United Nations ECE/EB.AIR/2023/7

Economic and Social Council

Distr.: General
25 September 2023

Original: English

Economic Commission for Europe

Executive Body for the Convention on Long-range Transboundary Air Pollution

Forty-third session
Geneva, 11–14 December 2023
Item 3 (b) of the provisional agenda
Review of the implementation of the 2022–2023 workplan: policy

Draft guidance document on technical measures for reduction of air pollutant emissions from shipping

Summary

The present document, prepared by the Task Force on Techno-economic Issues in accordance with its mandate, was discussed by the Working Group on Strategies and Review at its sixty-first session (Geneva, 4–6 September 2023) and forwarded as amended during the session to the Executive Body for adoption at its forty-third session (ECE/EB.AIR/130, forthcoming). The document presents updated information on the effective means to reduce emissions from maritime shipping.

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), PM_{10} 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 greenhouse gas emission (GHG) reductions. Further analysis and complementary information are provided in the associated background informal technical report.[1]

3. In general, all techniques assessed provide measurable emission reductions, over a reference technology, and they are technically implementable under certain specific conditions, depending on the techniques. However, the list of all existing and/or promising future measures is not exhaustive.

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 in marine fuel combustion. According to the European Monitoring and Evaluation Programme/European Environment Agency air pollutant emissions inventory guidebook,[2] the granulometry is 100 per cent for PM_{10} (meaning that all particles measured are 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 exhaust gases are diluted before measurement, 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 (SO_2) 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 from 1 May 2025,

[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 Environment Agency (EEA), *EMEP/EEA air pollutant emission inventory guidebook 2019: Technical guidance to prepare national emission inventories*, Report No 13/2019 (Luxembourg, Publications Office of the European Union, 2019).

and the implementation of North-East Atlantic and Canadian ECAs is under discussion. See also the International Institute for Applied Systems Analysis study (2018).[3]

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 constantly increasing, and was the highest ever observed in 2019 (11 megatons (Mt)), which was almost double the amount for the year 2000 (5.9 Mt), and almost reached its pre-crisis level in 2021.[4] 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.[5]

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 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 GHG efficient modal transport due to its low GHG emission rate per ton of transported goods, as compared to other types of transport, shipping transport was still responsible for about 2.9 per cent of all anthropogenic carbon dioxide (CO_2) 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 SO_2 per ton-km, among the various transport modes. As compared to large trucks, maritime shipping NO_x emissions per ton-km are slightly lower, but the PM_{10} 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 and potentially higher emission rates at berth than in the cruise phase, because engines operate at low loads. Indeed, emissions in harbours are estimated from a few per cent up to 20–30 per cent of total ship emissions of SO_2, NO_x and PM depending upon vessel type.[6]

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

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[3] Janusz Cofala and others, *Final Report: The potential for cost-effective air emission reduction from international shipping through designation of further Emission Control Areas in EU waters with focus on the Mediterranean Sea* (Laxenburg, International Institute for Applied Systems Analysis, 2018). Available at https://pure.iiasa.ac.at/id/eprint/15729/1/RR-18-002.pdf.

[4] United Nations Conference on Trade and Development, *Review of Maritime Transport: 2022 – Navigating Stormy Waters* (United Nations publication, UNCTAD/RMT/2022 and Corr.1).

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

[6] ibid.

introduced for diesel engines with a nominal power output higher than 130 kW, for 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 to achieve emission abatement and improve air quality. About 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.[7] 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 study[8] 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. The impact analysis carried out in the North American ECA resulted in significant air quality improvements in five Canadian port cities (Halifax, Vancouver, Victoria, Montreal and Quebec City).[9]

11. No specific rules are established in port areas by international regulations, although IMO SO_x and NO_x regulations are enforced, when applicable, but regional or local regulatory authorities may define some additional, even stricter 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.[10] 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 (nm) 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 (OPS) 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. SO_2 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 reduced the sulfur cap from 3.5 weight per cent to 0.5 weight per cent. In SECAs, the sulfur content limit is established at 0.1 weight per cent. Thus, these rules limit the use of heavy fuel oil (HFO) (without post-treatment of exhaust gases) and, furthermore, discussions are ongoing at IMO to consider banning HFO use in the Arctic. For instance, switching from a 0.5 weight per cent marine fuel to marine diesel oil, with 0.1 weight per

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

[8] Laurence Rouïl 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).

[9] Angelos T. Anastasopolos and others, “Air quality in Canadian port cities after regulation of low-sulphur marine fuel in the North American Emissions Control Area”, *Science of the Total Environment*, vol. 791 (October 2021).

[10] 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.

cent, would lead to an 80 per cent SO_2 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.

13. In addition to SO_2 emission reductions, switching from HFO to lower sulfur distillate fuels makes it possible to achieve PM emission reductions of 50–90 per cent,[11] 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.[12]

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 ton and €754 per ton (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 ton.

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 SO_2, NO_x, PM and BC. Compared to other oil products, LNG combustion barely generates SO_2 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.[13] Furthermore, BC emission reductions of 75–90 per cent are achievable when switching to 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 sector's willingness 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 engine installation.[14]

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.[15] 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

[11] Rouïl, "ECAMED".

[12] 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).

[13] Hulda Winnes and others, *Evaluation, control and Mitigation of the EnviRonmental impacts of shippinG Emissions (EMERGE): Deliverable 1.1, "Summary and analysis of available abatement methods for SO_x, NO_x and PM, together with data on emissions, waste streams, costs and applicability*" (n.p., 2021), available at https://cordis.europa.eu/project/id/874990/results.

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

[15] 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).

power.[16] In terms of operational costs, fuel savings of about 5–10 per cent are 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 investment estimated at approximately 8 per cent, at 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 CO_2 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 LNG-ship methane emissions 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, 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.[17] Manufacturers are making progress using a lean-burn principle,[18] 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 of 12–70 per cent, as compared to conventional fuel oils, depending on the percentage of biofuel in the final fuel mixture.[19] Similarly, BC emission reductions of 38–75 per cent have been observed.[20] Lastly, some SO_2 emission reductions are also expected from the use of biofuels as compared to fuel oils. However, an increase in NO_x emissions is expected while using biofuels.

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.[21] 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.

[16] 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.

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

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

[19] 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.

[20] Lack, *Investigation of Appropriate Control Measures*.

[21] IRENA, *A Pathway*.

Methanol and dimethyl ether

23. Methanol and DME have a very low sulfur content, therefore, SO_2 emissions can be drastically reduced, as well as PM emissions, with observed reductions of more than 90 per cent compared with conventional fuel oils.[22] In addition, the fuel switch to methanol or DME enables the achievement of NO_x emission reductions from 30–60 per cent.[23]

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 CO_2 emission reductions, from 95–100 per cent, can be expected. However, as with biofuels, LCA should be considered to assess the potential drawbacks and CO_2 emissions associated with production of methanol from biomass. If methanol or DME fuels are produced from fossil fuels, CO_2 emission reduction is moderate as compared to conventional marine fuel emissions; however, pollutant emission reductions are still associated.

25. As methanol and DME have a lower energy content, a fuel penalty of around 9 per cent is expected with 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 for nitrogen supply (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.[24]

Hydrogen

26. Hydrogen can be used either in fuel cells, dual fuel engines, or to replace HFO 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, with no emissions. The combustion of H_2 does not generate SO_2, PM or CO, but NO_x emissions are present and can even be higher than NO_x emissions from 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 CO_2-free fuel.

27. However, hydrogen use has drawbacks, including the need for space. In fact, as compared to HFO, the use of hydrogen requires five times more volume when liquid, and 10–15 times more volume when gaseous[25] because, due to the high flammability of hydrogen (H_2), 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 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;[26] for

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[22] 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).

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

[24] Winnes, *Evaluation, control and Mitigation*.

[25] Marketa Pape, "Decarbonizing maritime transport: the EU perspective", Briefing (European Parliamentary Research Service, 2020).

[26] DNV GL, "Comparison of alternative marine fuels", Report No. 2019-0567, rev. 4 (n.p., 2019).

instance, a scale-up of three times current H_2 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. 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 H_2 production ranged between €126–€144 per MWh, in 2020, considering an average electricity price of €60 per MWh.[27] However, with the development of renewable energy production and increasing demand, green H_2 is expected to achieve competitive costs as compared to LNG and VLSFO by 2030.

Ammonia

29. Ammonia (NH_3) is a carbon- and sulfur-free substance, therefore its use as fuel does not imply CO_2, SO_2 and PM emissions. Used in fuel cells, NO_x emissions are also null, whereas they are rather similar to emissions from conventional fuels when used with H_2 in internal combustion engines.[28] 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 infrastructure already exists 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.[29] The cost of bunkering facilities should also be considered, because existing bunkering infrastructures are not compatible with ammonia storage.

32. Lastly, it should be noted that there is an ongoing discussion in IMO on banning the use of HFO in the Arctic to significantly reduce black carbon emissions.

33. The expected emission reductions, fuel consumption penalties and related costs of implementation are reported in table 1 below, for some fuel switch options.

[27] IRENA, *A Pathway*.
[28] Niels de Vries, “Safe and effective application of ammonia as a marine fuel”, thesis, Delft University of Technology, 2019.
[29] ibid.

Table 1
Emission reductions by fuel switch technique
(Percentage)

Primary fuel switch techniques	*SO_2*	*NO_x*	*PM*	*BC*	*Fuel penalty*	*Investment costs (Euros/kW)*	*Operations and maintenance costs (Euros)*
Switch to low sulfur fuels	Up to 99	-	50–90	0–80 (median: 30)	-	-	222–594 per ton of fuel
Switch to LNG	90–100	64–90	60–98	75–90	- 5–10	219–1 603	- 43 per ton of fuel (+ fuel savings)
Switch to water-in-fuel emulsions	-	1–60	20–90	0–85	+ 0–2	11–44	33 000–271 000 per year
Switch to biodiesel and biofuels	-	-	12–70	38–75	+ 8–11	-	-
Switch to methanol	100	30–60	90–99	97	+ 9	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

34. 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.[30] 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.[31]

35. 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 at 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, at 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.

36. 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 on its size.[32] Annual operational and maintenance costs are estimated at around €9–€9.5 per kW per year.[33]

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

[31] 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 Artic shipping”, *Carbon Management*, vol. 1, No. 2 (2010), pp. 207–225.

[32] Lack, *Investigation of Appropriate Control Measures*.

[33] Jordal-Jørgensen, *Reducing Air Pollution from Ships*.

Slide valves technique

37. 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 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.[34] However, the implementation of slide valves implies a 2 per cent increase in fuel consumption, with consequent additional CO_2 and SO_2 emissions and costs.

38. The investment costs for slide valve implementation 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.[35] Moreover, unlike other reducing techniques, no additional operational and maintenance costs are associated with slide valves.

39. The emission reductions by combustion modification technique are reported in table 2 below.

Table 2
Emission reductions by combustion modification technique
(Percentage)

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	20–90	0–85	0–2	11–44	9-10
Slide valves		0–20	10–50	10–50	+ 2	0.3–1.4	None

C. Adjustment in the propulsion mode

Slow steaming technique

40. 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 SO_2 and CO_2 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.[36] 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.

41. In terms of cost, increased delivery times are the main consequence of the slow steaming technique to be considered by shipowners. Therefore, the need for additional ships

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

[35] Corbett, “An assessment of technologies”.

[36] 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).

in the fleet, to compensate for increased delivery times, would adversely bias the environmental benefits. One study[37] revealed that imposing the slow steaming technique in the European Union territorial sea area (within 12 nm of the coastline) or exclusive economic zone (i.e. 12–200 nm from the coastline) 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 study[38] reported that, for a 4,000 twenty-foot equivalent unit[39] ship category, reducing the speed from 23 knots to 17 knots decreases 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)

42. Battery-powered ships for short-haul sea shipping with frequent stops have attracted greater interest. 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 CO_2 emission reductions of 10–40 per cent can be achieved for hybrid ships, whereas total CO_2 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 pollutant abatement equipment is installed. As another example, in Canada, several hybrid (battery-LNG) vessels (especially ferries) are in operation in British Columbia.

43. However, it should be considered that, since the lifetime of batteries is about 8–10 years, this equipment is a significantly more costly option, as compared to diesel engines. Moreover, in terms of CO_2 emissions, a wider perspective considering LCA would be useful to assess the CO_2 upstream emissions, similarly to what happens in electricity generation or battery production.

Wind-propulsion assistance

44. 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.[40] In one specific case, it has been claimed that, if applied to the entire world tanker fleet, rotor sail technology could reduce CO_2 emissions by more than 30 Mt, which represents about 3 per cent of total GHG shipping emissions.

45. Nevertheless, some limitations to wind propulsion should 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).[41]

46. The emission reductions by adjustment in propulsion mode technique are reported in table 3 below.

[37] Paul Campling, Liliane 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).

[38] 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).

[39] Unit used for cargo capacity for container ships.

[40] 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/.

[41] 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).

Table 3
Emission reductions by adjustment in propulsion mode technique
(Percentage)

Primary technique	*SO_2*	*NO_x*	*PM*	*BC*	*Fuel savings*
Slow steaming	Proportional to fuel savings for all techniques	0–64	0–69	0–30 if engine derated, possible increase at low loads	0–50
Battery-powered (electric or hybrid)		No emission if fully electric			100 if electric
Wind-propulsion assistance		No information found but reductions expected due to fuel savings			0–50 (8–10 observed in practice)

VI. Best available techniques for ships: secondary techniques

Wet scrubbers

47. 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 m^3/MWh is necessary when a 3.5 weight per cent fuel oil is used.[42] 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 m^3/MWh, and running the water system represents about 0.5–1 per cent of engine power.[43] 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.

48. The installation of wet scrubbers makes it possible to reduce ship emissions by up to 98 per cent for SO_2, 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).[44] 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

[42] Lloyd's Register, *Understanding Exhaust Gas Treatment Systems. Guidance for Shipowners and Operators* (London, 2012).
[43] ibid.
[44] Winnes, *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).

increases CO_2 emissions. The International Council on Clean Transportation published a report on the subject in 2020.[45]

49. 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 upstream of the scrubber, and also with PM removal technologies. Nevertheless, some limitations rise from scrubber installation, and, in particular, space requirements, as the unit can vary from about 65 m^3, for small engines, to more than 800 m^3, for larger units.[46] 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.

50. 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.[47] 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.[48] 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.[49] 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.[50] 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.

51. 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.[51] 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, Canada for the Ports of Vancouver, Prince Rupert and Sept-Îles), thus open-loop scrubbers, or have imposed the use of the closed-loop mode for hybrid scrubbers.

Dry scrubbers

52. Dry scrubbers have also been adapted to marine engines and have fulfilled their potential in SO_2 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

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45 Bryan Comer, Elise Georgeff and Liudmila Osipova, *Air Emissions and Water Pollution Discharges from Ships with Scrubbers: ICCT Consulting Report* (Washington D.C., International Council on Clean Transportation, 2020).

46 MAN Diesel and Turbo, "*MAN B&W*".

47 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".

48 Cofala, *Final Report*.

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

50 Winnes, *Evaluation, control and Mitigation*.

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

the reaction products, as well as soot, BC and heavy metals resulting from the combustion, which will lastly be discharged into a proper container.

53. 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).[52] 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; it has 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

54. 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.

55. 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.[53] 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 SO_2 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 CO_2 emissions. Moreover, EGR implementation can even result in CO and PM emission increases, if not operated properly.

56. 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.[54] 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.[55] 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

57. 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 principle consists of inducing a chemical reaction within a catalyst by introducing nitrogen-reducing compounds,

[52] IMO, "Evaluation and harmonization of rules and guidance on the discharge of liquid effluents from EGCS into waters, including conditions and areas, document No. MEPC 75/INF.13.

[53] 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).

[54] 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).

[55] ibid.

such as an ammonia water solution (NH_3) 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 (N_2) and water (H_2O), 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.[56] When an oxidation catalyst is applied to oxidize the remaining NH_3, 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.[57]

58. 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.[58] 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.[59]

59. 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 SO_2 levels in the exhaust gases and at higher temperatures, while SCR is ineffective in terms of reducing NO_x to the desired levels at low temperatures (below 250° C).[60] 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 NH_3 and increase SO_3 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.

60. 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.

61. The capital investments for the implementation of SCR units vary from about €19–€100 per kW[61] 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.[62] 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.[63] Lastly, the maintenance costs are about 1.2 per cent of the annualized investments.

Diesel particulate filters

62. 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.

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[56] Winnes, *Evaluation, control and Mitigation*.
[57] ibid.
[58] Incentive Partners and Litehauz, *Economic Impact Assessment*.
[59] Lloyd’s Register, *Understanding Exhaust Gas Treatment Systems*.
[60] IMO, “Assessment of Low-load Performance of IMO NOX Tier III Technologies”, document No. MEPC 80/5/1.
[61] Hulda Winnes and others, “NOx controls for shipping in EU Seas. Transport and Environment”, Report No. U5552 (Stockholm, IVL Swedish Environmental Research Institute, 2016).
[62] Incentive Partners and Litehauz, *Economic Impact Assessment*.
[63] Rouïl, “ECAMED”.

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.[64] 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 CO_2 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.

63. 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 would 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

64. Baghouse filters are high-performing filters that have more recently 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.[65] 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 NH_3 emissions, through NH_3 slip.

65. 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

66. 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 SO_2 emission reductions of 81 per cent, 55 per cent and 89 per cent, respectively, between 2005 and 2013, thanks to the reduction strategy adopted.[66] 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. 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.

67. 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. Use of AMS made it

[64] Papadimitriou, *Best Available Techniques*.
[65] LAB, DeepBlueLAB - Bag particle filters. Personal communication (2020).
[66] IMO, “Study of emission control and energy efficiency measures for ships in the port area”, document No. MEPC 68/INF.16.

possible to tackle annual NO_x emissions equivalent to 5,000 diesel cars in Helsinki,[67] as well as saving fuels and CO_2 emissions thanks to shorter berth times. Another study reported annual emission reductions of 3.6 per cent, 11.2 per cent, 3.5 per cent and 3.6 per cent for NO_x, PM, SO_2 and CO_2, respectively, thanks to AMS infrastructures in the port of Izmit Bay.[68] 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.[69]

B. Onshore and barge power supply systems

68. Shore power, also known as "cold ironing", consists of supplying electricity to vessels at berth[70], so that their main and auxiliary engines can be switched off. Hence, as with most electrification techniques, this technique is efficient when the electrical supply is generated in a cleaner way, as compared to fuel combustion in ship engines. 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.

69. In regions where electricity generation from power plants is well regulated, the implementation of OPS made it possible to achieve emissions reductions of NO_x, SO_2, PM and VOC of up to 95 per cent.[71] 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 generated by renewable energies or nuclear power, applied to all ships at berth in Chinese terminals, resulted in emission reductions of 81 per cent for SO_2, 97 per cent for NO_x, 77 per cent for PM and 22 per cent for CO_2.[72] In terms of carbon neutrality, the implementation of shore-power supply in Europe (the European Union is in the process of introducing a regulatory regime that will make OPS mandatory) has been estimated to reduce shipping CO_2 emissions by 39 per cent, whereas, at local levels, emission reductions of 54–99 per cent are observed (99 per cent in Oslo, probably due to very low electricity carbon content).[73]

70. 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.

71. 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

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[67] Cavotec, "Automated mooring substantially reduces harmful emissions in Helsinki city centre" (19 July 2021). Available at www.mynewsdesk.com/cavotec/pressreleases/automated-mooring-substantially-reduces-harmful-emissions-in-helsinki-city-centre-3116249.

[68] Alper Seyhan, Cenk Ay and Cengiz Deniz, "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*, vol. 15, No. 2 (2023), pp. 227–245.

[69] Winnes, "NOx controls for shipping in EU Seas".

[70] European Maritime Safety Agency, *Shore-Side Electricity (SSE): Guidance to Port Authorities and Administration* (n.p., 2022). Available at www.emsa.europa.eu/electrification/sse.html.

[71] LAB, DeepBlueLAB - Bag particle filters.

[72] 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).

[73] IMO, "Reduction of GHG emissions from ships: Vessel shore power installation worldwide", document No. MEPC 73/INF.29/Rev.1.

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 million–€14 million at mid-2022 exchange rate), based on several studies carried out in ports of the United States of America and Canada.[74] 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 million–€1.87 million at mid-2022 exchange rate), depending on the ship design, and such costs are expected to decrease as technology implementation increases.[75] Furthermore, nowadays, most new-build vessels are already designed for OPS. See also the European Commission study[76] on OPS.

72. The barge power supply system 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 and high movability from one dock to another, as well as requiring less infrastructure investment 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 SO_2 and 30 per cent for CO_2 can be expected[77]. The cost for this technology has been estimated at about $0.2 million (€0.19 million at mid-2022 exchange rate), for the retrofit of the ship and about $1,000 per hour (i.e. €933 at mid-2022 exchange rate), for the operations of the barge power system.

C. Shore- or barge-based exhaust cleaning techniques

73. 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 OPS systems. Emission reductions of 98 per cent and 95 per cent, for PM and NO_x, respectively, can be achieved when implementing the described technique.[78]

74. The main advantage of this technique is that no ship modification is needed; moreover, the cleaning system can operate either at anchor, installed on a barge, or at berth. However, some limitations exist regarding this technique's application 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 requires further development 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 at mid-2022 exchange rate), when a large number of systems are implemented.[79]

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[74] 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 Strategie*s (n.p., 2018).

[75] Thalis Zis, "Prospects of cold ironing as an emissions reduction option", *Transportation Research Part A: Policy and Practice*, vol. 119 (January 2019), pp. 82–95.

[76] European Alternative Fuels Observatory, Ports and infrastructure, "Maritime Ports", available at https://alternative-fuels-observatory.ec.europa.eu/transport-mode/maritime-sea/ports-and-infrastructure.

[77] IMO, "Study of emission control".

[78] 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).

[79] GEF, *Port Emissions Toolkit*.

VIII. Conclusions and recommendations

75. 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.

76. There is a need for regulation at the international level, mainly within the framework of the MARPOL Convention. Some aspects can also be addressed at the local, national or regional level. At least in some areas of the United Nations Economic Commission for Europe region (e.g., the European Union subregion), regulations have been introduced to control marine fuel quality, and, at the local level, in some ports, OPS 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.

77. 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.

78. 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 development of international rules (e.g., MARPOL, the United Nations Convention on the Law of the Sea) and in developing their national emission reduction plans, also considering synergies tackling air pollution and climate change/decarbonization simultaneously.