rouïl and others, “ECAMED”.

¹⁰ Bryan Comer, “Black carbon and maritime shipping: the long road to regulating a short-lived climate pollutant”, *EM: The Magazine for Environmental Managers* (April 2019); and Daniel Lack and others, *Investigation of Appropriate Control Measures (Abatement Technologies) to Reduce Black carbon Emissions from International Shipping*, Air Pollution and Energy Efficiency Studies 1 (London, IMO, 2015).

¹¹ Hulda Winnes and others, “Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions (EMERGE). Deliverable 1.1, ‘Summary and analysis of available methods for SO_x, NO_x and PM, together with data on emissions, waste streams, costs and applicability’” (2020), available at <https://cordis.europa.eu/project/id/874990/results>.

¹² IMO, *Studies on the Feasibility and Use of LNG as a Fuel for Shipping*, Air Pollution and Energy Efficiency Studies 3 (London, 2016).

¹³ Jørgen Jordal-Jørgensen, *Reducing Air Pollution from Ships: A Cost Benefit Analysis and Feasibility Study on Possible Means for Further Reduction of Emissions – Environmental Project No. 1421 (2012)* (Copenhagen, Danish Ministry of the Environment – Environmental Protection Agency (EPA), 2012).

¹⁴ Stefan Åström and others, “The costs and benefits of a nitrogen emission control area in the Baltic and North Seas”, *Transportation Research Part D: Transport and Environment*, vol. 59 (March 2018), pp. 223–236.

achievable with LNG, compared to engines burning conventional fuel oils. In addition, switching from gas oil to LNG is estimated to have a positive impact on fuel price estimated at approximately 8 per cent for the same output energy generated.

18. When using LNG, the risk of methane slip, which is an important ozone precursor, and would also increase GHG emissions, is a potential significant drawback. In terms of CO₂ co-benefits, the use of LNG is advantageous, as compared to conventional fuel oils, because of the 25–28 per cent lower carbon content in LNG, along with some fuel savings.

19. Moreover, methane emissions generated by LNG burning are similar to those from burning conventional fuel oils. However, estimates of methane emissions of shipping due to the use of LNG should also take into account, on a wider scale, the upstream emissions generated in LNG production and transport (in terms of life cycle assessment (LCA)), as well as the above-mentioned methane slip during the use of LNG, corresponding to the amount of natural gas passing through the engine without burning. Methane slip is estimated to be relatively small for engines operating under diesel cycles, although it may become quite significant in engines operating under the Otto cycle, being estimated at approximately 2–5 per cent of fuel consumption on average.¹⁵ On this issue, manufacturers are making progress using a lean-burn principle,¹⁶ enhanced engine design or advanced control systems.

Biodiesels and biofuels

20. The switch to biodiesel or biofuels has recently attracted growing interest as an efficient way to decarbonize the shipping sector. Simultaneously, switching to biofuels enables PM reductions from 12–70 per cent, as compared to conventional fuel oils, depending on the percentage of biofuel in the final fuel mixture.¹⁷ Similarly, BC emission reductions from 38–75 per cent have been observed.¹⁸ Finally, some SO₂ emission reductions are also expected from the use of biofuels as compared to fuel oils.

21. Co-benefits in terms of GHG emission reductions are also expected. In order to fully assess these, the LCA of the upstream chain of production should be considered, as “land use and change” related to biofuel production could counterbalance the benefits. Nonetheless, significant progress in decarbonization can be achieved using biofuels, along with GHG reductions, from 70–100 per cent, achievable on an LCA basis.¹⁹ Fatty acid methyl ester biodiesel, hydrotreated vegetable oils, Fischer-Tropsch diesel, dimethyl ether (DME) and biomethanol are the most sustainable biofuels in terms of LCA.

22. Since biofuels have a lower energy content than fuel oils, an 8–11 per cent higher fuel consumption is expected for the same amount of energy delivered, consequently leading to increased operational costs for shipowners. In addition, biofuel prices are globally higher as compared to the usual fuel oils and, depending on the biofuel and its production mode, prices vary from +30 per cent to almost three times higher. Depending on the biofuel used, some engine modifications may be required (e.g., for DME), increasing the necessary overall investment, while other biofuels are already compatible with current engines (e.g., hydrated vegetable oils or Fischer-Tropsch diesel). Lastly, future possible growing demand in biofuels might result in some limits in production capacity and, consequently, in biofuel availability for final use, especially in the case of growing demand

¹⁵ International Renewable Energy Agency (IRENA), *A Pathway to Decarbonize the Shipping Sector by 2050*, (Abu Dhabi, 2021).

¹⁶ Air diluted by the excess amount of air as compared to the stoichiometric air required for combustion of unit mass of fuel.

¹⁷ Francesco Di Natale and Claudia Carotenuto, “Particulate matter in marine diesel engines exhausts: Emissions and control strategies”, *Transportation Research Part D: Transport and Environment*, vol. 40 (October 2015), pp. 166–191.

¹⁸ Lack and others, *Investigation of Appropriate Control Measures*.

¹⁹ IRENA, *A Pathway*.

in other sectors and transport modes, raising the need for further development of supply infrastructure.

Methanol and dimethyl ether

23. Methanol and dimethyl ether are other possible substitutes for conventional fuel oils. As these fuels have a very low sulfur content, SO₂ emissions can be drastically reduced, as well as PM emissions, with observed reductions of more than 90 per cent.²⁰ In addition, the fuel switch to methanol or DME enables the achievement of NO_x emission reductions from 30–60 per cent.²¹

24. In a scenario in which methanol or DME fuels are generated from biomass, such as biomass residues or black liquor gasification, major co-benefits in CO₂ emission reductions, from 95–100 per cent, can be expected. However, as with biofuels, LCA should be considered to assess the potential drawbacks and CO₂ emissions associated with production of methanol from biomass. In a scenario in which methanol or DME fuels are produced from fossil fuels, CO₂ emission reduction is moderate as compared to conventional marine fuel emissions but there would still be pollutant emission reductions associated.

25. As methanol and DME have a lower energy content, a fuel penalty of around 9 per cent is expected after the fuel switch. In addition, the fuel price of methanol or DME produced from biomass is higher by 36 per cent to more than triple, as compared to the price of VLSFO, and in the case of green e-methanol, combined with bioenergy with carbon capture storage, the fuel cost is expected to be 3.4–6.8 times higher. However, the cost of renewable e-methanol is expected to decrease significantly by 2050 and could fall to around 2.5–3.4 times the current price of VLSFO. However, other operating costs are associated with methanol use, due to safety requirements related to the supply of nitrogen as an inert gas blanket in methanol tanks, as well as the cost of staff training on managing hazard risks. Moreover, maintenance costs are estimated to be about €3–€4 per MWh generated. Lastly, in the cases of both newly built methanol compatible engines and existing retrofitted engines, the costs are higher as compared to the cost of conventional engines, the additional investment being estimated at €150–€225 per kW for new engines and €225–€450 per kW for retrofitted engines.²²

Hydrogen

26. The development of hydrogen as a fuel has attracted increasing attention in the past few years in the context of carbon neutral objectives. Hydrogen can be used either in fuel cells, dual fuel engines, or to replace heavy fuel oil in diesel engines. In terms of air pollutants, when used in fuel cells, the electrochemical reaction between hydrogen and oxygen generates heat and water only, therefore suppressing all emissions. The combustion of H₂ does not generate SO₂, PM or CO, but NO_x emissions are present and can even be higher than conventional fuels as the combustion temperatures are very high. Furthermore, where hydrogen is produced via water electrolysis, and when electricity is generated by renewable energy or nuclear power plants, the result is a CO₂-free fuel.

27. However, hydrogen use has drawbacks, including a major one in the form of the need for additional space, as compared to conventional fuel use. In fact, as compared to heavy fuel oil, the use of hydrogen requires five times more volume when liquid, and 10–15 times more volume when gaseous²³ because, due to the high flammability of hydrogen (H₂), specific storage solutions and safety procedures are necessary. In addition, in terms of technology readiness, hydrogen fuel cells for shipping are still under development and

²⁰ Joanne Ellis and Martin Svanberg, “Expected benefits, strategies, and implementation of methanol as a marine fuel for the smaller vessel fleet. SUMMETH - Sustainable Marine Methanol Deliverable D5.1.”, Final Report No. D5.1 (n.p., 2018).

²¹ DNV GL, “Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility”, Report No. 2015-1197, rev. 2 (n.p., 2016).

²² Winnes and others, “Evaluation, control and Mitigation”.

²³ Marketa Pape, “Decarbonizing maritime transport: the EU perspective”, Briefing (European Parliamentary Research Service, 2020).

current applications are more suitable for small- and medium-sized vessels, such as ferries or passenger ships. Lastly, some limits could arise in the availability of hydrogen generated by renewable electricity, with an increase in demand in various sectors, considering that, in 2019, the production of “green hydrogen” was only 4 per cent of total production;²⁴ for instance, a scale-up of three times current H₂ production would be necessary to supply the whole maritime shipping sector alone.

28. Lastly, limited information is available about the estimation of the additional investments needed, as compared to conventional diesel engines. The cost of equipment for electrolysis is estimated at \$650–\$1000 per kW (€606–€933 per kW according to the mid-2022 exchange rate). The cost of green H₂ production ranged between €126–€144 per MWh, in 2020, considering an average electricity price of €60 per MWh.²⁵ However, with the development of renewable energy production and increasing demand, green H₂ is expected to achieve competitive costs as compared to LNG and VLSFO by 2030.

Ammonia

29. Ammonia (NH₃) is a carbon- and sulfur-free substance, therefore its use as fuel do not imply CO₂ and SO₂ emissions, nor PM emissions, which is of great interest for the shipping sector. Used in fuel cell, NO_x emissions are also null, whereas they are rather similar to conventional fuels when used with H₂ in internal combustion engines²⁶. Additionally, ammonia can be of great interest for decarbonization, but its production mode needs to be considered.

30. The toxicity of ammonia and its risk of slip are the main limits to its use as fuel, thus no ammonia-powered ships are operational yet, despite numerous ongoing pilot and research projects. In addition, as compared to hydrogen, ammonia has a higher liquefaction temperature (-33°C), as well as a higher liquid density, making its storage simpler and cheaper. Hence, the resulting volume of fuel is 1.6–2.3 times higher, as compared to conventional fuel oils. Moreover, ammonia storage and transport infrastructures already exist around the world.

31. Currently, the production cost of green ammonia is €133–€205 per MWh, although it is expected to decrease significantly by 2050, and to fall as low as €62–€107 per MWh, making it cheaper than VLSFO.²⁷ The cost of bunkering facilities is another significant factor to be considered, because existing bunkering infrastructures are not compatible with ammonia storage.

Summary

32. In the table below the expected emission reductions, fuel consumption penalties and related costs of implementation are reported for some fuel switch options.

Emission reductions (per cent) by fuel switch technique

<i>Primary fuel switch techniques</i>	<i>SO₂</i>	<i>NO_x</i>	<i>PM</i>	<i>BC</i>	<i>Fuel penalty</i>	<i>Investment costs (Euros/kW)</i>	<i>Operations and maintenance costs (Euros)</i>
Switch to low sulfur fuels	Up to 99 per cent	-	50–90 per cent	0–80 per cent (median: 30 per cent)	-	-	222–594 per tonne of fuel
Switch to LNG	90–100 per cent	64–90 per cent	60–98 per cent	75–90 per cent	- 5–10 per cent	219–1 603	- 43 per tonne of fuel

²⁴ DNV GL, “Comparison of alternative marine fuels”, Report No. 2019-0567, rev. 4 (n.p., 2019).

²⁵ IRENA, *A Pathway*.

²⁶ Niels de Vries, “Safe and effective application of ammonia as a marine fuel” (2019)

²⁷ *ibid.*

<i>Primary fuel switch techniques</i>	<i>SO₂</i>	<i>NO_x</i>	<i>PM</i>	<i>BC</i>	<i>Fuel penalty</i>	<i>Investment costs (Euros/kW)</i>	<i>Operations and maintenance costs (Euros)</i>
							(+ fuel savings)
Switch to water-in-fuel emulsions	-	1–60 per cent	20–90 per cent	0–85 per cent	+ 0–2 per cent	11–44	33 000–271 000 per year
Switch to biodiesel and biofuels	-	-	12–70 per cent	38–75 per cent	+ 8–11 per cent	-	-
Switch to methanol	100 per cent	30–60 per cent	90–99 per cent	97 per cent	+ 9 per cent	150–450	10–15 per MWh for fuel and 3–4 per MWh for other operations and maintenance costs

B. Combustion modification

Water-in-fuel emulsions

33. The use of a stable solution of water-in-fuel (WiFE), or the injection of water directly into the combustion chamber, decreases the combustion temperature and, consequently, the thermal NO_x formation is also reduced by 1–60 per cent, depending on the water content.²⁸ Moreover, PM emission reductions of 20–90 per cent can be achieved by using WiFE, as well as BC emission reductions up to 85 per cent.²⁹

34. The use of WiFE tends to increase fuel oil consumption, although the fuel increase is marginal when the water content is equal to or lower than 30 per cent, and is estimated as about 1–2 per cent for higher water content values. The use of WiFE in existing marine engines implies a careful consideration of fuel injection capacity, while maintaining the same power output level. Moreover, the risk of formation of sulfurous acid should be carefully considered, because the acid could lead to undesired corrosion effects into the engine.

35. The capital investments related to the use of WiFE vary between about €11–€44 per kW, depending on whether the engine is retrofitted or new and its size.³⁰ Annual operational and maintenance costs are estimated at around €9–€9.5 per kW per year.³¹

Slide valves technique

36. Combustion modifications are another technique for decreasing shipping emissions. The modification of the combustion process by the implementation of slide valves, in replacement of convention fuel valves, enables a more complete combustion at lower peak-flame temperatures. At lower combustion temperatures, thermal NO_x formation decreases and emission reductions of up to 20 per cent can be achieved. Other co-benefits in PM and

²⁸ Incentive Partners and Litehauz, *Economic Impact Assessment of a NO_x Emission Control Area in the North Sea: Environmental Project No. 142. (2012)* (Copenhagen, Danish Ministry of the Environment – EPA, 2012).

²⁹ James J. Corbett, James J. Winebrake and Erin H. Green, “An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for Arctic shipping”, *Carbon Management*, vol. 1, No. 2 (2010), pp. 207–225.

³⁰ Lack and others, *Investigation of Appropriate Control Measures*.

³¹ Jordal-Jørgensen, *Reducing Air Pollution from Ships*.

BC emissions are also observed, with possible emission reductions from 10–50 per cent (25 per cent on average) for PM and 25–50 per cent, for BC.³² However, the implementation of slide valves implies a 2 per cent increase in fuel consumption, with consequent additional CO₂ and SO₂ emissions and costs.

37. The investment costs related to the implementation of slide valves are relatively moderate, with each valve cost estimated at around €230, leading to additional costs of power generated estimated between €0.33–€1.43 per kW.³³ Moreover, unlike other reducing techniques, no additional operational and maintenance costs are associated with slide valves.

Summary

Emission reductions (per cent) by combustion modification technique

Primary technique	SO ₂	NO _x	PM	BC	Fuel penalty	Investment costs (Euros/kW)	Operations and maintenance costs (Euros/kW)
Water-in-fuel emulsions	Proportional to fuel penalty	1–60 per cent	20–90 per cent	0–85 per cent	0–2 per cent	11–44	9–10
Slide valves		0–20 per cent	10–50 per cent	10–50 per cent	+ 2 per cent	0.3–1.4	none

C. Adjustment in the propulsion mode

Slow steaming technique

38. The slow steaming technique consists in reducing cruising speed to save the fuel used, as fuel consumption is roughly proportional to the third power of the ship speed. Hence, as an example, reducing the cruising speed from 23 knots to 18 knots (-21.7 per cent) may allow for a reduction in fuel consumption of 50 per cent, while speed reductions of 10 per cent and 20 per cent are reported to result in fuel savings of 15–19 per cent and 36–39 per cent, respectively. Emissions of SO₂ and CO₂ are directly proportional to fuel consumption, therefore considerable emission reductions can be achieved through reducing cruising speed. Simultaneously, the fuel savings make it possible to decrease NO_x and PM emissions during the cruising time by up to 64 per cent and 69 per cent, respectively, for speed reductions of around 50 per cent.³⁴ In addition, BC emission reductions of up to 30 per cent can be obtained when the engine is derated (i.e. tuned so that the output power is lower than in normal operating conditions). However, BC emissions may increase at lower values of the engine load, even without derating. At the same time, carbon monoxide (CO) emissions are negatively affected by lower engine load values.

39. In terms of cost, the main consequence of implementation of the slow steaming technique to be considered by shipowners is increased delivery times. Therefore, the need for additional ships in the fleet, to compensate for increased delivery times, would adversely bias the environmental benefits. One study³⁵ revealed that imposing the slow steaming technique in the European Union territorial sea area (within 12 nautical miles of the coastline) or exclusive economic zone (i.e. 12–200 nautical miles from the coastline)

³² Bryan Comer and others, *Black carbon emissions and fuel use in global shipping: 2015* (n.p., International Council on Clean Transportation, 2017).

³³ Corbett and others, “An assessment of technologies”.

³⁴ J. Wayne Miller and others, *In-use Emissions Test Program at VSR Speeds for Oceangoing Container Ship: Report* (n.p., California Air Resources Board, 2012).

³⁵ Paul Campling Liliame Janssen and Kris Vanherle, *Specific Evaluation of Emissions from Shipping Including Assessment for the Establishment of Possible New Emission Control Areas in European Seas*, (n.p., Flemish Institute for Technological Research NV, 2012).

may result in fuel savings of up to €410 million and €3,447 million in 2030, respectively (no additional maintenance or ship fleet resize included). Another study³⁶ reported that, for a 4,000 twenty-foot equivalent unit³⁷ ship category, reducing the speed from 23 knots to 17 knots reduces the bunker contribution to the total operational costs from 68 per cent to 51 per cent while running on fuel oil (intermediate fuel oil 380) and from 77 per cent to 62 per cent for marine gas oil. Lastly, engine conversion to an electronically controlled engine would imply additional investments, estimated at around €71 per kW for a 9.5 MW engine.

Battery-powered ships (electric or hybrid)

40. There has been increased interest in the use of battery-powered ships for short-haul sea shipping, where frequent stops are required and infrastructures are more available. For instance, Norway has electrified its ferries since 2015. In the light of the sector decarbonization process, hybrid/electric ships are of great interest and CO₂ emission reductions of 10–40 per cent can be achieved for hybrid ships, whereas total CO₂ emissions elimination is possible for fully electric ships, if electricity is generated from renewable or nuclear sources. In addition, the exhaust emission generation switches from the ship engines to the thermal power plant, where much more efficient equipment is installed to abate air pollutants.

41. However, it should be considered that the installation of battery systems, having a lifetime of about 8–10 years, makes this equipment a significantly more costly option as compared to diesel engines. Moreover, in terms of CO₂ emissions, a wider perspective considering LCA would be useful to assess the CO₂ upstream emissions, similarly to what happens in electricity generation or battery production.

Wind-propulsion assistance

42. The use of wind propulsion to reduce fuel consumption is also a technique that has attracted more interest. The first prototypes in the testing phase are rotor sails, wing sails and towing kites. Depending on the technology implemented, the ship type and the meteorological conditions, fuel savings of up to 50 per cent can be expected, although the average annual savings of the tested ships was about 8–10 per cent.³⁸ In one specific case, it has been claimed that, if applied to the entire world tanker fleet, rotor sail technology could reduce CO₂ emissions by more than 30 Mt, which represents about 3 per cent of total GHG shipping emissions.

43. Nevertheless, some limitations to wind propulsion have to be considered, such as deck layout, loading processes and increased ship heeling. In addition, kites and rotors, the most common wind-propulsion solutions are estimated to be more effective at lower speed regimes (e.g., below 16 knots for kites).³⁹

³⁶ C. Chrysopoulos and M. Nijdam, “The effect of the revised 1999/32/EC directive on the liner service design in container shipping market” (n.p., 2012).

³⁷ Unit used for cargo capacity for container ships.

³⁸ Jon Excell, “The rise of the wind ships”, *The Engineer*, 19 February 2020. Available at www.theengineer.co.uk/content/in-depth/the-rise-of-the-wind-ships/.

³⁹ Päiva Aakko-Saksa and Kati Lehtoranta, *Ship Emissions in the Future: Review*, Research Report No. VTT-R-00335-19 (n.p., VTT Technical Research Centre of Finland, 2019).

Summary

Emission reductions (per cent) by adjustment in propulsion mode technique

Primary technique	SO ₂	NO _x	PM	BC	Fuel savings
Slow steaming		0–64 per cent	0–69 per cent	0–30 per cent if engine derated, possible increase at low loads	0–50 per cent
Battery-powered (electric or hybrid)	Proportional to fuel savings for all techniques	No emission if fully electric			100 per cent if electric
Wind-propulsion assistance		No information found but reductions expected due to fuel savings			0–50 per cent (8–10 per cent observed in practice)

VI. Best available techniques for ships: secondary techniques

Wet scrubbers

44. The functional principle of wet scrubbers is based upon channelling the exhaust gas flow through a liquid alkaline solution (e.g., seawater or chemical solution), which neutralizes the SO_x present in the exhaust gas through chemical reactions. Three types of wet scrubbers exist:

(a) Open-loop: seawater is pumped and used as alkaline solution to neutralize the SO_x compounds to generate sulfuric acid. A flowrate of wash water, ranging between 45–60 m³/MWh is necessary when a 3.5 weight per cent fuel oil is used.⁴⁰ The wastewater, properly treated, is then discharged into the sea;

(b) Closed-loop: in this system, fresh water mixed with added alkaline chemicals (e.g., sodium hydroxide) is used to react with SO_x and generate sodium sulfate. The wastewater then flows through a tank to be cleaned, and then recirculates into the scrubber. The waterflow required is lower than in the case of open-loop systems, estimated at about 20–30 m³/MWh, and running the water system represents about 0.5–1 per cent of engine power.⁴¹ This configuration is particularly useful for ships travelling in low-alkalinity seawaters or areas where water discharge is prohibited;

(c) Hybrid: the technology combines both open- and closed-loop scrubbers and enables ships to be flexible and adapt to the conditions/restrictions of the seas on which they operate.

45. The installation of wet scrubbers makes it possible to reduce ship emissions by up to 98 per cent for SO₂, up to 90 per cent for PM, with average reduction rates of around 30 per cent, and up to 70 per cent for BC, with average observed reductions of 16–37 per cent, depending on the fuel used, the engine type and the operating conditions, including the operating conditions of the scrubber (i.e., unit dimension, residence time of the exhaust gases and reagent consumption).⁴² The implementation of scrubbers implies a fuel consumption penalty of 0.5–3 per cent, depending on the expected exhaust gases emission level, the fuel used, the scrubber type and design and the engine characteristics, which indirectly slightly increases CO₂ emissions.

⁴⁰ Lloyd's Register, *Understanding Exhaust Gas Treatment Systems. Guidance for Shipowners and Operators* (London, 2012).

⁴¹ *ibid.*

⁴² Winnes and others, "Evaluation, control and Mitigation"; and MAN Diesel and Turbo, *MAN B&W Two-stroke Marine Engines - Emission Project Guide for Marpol Annex VI Regulations* (n.p., 2018).

46. Scrubbers have the advantage of being compatible with waste heat recovery systems or other exhaust gas treatments, such as exhaust gas recirculation (EGR), selective catalytic reduction (SCR), placed downstream of the scrubber, and also with PM removal technologies. Nevertheless, some limitations arise from scrubber installation, and, in particular, space requirements, as the unit can vary from about 65 m³, for small engines, to more than 800 m³, for larger units.⁴³ In particular, in the case of closed-loop systems, more space is required because of the wastewater treatment and storage units, as well as the reagent storage tank.

47. The implementation of scrubbers is expensive with capital investments of €100–€433 per kW, depending on the scrubber type, new installation or retrofit. In particular, open-loop scrubbers have costs of €100–€216 per kW, while closed-loop scrubbers have costs of €200–€433 per kW, depending on the engine size and the scrubber design.⁴⁴ Hybrid scrubbers are less common in pilot projects but, in one case reported, the capital cost for such installation was about €225 per kW for new built and €338 per kW for retrofit.⁴⁵ Besides that, while in the case of open-loop scrubbers, only operational costs for the increased fuel consumption are considered, in the case of closed-loop systems, along with the fuel penalty, the costs of sodium hydroxide and water, as well as sludge disposal, also have to be computed, for total operational costs of about €6–€11 per MWh.⁴⁶ Lastly, maintenance costs are estimated to be about €0.6–€0.9 per MWh for open-loop scrubbers and €0.3–€1.2 per MWh for closed-loop units.⁴⁷ In total, considering the whole scrubber lifetime, operational and maintenance costs are expected to be about 2–3 per cent of the total investment costs for both scrubber types.

48. During the use of scrubbers, hazardous substances, such as sulfur, PAH, heavy metals and nitrates, can be transferred to the wastewater, depending on the fuel used, the water treatment and the chemicals added.⁴⁸ In addition, scrubber wastewaters are characterized by low pH values and high temperatures. Therefore, specific rules are applied to wastewater discharge into seawaters in order to prevent its negative impact, such as acidification, and to introduce suitable requirements on pH value and PAH, nitrate and particle concentrations. Hence, several ports and specific areas around the world have restricted or banned wastewater discharge (e.g., China, Singapore, Belgium, Ireland, California, the Suez Canal, the Panama Canal, the German part of the Rhine River), thus open-loop scrubbers, or impose the use of the closed-loop mode for hybrid scrubbers.

Dry scrubbers

49. Dry scrubbers have also been adapted to marine engines and have fulfilled their potential in SO₂ emission reduction. The functional principle is similar to that of wet scrubbers but, instead of injecting a liquid solution into the scrubber unit, powdered sodium bicarbonate or calcium hydroxide granules can be directly injected into the exhaust gas duct, to react with SO_x compounds and generate solid sodium sulfate or carbonate. Then, the exhaust gases flow through a PM removal equipment such as a baghouse filter, to remove the reaction products, as well as soot, BC and heavy metals resulting from the combustion, which will lastly be discharged into a proper container.

⁴³ MAN Diesel and Turbo, “MAN B&W”.

⁴⁴ Peter Bosch and others, “Cost Benefit Analysis to support the impact assessment accompanying the revision of Directive 1999/32/EC on the sulfur content of certain liquid fuels”, AEA/ED45756/Issue 3 (n.p., AEA, 2009); and Åström and others, “The costs and benefits of a nitrogen emission control area”.

⁴⁵ Janusz Cofala and others, “The potential for cost-effective air emission reductions from international shipping through designation of further Emission Control Areas in EU waters with focus on the Mediterranean Sea” (n.p., International Institute for Applied Systems Analysis, 2018).

⁴⁶ Eelco Den Boer and Maarten't Hoen, *Scrubbers: An Economic and Ecological Assessment* (Delft, CE Delft, 2015).

⁴⁷ Winnes and others, “Evaluation, control and Mitigation”.

⁴⁸ Christer Ågren, “Environmental impacts of ship scrubbers”, *Acid News*, No. 3 (October 2019), pp. 17–18.

50. Dry scrubbers make it possible to achieve SO_x emission reductions of over 99 per cent, as well as similar PM emission reductions (both in concentration and weight).⁴⁹ Dry scrubber technology, as compared to open-loop scrubbers, has the advantage that no wastewater is discharged into the sea and, compared to closed-loop units, produces a lower volume of residues. In addition, the energy consumption necessary to its working is rather modest, with no risk of corrosion. As compared to wet scrubbers, the baghouse filters with sodium bicarbonate injection have the advantage of low electrical consumption and the fuel consumption penalty is estimated to be about 0.2–0.3 per cent. Moreover, as compared to diesel particulate filters (DPF), the pressure drop is not significantly increased in the baghouse filters. As for closed-loop scrubbers, some additional room is necessary for the storage of the reactive agent and the residues. Such a system is compatible with SCR or EGR. No information on economic aspects has been collected for this technology and further development is necessary for a wider implementation. This technology has already been tested in a few pilot projects, although further development is needed to increase its robustness in shipping applications and assess the associated economic investments.

Exhaust gas recirculation

51. Exhaust gas recirculation (EGR) systems redirect engine exhaust gases back into the combustion chamber after cleaning the gases, in order to decrease the combustion temperature and pressure and hinder thermal NO_x formation. The exhaust gases flow through an intercooler device to lower its temperature and oxygen content, while increasing its heat capacity, and then a diesel particulate filter (or scrubber) placed downstream removes the combustion residues and prevents engine corrosion or clogging. An electronic control system is necessary to operate the EGR system.

52. The NO_x removal efficiency of the EGR system depends on the recirculation rates, and emission reductions of 25–80 per cent have been observed in diesel engines.⁵⁰ The MARPOL tier III NO_x limits can be fulfilled with a 40 per cent recirculation rate in some recent EGR systems applied to two-stroke engines. However, in medium-speed engines, compliance with the limits needs to be demonstrated, the main challenges being the high flue-gas SO₂ and PM concentrations. Implementation of EGR units results in engine power reduction, as well as a fuel consumption penalty varying up to +4 per cent, which thus implies an increase in CO₂ emissions. Moreover, EGR implementation can even result in CO and PM emission increases, if not operated properly.

53. In terms of cost estimation, the investments needed for EGR are quite reasonable and the cost of the hardware to control the recirculating flow is the most considerable part of the investment costs. In total, capital investments are estimated to vary between €36–€60 per kW depending on the desired recirculating rate and NO_x emission reduction level.⁵¹ The operational costs vary between €17–€25 per kW and, considering also the maintenance costs, the total costs can be estimated at about €1–€3 per MWh.⁵² Implementation of EGR implies a fuel consumption penalty of 1–2 per cent, which can be compensated for by some fuel savings if the engine is downgraded from tier II to tier I.

Selective catalytic reduction

54. Selective catalytic reduction (SCR) is a robust and mature technology in the industrial sectors and in marine shipping applications, which makes it possible to significantly tackle NO_x emissions and achieve tier III emission levels. The SCR functional

⁴⁹ International Maritime Organization, “Evaluation and harmonization of rules and guidance on the discharge of liquid effluents from EGCS into waters, including conditions and areas”, submission to seventy-fifth session of the Marine Environment Protection Committee, document MEPC 75/INF.13.

⁵⁰ Giannis Papadimitriou and others, *Best Available Techniques for Mobile Sources in Support of a Guidance Document to the Gothenburg Protocol of the LRTAP Convention* (n.p., European Commission, 2015).

⁵¹ Rasmus Parsmo and others, *NO_x Abatement in the Baltic Sea: An Evaluation of Different Policy Instruments*, No. C 247 (Stockholm, IVL Swedish Environmental Research Institute, 2017).

⁵² *ibid.*

principle consists of inducing a chemical reaction within a catalyst by introducing nitrogen-reducing compounds, such as an ammonia water solution (NH₃) or urea, into the exhaust gas duct, so as to have a chemical reaction with the NO_x present in the exhaust gas, and generate nitrogen (N₂) and water (H₂O), as reaction products. The most common reducing solution is a mixture of 40 per cent of urea in water. Implementing SCR units makes it possible to achieve NO_x emission reductions of 70–95 per cent, depending on the engine operating conditions.⁵³ When an oxidation catalyst is applied to oxidize the remaining NH₃, co-benefits in emission reduction can also be obtained for VOCs, CO and PM, estimated at 50–90 per cent, 50–90 per cent and 10–40 per cent, respectively.⁵⁴

55. However, the use of SCR technology implies fuel consumption penalties of around 2 per cent, with a consequent negative impact on ship emissions. In addition, an additional power of about 5 kW per MW of engine power is needed to supply the reducing agent, the compressed air and the heat. In terms of emissions, operating the SCR implies the risk of ammonia leak, which increases over time, as the SCR deteriorates. However, controlling techniques, such as calibration optimization, catalyst dimensioning or catalyst introduction, can be applied to minimize the risk increase.⁵⁵ Outside NECAs, tier I engines equipped with SCR are more efficient than tier II engines by 4 per cent, and can be used to comply with tier II emission levels to save fuel.⁵⁶

56. Some specific limitations may arise when implementing SCR in marine vessels. SCR can be used with any marine fuel oil, although the catalytic reaction is more efficient at lower SO₂ levels in the exhaust gases and at higher temperatures. In addition, special care must be taken to avoid the formation of ammonium bisulfate or sulfuric acid, which is more probable while operating with higher sulfured fuels at low temperatures. Conversely, the exhaust gas temperature has to be low enough to avoid damage to the catalyst, oxidize the NH₃ and increase SO₃ formation. Hence, exhaust gas temperature monitoring equipment is vital and is often provided within the SCR unit. The size of the SCR unit depends on the engine power, the gas flow, the reducing agent used (e.g., ammonia solutions require a smaller mixer than urea but the storage is more complex and hazardous), as well as the catalyst lifetime (i.e., larger catalysts last longer). Periodic maintenance and controlled operations are necessary to ensure adequate SCR efficiency and durability, especially taking into account the possibility of dust trapped or chemical compounds poisoning the catalyst.

57. SCR technologies can be readily combined with PM removal technologies, such as DPFs, and/or with scrubbers, placed downstream from the SCR to optimize heat transfer efficiency.

58. The capital investments for the implementation of SCR units vary from about €19–€100 per kW⁵⁷ depending on the engine size (smaller engines may have a higher cost per kW), newbuild application or a retrofit, and the engine type (two- or four-stroke). The operating and maintenance costs of SCR vary from €3–€10 per MWh, and higher average costs are observed for two-stroke engines, as compared to four-stroke engines.⁵⁸ The operational costs concern mostly catalyst replacement, urea or ammonia consumption and associated manpower costs. Nitrogen reagent consumption is the highest contribution to the cost and, for instance, urea consumption costs are estimated to be €1–€5 per MWh.⁵⁹ Lastly, the maintenance costs are about 1.2 per cent of the annualized investments.

⁵³ Winnes and others, “Evaluation, control and Mitigation”.

⁵⁴ *ibid.*

⁵⁵ Incentive Partners and Litehauz, *Economic Impact Assessment*.

⁵⁶ Lloyd’s Register, *Understanding Exhaust Gas Treatment Systems*.

⁵⁷ Hulda Winnes and others, NO_x controls for shipping in EU Seas. Transport and Environment, Report No. U5552 (Stockholm, IVL Swedish Environmental Research Institute, 2016).

⁵⁸ Incentive Partners and Litehauz, *Economic Impact Assessment*.

⁵⁹ Rouïl and others, “ECAMED”.

Diesel particulate filters

59. Diesel particulate filters (DPFs) consist of a porous ceramic substrate to trap the solid particles present in the exhaust gases, thus cleaning the gases as they flow through the filter. In compression ignition diesel engines, PM emission reductions of 45–92 per cent can be achieved with DPF implementation, and BC emissions can also be reduced up to 70–90 per cent.⁶⁰ In addition, when a diesel oxidation catalyst or a catalytic coating, in wall-flow design, is implemented, reductions of CO and VOC emissions of 60–90 per cent can be achieved. However, diesel oxidation catalyst application is limited in the case of fuel sulfur content higher than 50 parts per million. Moreover, after some time in use, the captured particles accumulate onto the filter and increase the pressure drop; therefore a burning or oxidation system has to be introduced, with consequent negative effects on NO_x and CO₂ emissions. Lastly, DPF application implies a fuel consumption penalty of 1–4 per cent, which also worsens the ship environmental footprint, as do most of the flue gas treatment technologies.

60. In order to ensure proper functioning, the DPF technique requires a relatively low-sulfur content in the fuels used (lower than 0.5 per cent/weight, which should not be a problem since the IMO 2020 sulfur cap entered into force), as well as temperature monitoring of the exhaust gas. The additional space necessary to implement DPF, because of its large dimensions, can be an additional limitation, in particular considering the soot burners for regeneration. Lastly, DPF applications on sea-going ships are still rather scarce as compared to in the automotive sector; moreover, recent studies reported that only short-term tests have been performed, therefore this technology is still at the experimental phase in marine applications.

Baghouse filters

61. Baghouse filters are high-performing filters that are widely implemented in land-based plants, and, more recently, have been applied to a few marine pilot projects. By using baghouse filters, important reductions in PM and BC emissions, higher than 99 per cent, have been observed.⁶¹ In general, to ensure good efficiency and longevity of the baghouse filter, the exhaust gases need to be desulfurized prior to entering the filter. Therefore, SO_x emissions can also be drastically reduced when a reactive agent, such as sodium bicarbonate, is injected into the baghouse filter. Lastly, a decrease in NO_x emissions is also achievable by using catalytic bags, with urea injection upstream, which, however, could increase NH₃ emissions, through NH₃ slip.

62. The main advantages of this technology are its compatibility with DeSO_x and DeNO_x techniques, for the purposes of compliance with the MARPOL annexes, the additional needed power consumption is small, the pressure drop (10–20 millibars) and the maintenance needs are rather low.

VII. Best available techniques in ports

A. Generic reduction techniques

63. The implementation of reduction techniques for ships at berth in port areas has proven efficient; for instance, the Los Angeles and Long Beach ports achieved PM, NO_x and SO₂ emission reductions of 81 per cent, 55 per cent and 89 per cent, respectively, between 2005 and 2013, thanks to the reduction strategy adopted.⁶² The best available techniques (BATs) for propulsion engines presented above make it possible to achieve emission reductions in ports as well, while only some of the exhaust gas cleaning techniques (i.e., secondary measures) could be unavailable at very low engine loads.

⁶⁰ Papadimitriou and others, *Best Available Techniques*.

⁶¹ LAB, DeepBlueLAB - Bag particle filters. Personal communication (2020).

⁶² IMO, “Study of emission control and energy efficiency measures for ships in the port area”, MEPC 68/INF.16.

Furthermore, auxiliary engines contribute as much as, or even more, than main propulsion engines to ship emissions at berth; therefore, auxiliary engines also need to be equipped with exhaust gases treatment systems.

64. The optimization of scheduled time at-berth, and the implementation of automated mooring systems (AMS) and shore-side pumps for bulk liquid unloading operations are other effective means of limiting air quality degradation in harbour areas. Using AMS enables to tackle annual NO_x emissions equivalent to 5,000 diesel cars in Helsinki⁶³, as well as saving fuels and CO₂ emissions thanks to shorter berth times. Another study reported annual emission reductions of 3.6, 11.2, 3.5 and 3.6 per cent for NO_x, PM, SO₂ and CO₂, respectively, thanks to AMS infrastructures in the port of Izmit Bay⁶⁴. For the loading and unloading of volatile bulk liquids, vapour recovery systems are suitable to reduce VOC fugitive emissions by up to 99 per cent.⁶⁵ Moreover, it is also important to analyse other sources of emissions in port areas, such as vehicles circulating in the area, paving roads, engines for energy supply and cargo-handling equipment. The replacement of machines with more modern models, in compliance with the best environmental standards, or switching to cleaner fuels, also make it possible to improve ambient air quality in port areas.

B. Onshore and barge power supply systems

65. Shore power, also known as “cold ironing”, consists of supplying electricity to vessels at berth⁶⁶, so that their main and auxiliary engines can be switched off. Hence, as with most electrification techniques, such as electric vehicles, this technique is efficient when the electrical supply is generated in a cleaner way, as compared to fuel combustion in ship engines. In general, this is the case, because, in large combustion plants such as thermal power plants, pollutant emissions are much better controlled and regulated. In addition, when electricity is generated by renewable or nuclear energy, this technique supplies virtually zero emission power in terms of exhaust emissions, although this is not true considering the whole LCA analysis, which is of great interest in the decarbonizing pathway of the sector. This technique is particularly interesting and important for health matters as berths are often densely populated areas.

66. In regions where electricity generation from power plants is well regulated, the implementation of onshore power supply (OPS) made it possible to achieve emissions reductions of NO_x, SO₂, PM and VOC of up to 95 per cent.⁶⁷ The experience in China of switching to medium diesel oil (MDO) with a sulfur content of 0.5 weight per cent, burnt in auxiliary engines, and implementing shore supply with electricity, 65.5 per cent of which is generated by power plants equipped with abatement technologies and burning desulfurized coal, with remaining electricity needs being met by renewable energies or nuclear power, applied to all ships at berth in Chinese terminals, resulted in emission reductions of 81 per cent for SO₂, 97 per cent for NO_x, 77 per cent for PM and 22 per cent for CO₂.⁶⁸ In terms of carbon neutrality, the implementation of shore-power supply in Europe (EU is in the process of introducing a regulatory regime making OPS mandatory) has been estimated to reduce CO₂ emissions by 39 per cent globally, whereas, at local levels, emission reductions

⁶³ Cavotec “Automated mooring substantially reduces harmful emissions in Helsinki city centre” (2021) available at: <https://www.mynewsdesk.com/cavotec/pressreleases/automated-mooring-substantially-reduces-harmful-emissions-in-helsinki-city-centre-3116249>

⁶⁴ Seyhan and others, “Evaluating the emission reduction efficiency of automatic mooring system and cold ironing: the case of a port in Izmit Bay”. *Australian Journal of Maritime & Ocean Affairs*, 15(2), 227-245 (2023).

⁶⁵ Winnes and others, “NO_x controls for shipping in EU Seas”.

⁶⁶ European Maritime Safety Agency “Shore-Side Electricity (SSE). Guidance to Port Authorities and Administration” (2022) available at <https://www.emsa.europa.eu/electrification/sse.html>

⁶⁷ *ibid*⁶⁵.

⁶⁸ Cheng Jieling and Li Haibo, “Analysis of Environmental Benefits of Shore Power for Preventing and Controlling Air Pollution Caused by Vessels at Berth”, *E3S Web of Conferences*, vol. 53, art. No. 04036 (2018).

of 54–99 per cent are observed (99 per cent in Oslo, probably due to very low electricity carbon content).⁶⁹

67. When considering OPS system, some challenges arise regarding the grid frequency, the voltage system on board, the dynamic or static loading of power, the grounding, the number of connecting points, the berth configuration, the retrofit potential in existing ships, as well as the cost of electricity. However, it should be considered that OPS also has the benefits of reducing overall port noise and ship vibrations, and, implicitly, encouraging the shift to electric or hybrid batteries. Container ships, reefer ships, cruise ships and ferries are the best candidates for implementing cold ironing, as they operate in regular liner-type services and need significant amounts of electricity while at berth.

68. OPS systems should include the utility grid connection, underground electrical vaults, power converter, as well as suitable space for the unit, receptacle pits, cabling and synchronization equipment and wharf infrastructures. All these infrastructures require investments, which are estimated to vary between \$1 million to \$15 million per berth (€0.9–€14 million using the mid-2022 exchange rate), based on several studies carried out in ports of the United States of America and Canada.⁷⁰ Planning and designing cold ironing implementation, prior to port construction, makes possible lower investments. From the point of view of the shipowner, the vessel retrofit costs to allow existing ships connection to onshore-power vary between \$0.4 million and \$2 million (€0.37–€1.87 million using the mid-2022 exchange rate), depending on the ship design, and such costs are expected to decrease, as implementation of the technology implementation increases.⁷¹ Furthermore, nowadays, most newbuild vessels are already designed for OPS.

69. The barge power supply system is another similar available technique, which consists of providing electrical power using an engine external to the ship, which has complied with better emission standards as compared to the ship engines. In general, LNG or other alternative fuels, such as biofuels, are used in barge power engines. In addition, this technique offers the advantage of easy use, high movability from one dock to another and require less infrastructure investments than OPS. The same constraints as in the case of onshore power systems are raised for ships. Several and various emission reductions can be obtained, depending on the barge of the power unit equipment and the operating conditions. In the case of an Otto cycle engine, powered with LNG, emission reductions of up to 80 per cent for NO_x, 98 per cent for PM, almost 100 per cent for SO₂ and 30 per cent for CO₂ can be expected⁷². The cost for this technology has been estimated at about \$0.2 million (€0.19 million using the mid-2022 exchange rate), for the retrofit of the ship and about \$1,000 per hour (€933 using the mid-2022 exchange rate), for the operations of the barge power system.

C. Shore- or barge-based exhaust cleaning techniques

70. Another possibility to reduce ship emissions in ports is to clean the exhaust gases at the exit of the stack of the ship, which is directly connected to exhaust gas cleaning systems on shore. Moreover, these systems require power supply to operate and generate exhaust gases themselves, which can be cleaned simultaneously to the ship exhaust gases. These systems generally comprise a wet scrubber in combination with a SCR and are aimed at achieving emission levels similar to the case of onshore power supply systems. Emission

⁶⁹ IMO, “Reduction of GHG emissions from ships. Vessel shore power installation worldwide”, MEPC 73/INF.29/Rev.1.

⁷⁰ Global Environment Facility (GEF)-United Nations Development Programme (UNDP)-IMO GloMEEP Project and International Association of Ports and Harbours (IAPH), *Port Emissions Toolkit, Guide No.2 – Development of Port Emissions Reduction Strategies* (n.p., 2018).

⁷¹ Thalís Zis, “Prospects of cold ironing as an emissions reduction option”, *Transportation Research Part A: Policy and Practice*, vol. 119 (January 2019), pp. 82–95.

⁷² IMO, “Study of emission control and energy efficiency measures for ships in the port area”, MEPC 68/INF.16.

reductions of 98 per cent and 95 per cent, for PM and NO_x, respectively, can be achieved when implementing the described technique.⁷³

71. The main advantage of this technique is that no modifications on the ship are needed; moreover, the cleaning system can operate either at anchor, installed on a barge, or at berth. However, some limitations exist regarding the application of this technique in relation to port and dock configurations, terminal space and possible interference with loading and unloading operations. This technique is considered not yet fully mature and needs to be further developed in order to prove its effectiveness at different exhaust loads. Currently, scant cost information is available for this technique. In one case, the manufacturer estimated the individual cost of this system at around \$8 million (€7.5 million using the mid-2022 exchange rate), when a large number of systems are implemented.⁷⁴

VIII. Conclusions and recommendations

72. In the above paragraphs, several techniques for abatement of ship-generated emissions, both during navigation and at berth, have been illustrated, also considering limits in the application, advantages and disadvantages, efficiency in the emission reductions, including estimation of investment and operational costs. Some of the techniques discussed are mature technology while others require further development. On the other hand, it is clear that not all the techniques are suitable for and applicable to all vessel types and sizes.

73. There is a need for regulation at the international level, mainly in the frame of the MARPOL Convention. Some aspects can also be addressed at local, national or regional level. At least in some areas of the UNECE region (e.g., the European Union subregion), regulations have been introduced to control marine fuel quality, and, at the local level, in some ports, onshore power supply projects are being pursued. Measures implemented at the local level, especially on the quality and type of fuels and on port infrastructure, are of the utmost importance in improving air quality in the concerned cities.

74. Innovative techniques are under development and they might contribute to further emission reductions once they have moved from the experimental phase to the application phase on a large scale.

75. It is recommended that the Parties' experts take into due consideration the techniques illustrated in the present guidance document when participating in further discussions and developments of international rules (e.g., MARPOL, UNCLOS) and in developing their national emission reduction plans, also considering synergies tackling air pollution and climate change/decarbonisation simultaneously.

⁷³ G. Tan Weiwei and others, "Application of the DOC-DPF integrated exhaust particle treatment device for new diesel marine engines", *IOP Conference Series: Earth and Environment Science*, vol. 358, No. 4 (2019).

⁷⁴ GEF-UNDP-IMO GloMEEP Project and IAPH, *Port Emissions Toolkit*.