TRACE METALS AND PAHs DISCHARGE FROM SHIPS WITH EXHAUST GAS CLEANING SYSTEM (EGCS)

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Abstract: With the new global sulphur shipping emission regulations of International Maritime Organization (IMO), remarkable increase of exhaust gas cleaning systems (EGCS) installations was noted recently. EGCS, also known as "scrubbers", is an alternative technical solution reducing air emission of sulphur oxides, appeared as an attractive, less-expensive solution for many ship companies. EGCS allows ships to continue to use low-cost, high-sulfur heavy fuel oil (HFO) and consequently the shipping industry remains main market for HFO. In the scrubber, the ship exhaust gas is washed out by a high flow rate of the seawater and this process results in the effective reduction of sulphur air emission and in the discharge overboard into surrounding environments of a large amount of polluted washwaters. The resulting discharged washwaters contain a chemical mixture of acidifying and eutrophying substances and toxic pollutants such as heavy metals and polycyclic aromatic hydrocarbons (PAHs), which together with SO_x are effectively washed out from the ship exhausts. The use of scrubbers generates thus a new stream of shipping liquid wastes, which will dominate metals and PAH discharges from ships.

In this context, there is a growing need to elaborate and improve the methods for evaluation of pollutant discharge through scrubbers and the routine monitoring of this chemical pollution transferred from air to marine waters. In the present report the focus is given primarily on emission discharges of heavy metals and PAHs that is two groups of ship exhaust contaminants, which were less studied and regulated. In essence, the proposed method for scrubber emission discharge evaluation, is built on the same basis as approved methods developed for green-house gases (GHGs) and main shipping air pollutant emission inventories. In this respect, the proposed approach is based on the estimates using pollutant emission factors, washwater volumes and flow rates, assumed scrubber trapping efficiencies, ship fuel consumption and energy demand. The case study of the metals and PAHs discharge estimation is proposed for the model Ro-Pax ferry - one ship scenario and its real-world operation between two ports Marseille and Ajaccio (France). A larger scale projection is also presented, consisting of the potential pollutant discharges by EGCS of 11 Ro-Pax ships fleet also operating in the Gulf of Lion and the Ligurian Sea basins, between mainland France and Corsica. Furthermore, building on the recent work by Osipova *et al*. (2021) on the global assessment of the mass of washwater discharges from vessels using scrubbers, our report provides various scenarios of washwater and pollutant loads into French Exclusive Economic Zone (EEZ). The calculations are presented for the entire French EEZ as well as the French Mediterranean EEZ and its ports in the Gulf of Lion (GoL) and Corsica.

It appears that in France about 75 % of scrubber washwater discharges occur beyond territorial sea of 12 nautical miles, whereas 15 % is released in the territorial seas (TS), 6 % in internal waters (IW) and 4% in their ports. The distribution of pollutant loads will follow washwater discharges. Pollutant quantities amounting to hundreds and thousands of kilograms of main metals (V, Fe, Ni, Zn) and PAHs discharged annually by a given fleet of 11 Ro-Pax ships into the Western Mediterranean Sea come into the same category as other large-scale environmental inputs and emissions of these compounds. The estimated annual EGCS potential loads to the Gulf of Lion and the Ligurian Sea compare to the amounts of vanadium, nickel and ΣPAH_{16} dumped with major oil spills or to the Rhone river annual flux of PAHs entering the Gulf of Lion. These estimates clearly indicate that ship scrubber washwaters may represent significant source of pollutants entering the western Mediterranean Sea.

Key words:
Ship scrubbers, washwater, exhaust gas, contaminant emissions and discharges, the Mediterranean Sea, the Gulf of Lion, the Ligurian Sea, pollutant emission factors, heavy metals, polycyclic aromatic hydrocarbons, PAHs, EGCS.

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Abstract

With the new global sulphur shipping emission regulations of International Maritime Organization (IMO), remarkable increase of exhaust gas cleaning systems (EGCS) installations was noted recently. EGCS, also known as “scrubbers”, is an alternative technical solution reducing air emission of sulphur oxides, appeared as an attractive, less-expensive solution for many ship companies. EGCS allows ships to continue to use low-cost, high-sulfur heavy fuel oil (HFO) and consequently the shipping industry remains main market for HFO. In the scrubber, the ship exhaust gas is washed out by a high flow rate of the seawater and this process results in the effective reduction of sulphur air emission and in the discharge overboard into surrounding environments of a large amount of polluted washwaters. The resulting discharged washwaters contain a chemical mixture of acidifying and eutrophying substances and toxic pollutants such as heavy metals and polycyclic aromatic hydrocarbons (PAHs), which together with SO_x are effectively washed out from the ship exhausts. The use of scrubbers generates thus a new stream of shipping liquid wastes, which will dominate metals and PAH discharges from ships.

In this context, there is a growing need to elaborate and improve the methods for evaluation of pollutant discharge through scrubbers and the routine monitoring of this chemical pollution transferred from air to marine waters. In the present report the focus is given primarily on emission discharges of heavy metals and PAHs that is two groups of ship exhaust contaminants, which were less studied and regulated. In essence, the proposed method for scrubber emission discharge evaluation, is built on the same basis as approved methods developed for green-house gases (GHGs) and main shipping air pollutant emission inventories. In this respect, the proposed approach is based on the estimates using pollutant emission factors, washwater volumes and flow rates, assumed scrubber trapping efficiencies, ship fuel consumption and energy demand. The case study of the metals and PAHs discharge estimation is proposed for the model Ro-Pax ferry - one ship scenario and its real-world operation between two ports Marseille and Ajaccio (France). A larger scale projection is also presented, consisting of the potential pollutant discharges by EGCS of 11 Ro-Pax ships fleet also operating in the Gulf of Lion and the Ligurian Sea basins, between mainland France and Corsica. Furthermore, building on the recent work by Osipova *et al*. (2021) on the global assessment of the mass of washwater discharges from vessels using scrubbers, our report provides various scenarios of washwater and pollutant loads into French Exclusive Economic Zone (EEZ). The calculations are presented for the entire French EEZ as well as the French Mediterranean EEZ and its ports in the Gulf of Lion (GoL) and Corsica.

It appears that in France about 75 % of scrubber washwater discharges occur beyond territorial sea of 12 nautical miles, whereas 15 % is released in the territorial seas (TS), 6 % in internal waters (IW) and 4% in their ports. The distribution of pollutant loads will follow washwater discharges. Pollutant quantities amounting to hundreds and thousands of kilograms of main metals (V, Fe, Ni, Zn) and PAHs discharged annually by a given fleet of 11 Ro-Pax ships into the Western Mediterranean Sea come into the same category as other large-scale environmental inputs and emissions of these compounds. The estimated annual EGCS potential loads to the Gulf of Lion and the Ligurian Sea compare to the amounts of vanadium, nickel and ΣPAH_{16} dumped with major oil spills or to the Rhone river annual flux of PAHs entering the Gulf of Lion. These estimates clearly indicate that ship scrubber washwaters may represent significant source of pollutants entering the western Mediterranean Sea.

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1 Introduction

1.1 Background

With more than 80% of global trade by volume carried by maritime transport, ocean shipping is the most important mode of transport for the international merchandise trade (UNCATD, 2018). While shipping transport is recognized as to energy-efficient (Faber *et al*. 2020) it is also depicted by the very tolerant emission standards for marine engines comparatively to other means of transport (Turner *et al*. 2017). In 2019, residual heavy fuel oils (HFO) still remain the dominant fuels used by shipping industry, with high, on average 2,6 %, sulphur content compared to 0,0015% for on-road diesel and gasoline in the North America and Europe (Turner *et al*. 2017, IEA 2020). As the new IMO rules are introduced, in 2020, HFO consumption is however forecast to decrease as ship operators switch to low sulphur fuels (IEA 2020). Ships are recognized as significant emission sources, of both greenhouse gases (GHGs) climate pollutants (carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O) and other prevalent air pollutants (fine particulate matter PM_{10} and $PM_{2,5}$, black carbon BC, sulphur oxides SO_x, nitrogen oxides NO_x, non-methane volatile organic compounds NMVOCs, heavy metals and polycyclic aromatic hydrocarbons (PAHs). The share contribution of shipping to global amounts of certain pollutant emissions is also seen as increasing in a number of prospective studies (Smith *et al*. 2015).

In the last decades, the International Maritime Organization (IMO) has taken regulations aiming at the prevention of operational and accidental pollution from ships under the International Convention for the Prevention of Pollution from Ships (MARPOL). The IMO's regulations concerning sulphur oxides emissions from ship exhausts are mainly controlled by limiting the sulphur content in fuels, as already agreed in 2008, in Regulation 14 (MARPOL, Annex VI) and its later amendments. The maximum allowable sulphur content of marine fuels was decided to be progressively reduced from 4.5% to 3.5% in 2012 and then to 0.5% as global limit in 2020. Sulphur Emission Control Areas (SECAs) were also established, where the maximum sulphur fuel content was limited to 1.0%, already in 2010 and to 0.1% in 2015. IMO's Regulations 14 and 4 (MARPOL, Annex VI) proclaim also sulphur emission compliance conditions. The compliance is obtained by use of low-sulphur fuels or by installation of exhaust gas cleaning systems (EGCS) called also "scrubbers", as abatement technology for air emission of sulphur, which is authorized as long as it is at least as effective in reducing sulphur air emissions as is use of low sulphur fuels (IMO 2008).

With implementation of more stringent global 0.5 % sulphur regulation, entering into force on January 2020, and also because of economic aspects related to the price difference between HFO and low sulphur fuels (Abadie *et al.* 2017), the scrubber installations appeared as an attractive, less-expensive, and preferred alternative solution for many ship companies. In recent years, a remarkable increase of EGCS installations was noted. Between 2018 and 2019, a fourfold expansion was reported in only one year, with 4341 ships expected to be equipped with EGCSs by the end of 2020 (Comer *et al*. 2020), which may already represent about 4% of the international fleet potentially fitted with scrubbers. Scrubbers allow ships to continue to use low-cost HFO and the shipping industry remains the main market for this fuel (Hassellöv *et al*. 2020).

The perspective of broad use of scrubbers on ships has raised environmental and legal concerns, because of the transfer of considerable amounts of air pollutants to the marine waters (Endres *et al*. 2018, Linders *et al*. 2019). In the scrubber, operating in so-called "open-loop" mode, the ship exhaust gas is washed out by high flow rate of the seawater (amounting to several hundreds of tons per hour), which after washing process is typically discharged overboard into surrounding environments. The resulting discharge waters contain a chemical mixture of acidifying and eutrophying substances and toxic pollutants such as heavy metals and PAHs, which are thus emitted into marine water environment (Figure 1). The potential environmental impacts of scrubber discharges were recently broadly examined and reviewed, mainly focusing on their impacts on the ocean acidification and on chemical pollution increase and its effects on marine life (Endres *et al*. 2018, Hassellöv *et al*. 2020, ICES 2020).

From the legal and environmental policy point of view, regulations on scrubbers have been discussed and to some extent introduced on very different levels (IMO, EU, Regional Sea Conventions, individual states) and they are not yet fully harmonized. Coastal states and even individual ports are allowed, under Regulation 4 of MARPOL, to unilaterally limit or prohibit the use of scrubbers in their jurisdictions, but this may introduce imbalanced commercial standards (Comer *et al*. 2020). France and several other European countries have limited use of open-loop scrubbers in their internal waters, ports and within 3 nautical miles (Comer *et al*. 2020). EU proposed that that IMO's Marine Environment Protection Committee (MEPC) should evaluate and harmonize the development "of rules and guidance on the discharge of liquid effluents from EGCS, including conditions and areas under which liquid effluents from EGCS can be discharged, and to regulate as appropriate access for ships equipped with such systems on that basis" (MEPC 2015). It was also noted that the use of open-loop EGCS on ships might be conflicting with Article 195 of United Nations Convention on the Law of the Sea UNCLOS *i.e.* "duty not to transfer damage or hazards or transform one type of pollution into another" (UNCLOS 1994), whereas scrubber-equipped vessels accept to transfer and to transform air pollution into marine pollution. Finally, pollution pressure coming from scrubber discharges, can undermine commitments to achieve several environmental quality standards as defined under various marine environmental agreements such as, for instance, Regional Sea Conventions (*e.g.* Helcom, Ospar, Barcelona) and European directives (*e.g*. Marine Strategy Framework Directive MSFD and Water Framework Directive WFD). The pollution from ships using scrubbers might also be conflicting with Sustainable Development Goals (SDGs), particularly SDG 14 and societal outcome of the UN Ocean Decade which is "a clean ocean, where sources of pollution are identified and removed" (IOC 2019, Linders *et al*. 2019, Hassellöv *et al*. 2020).

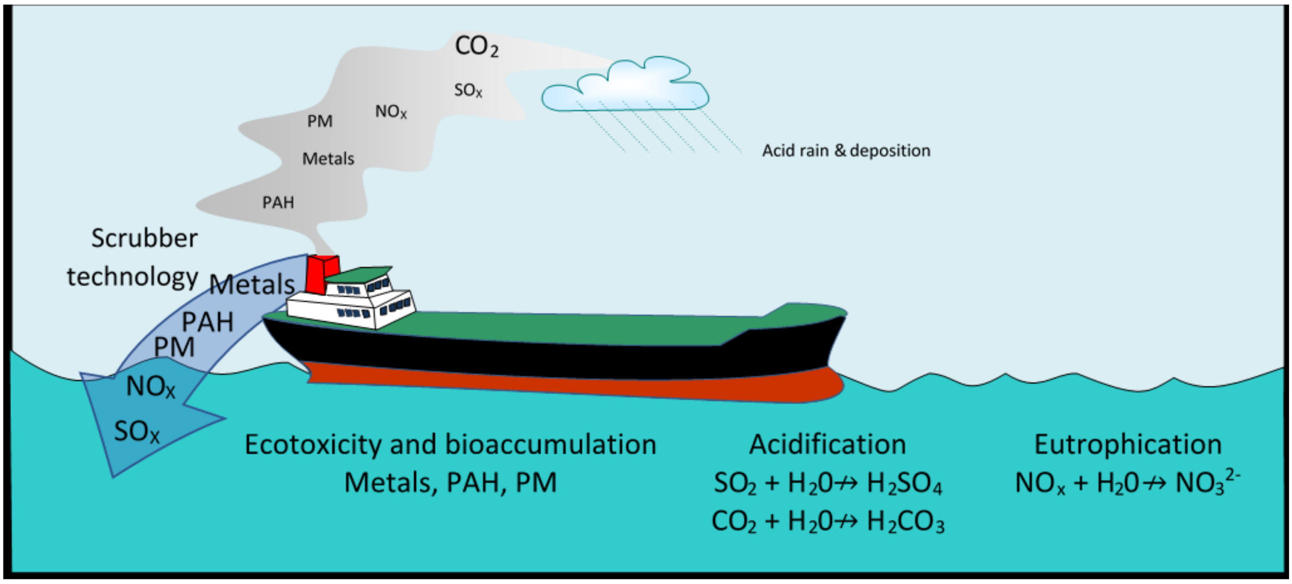

Figure 1. Redistribution of pollutants in air emissions to the sea and the potential impacts in the marine environment by use of scrubber technology: ecotoxicity, bioaccumulation, acidification and eutrophication (reproduced from Hassellöv *et al*. 2020).

IMO proposed in 2005 a first guidance for EGCS discharges and after multiple revisions, this work is still not fully accomplished (MEPC76 2021). The EGCS discharge guidelines are given only for certain pollutants and do not include all washwater pollutants, for instance there is no discharge limit for heavy metals. The question is also on the lack of the proper scientific justification for certain limits and uncertainty regarding their level of protection of marine ecosystems. Besides, the guidelines are not legally binding obligation and may be applied on voluntarily basis by the flag states (Linders at al. 2019, Comer *et al*. 2020).

Additionally, because scrubbers' issue is relatively recent, there is a lack of sound, proof-revised technical and scientific data and this situation is very much challenging for legal regulations and policy, which needs to be flexible and frequently updated to new knowledge and technical developments.

In this context, the use of scrubbers is poorly regulated and controlled. Improvement of the methods for the assessment of scrubber pollutant discharges is truly needed. A better appreciation is also needed for pollutant ship emissions inventory with the approved and regularly revised methods and protocols. The contributions are also sought for the evidence-based regulations on scrubber water discharge limits that consider their potential environmental impacts of a full suite of pollutants.

The scrubber impacts can be directly avoided through its ban and the use of alternative low sulphur distillate fuels such as marine gas oil (MGO) and marine diesel oil (MDO). This would also result in a significant shift in shipping exhausts pollutant profiles and their potential impacts (Hassellöv *et al*. 2020, Lunde Hermansson et al. 2021). The transboundary nature of maritime transport renders difficult the enforcement of the rules on ship-source discharges of polluting substances. Under current revision of EU Directive 2005/35/EC EU Member States must ensure that ship-source discharges of polluting substances are surveyed and controlled. A close collaboration between science, industry and policy-makers is necessary to achieve acceptable and sustainable solutions that will be implemented and can be monitored.

1.2 Objectives

Within this work, we firstly wanted to gain more insight on the expected order of magnitude of the chemical pollutants discharge into marine environment by sea-going vessel fitted with EGCS. The objective was mainly to describe the method for such estimations. Main pollutants of interest for this study are the metal elements (MEs) and polycyclic aromatic hydrocarbons (PAHs) that are two groups of ship exhaust contaminants, which were less studied and regulated by now. For comparison, a few other pollutants (e.g. PM_{10}, CO_2) emitted by ships were also briefly considered.

Secondly, the case study of the pollutants discharge estimation is proposed for the model ferry - one ship scenario and its real-world operation between two ports Marseille and Ajaccio (France). We also present a larger scale projection of potential pollutants discharge by EGCS of 11 ships fleet operating in the Gulf of Lion and the Ligurian Sea basins, on this regular crossing journey and maritime transport services between mainland France and Corsica. Furthermore, building on a recent work on the global assessment of the mass of washwater discharges from ships using scrubbers (Osipova *et al*. 2021), we also provide various scenarios of pollutants inputs. The pollutant EGCS discharge calculations are presented for the entire French Exclusive Economic Zone (EEZ) and the French Mediterranean ports in the Gulf of Lion (GoL) and Corsica.

Finally, by this report we want to bring additional contribution to the on-going debate about wide-scale use of scrubbers. A number of recent scientific reviews presented the actual situation and projections on the environmental impacts and potential harmful effects of scrubber washwater discharge on marine ecosystems and their subsequent risks (Endres *et al*. 2018, Linders *et al*. 2019, Georgeff *et al*; 2019, Hassellöv *et al*. 2020). But on the other hand, quite a few reports provide contrary conclusions, confusing the recognition and understanding of scrubbers potential damaging impacts (Faber *et al*. 2019, Japan 2019). In this context, our expertise aims to present a critical approach in the effort of pollutants discharge assessments; calling also for revisions, improvements in setting up of both pollutant emissions factors and discharge guideline limits. This would require using of harmonized procedures in terms of washwaters sampling and analysis to ensure better comparability in different data sets. The intention is to bring scientific support expertise to the national and European position instructions, regarding the use of scrubbers in Europe's coastal and territorial waters and more broadly to pollutant shipping emissions.

1.3 Scope and prospective

The scope of this work was kept relatively limited. The reported records of pollutant ship emissions and EGCS discharges do not intent to represent complete inventory assessments. We provide the basis for calculation of the scrubber's discharge, and we consider here only open loop scrubbers – that is the most common EGCS technique installed and used by shipowners (about 85% of installations). When focusing our attention primarily on PAHs and metals potentially discharged, the report proposes a new approach and the needed improvements for the emission assessments of these two groups of pollutants. In essence, the assessment of PAHs and trace metals ship emission inventory should be built yet on the similar basis as approved methods developed for GHGs and main air pollutant shipping emissions assessment. The presented data are based mainly on a top-down approach. The development of so-called bottom-up methods and protocols based on combining ship specifications and traffic data with contaminants emission factors are fundamental for the improvement of EGCS contaminants loads monitoring and their spatial distribution assessments. This spatial representation of related discharges of pollutants will require further modeling efforts. The importance of amounts of EGCS contaminants discharged into Gulf of Lion and the Ligurian Sea basins is shortly discussed. This work provides useful data for further evaluation of EGCS pollutant environmental risk assessments.

The allocation of shipping emissions along the French EEZ waters will require larger scale studies, including precise Automatic Identification System (AIS) records of sea-going ships activities on the French continental shelf, maneuvering in coastal waters and harbors and staying at the berth. Furthermore, there is no emissions factors for metals and PAHs that are recommended and established on the consensus basis, like for GHGs. The development of these key parameters for pollutant emission estimations should be undertaken, akin it is carried, since many years, for the main shipping pollutants such as greenhouse gases (GHGs), nitrogen oxides (NO_x), sulphur oxides (SO_x) and fine particulate matter $PM_{10\ \text{and}\ 2.5}$ (Faber *et al*. 2020). Another shortcoming is the lack of data on precise chemical speciation in ships exhaust physical compartments, such as gaseous, particulate matter and aqueous phases. The detailed chemical characterization of exhaust gases is a very much demanding analytical task and can be faithfully performed only with the help of specialized research laboratories (Celo *et al* 2015, Käfer *et al.,* 2019, Jiang *et al*. 2019). In addition, especially with respect to metals, fuel analyses could be of interest. However, most of oil analysis analytical standards are not fully adjusted for environmental relevance. Emitted species posing a threat to human health, represent threats to the ecosystems and can also considerably influence the atmospheric and marine waters composition and processes for instance: ozone and photochemical smog formation, radiation balance, acidification and eutrophication (Stips, *et al.*, 2016 Endres, *et al.*, 2018, Fuglestvedt, *et al.*, 2009, Tronstad *et al*. 2012, Dulière *et al*. 2020*,* Hassellöv *et al.* 2013, Turner *et al.* 2018). Together with emission inventories, this knowledge is also needed for setting measurable and quantifiable targets for reduction of shipping share in environmental and climate change impacts.

2 Methodology and input data

2.1 Ship emissions and EGCS discharges

The methodology applied in our study recognizes that ship pollutant emission with exhaust gas represents the basis for specified pollutant discharge estimation with washwater of the scrubber systems. The scrubber discharge D_s is thus considered as a fraction of total emission of a given pollutant and therefore may be expressed as follows:

$$\mathrm{D_s} = \mathrm{EM_i} * F_i \quad (1)$$

Where EM_i is specific pollutant emission of a ship (i) main engine (can be expressed as pollutant emission in g/h) and F_i is a fraction, expressed as a proportion (from zero to one) of a ship pollutant emission, which is washed out by scrubber from exhaust gases and discharged overboard in the open-loop operational mode. The EGCS "scrubbing" efficiency varies with pollutant. As an example, the scrubbers almost do not remove from exhaust gas CO_2 and very weakly NO_x, whereas the almost total SO_x are removed (Comer *et al*. 2020). This mass balance approach stands that for a ship fitted with scrubber, main engine pollutant emissions will be split into air/atmosphere and the surrounding waters. We believe that this basic consideration was not yet effectively settled in the methodologies of a number of studies committed to scrubber's environmental impact assessments.

The EM_i estimation is mainly based on the approach presented in the *Fourth IMO Greenhouse Gas Study* (Faber *et al*., 2020). IMO systematically improves emission inventories of the climate GHGs and main air pollutants from a global ship fleet. Their inventories are calculated by both top-down and bottom-up methods. However, PAH and metal emissions are not considered in IMO's assessments. In the present work, the method is consequently adjusted to PAH and metal emissions, including literature review and setting for these pollutants' emission factors.

Whereas, for the second term F_i, possible pollutant discharge may vary from none to a total of emitted pollutant. When these results are compared and discussed together with reported data on PAH and metal concentrations in washwater, they provide additional insight on scrubber's transfer effectiveness of specific pollutants from ship exhaust gas to wash water. However, comprehensive literature, data and methodological protocols on how to estimate many pollutant discharges via scrubber's washwaters is still scarce (Kjølholt *et al*. 2012, Celo *et al*. 2015, Zhou *et al.,* 2017, Lehtoranta, *et al.*, 2019, Lunde Hermansson *et al*. 2021). The comprehensive studies on the efficiency of pollutants removal from exhaust gas by scrubber are mostly missing. Whereas, the determination of many pollutants' concentration in scrubber washwaters is very difficult and demanding, with analytical protocols which in our perception cannot be well implemented on-board conditions, in real time, of sea-going vessels (Linders *et al*. 2019).

2.2 Emission estimation

The methodology for GHGs and for main air pollutants emitted by shipping is now well established and systematically revised (Faber *et al*., 2020; Smith *et al*., 2015, Jalkanen *et al*., 2009, Johansson, *et al*., 2017; Olmer, *et al*., 2017a and b). The detailed account of the methodology may be found in Faber *et al*., 2020 and references therein.

Shortly, the pollutant emission estimation from a given ship is related to its power (W_i in kW), fuel consumption (FC, in kg fuel/h) and to its engine's relevant emission factors, that are energy-based (EF_e, in g pollutant/kWh) and fuel-based (EF_f, in g pollutant/kg fuel consumed). This is commonly expressed as fuel-based and energy-based emission calculations, which is normally pollutant dependent. The pollutant species that are mainly depending on the engine specific fuel consumption and also the fuel composition go into fuel-based estimations. These are carbon dioxide (CO_2), sulphur oxides (SO_x), metals and partially black carbon (BC). Their EM_i hourly emission in g pollutant/h is obtained by the following calculation:

$$EM_i = EF_f * FC_i \quad (2)$$

where EF_f is fuel-based emission factor in g pollutant/kg fuel and FC_i is hourly fuel consumption, while hourly emission may also be converted to mass emission of contaminant.
For pollutants, which emissions are dependent on combustion conditions, that is also on type of engine and its operational regime, the energy-based emission calculation is used as follows:

$$EM_i = EF_e * W_i \quad (3)$$

where EF_e is energy-based emission factor in g pollutant/kWh and W_i is hourly engine's power output. The pollutants, which emissions are dependent on combustion regime are: nitrogen oxides (NOx), carbon monoxide (CO), particular matter ($PM_{2.5}$ and PM_{10}), methane (CH_4), non-methane volatile organic compounds (NMVOC) and polyclic aromatic hydrocarbons (PAHs).

For all terms considered in these two basic equations a number of study efforts were carried (Faber *et al*. and references therein, Olmer, *et al*., 2017a, b). However, in recent years a progress was mainly dedicated to the methods allowing precise estimation of a fuel consumption and ship energy demand. Whereas engine emission factors for a number of pollutants, as for metals and PAHs, show yet a wide range of variations, which could introduce large levels of uncertainty to the emission inventories for these pollutants (Moldanova, *et al*., 2009; Agrawal 2008 a and b, Agrawal, *et al*., 2010; Copper *et al*. 2001, Cooper and Gustafsson, 2004; Corbin, *et al*., 2018; Zetterdahl, *et al*., 2016).

The exact determination of fuel consumption and energy demand, for any given ship in service, will also require a number of additional information describing operational conditions, including ship type and generation designation, main engine specific fuel oil consumption values, use of lubricant oils, auxiliary engines and boiler machinery energy demand and temporal operational phase assignment (cruise, maneuver, berth, anchor), fuel type characteristics, the engine speed and ship loading conditions as well as a number of external factors like hull fouling and weather conditions. Many reports presented on how these data are handled, including the development and adjustment of various factors and proxies (Omer *et al*. 2017, Smith *et al*. 2015, Faber *et al*. 2020). Whereas, the overall emissions for climate and air pollutants may be developed and summarized by the following equation (Olmer *et al*. 2017b):

$$EM_{i,j} = \sum_{t=0}^{t=n} \left(\left(P_{MEi} * LF_{i,t} * EF_{MEj,k,l,m} + D_{AEp,i,t} * EF_{AEj,k,l,m} + D_{BOp,i,t} * EF_{BOj,m} \right) * 1h \right) \quad (4)$$

Where: i = Ship; j = Pollutant; t = time (operating hour, h); k = engine type; l = engine tier; m = fuel type; p = phase (cruise, maneuvering, anchor, berth); $E_{i,j}$ = emissions (g) for ship i and pollutant j; P_{MEi} = main engine power (kW) for ship i; $LF_{i,t}$ = main engine load factor for ship i at time t, defined by the equation below; $EF_{ME\,j,k,l,m}$ = main engine emission factor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel m; $D_{AE\,p,i,t}$ = auxiliary engine power demand (kW) in phase p for ship i at time t; $EF_{AE\,j,k,l,m}$ = = auxiliary engine emission factor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel m; $D_{BOp,i,t}$ = boiler power demand (kW) in phase p for ship i at time t; $EF_{BO\,j,m}$ = boiler emission factor (g/kWh) for pollutant j and fuel type m.

Depending on the method of fuel consumption and power demand estimations for a given shipping fleet, we may refer either to top-down or bottom-up methodology. This distinction is practical in inventory studies of climate and air pollutants emissions by shipping, because requirement for data input into calculation scheme is different. Moreover, use of both methods provide further double-check of shipping emission inventories (Faber *et al*. 2020).

Top-down methods relay mostly on vessel's fuel-consumption sale and shipowner records, such as from World Energy Statistics provided by IEA (International Energy Agency), from information supplied by Lloyd's Maritime Information Services Ltd. and from EU database for Monitoring, Reporting and Verification (so called MRV system) of CO_2 emissions based on the fuel consumption of ships. The MRV database was used in the present study.

Bottom-up methods derive estimate of emissions from both detailed technical characteristics of individual ship and its operational activity profiles, matching this information with energy and fuel consumption calculation and pollutant emission factors. This method is considered as the current best practice, evolved now to fully developed models such as Ship Traffic Emissions Assessment Model – STEAM (Jalkanen *et al*. 2009, Jalkanen *et al*., 2012) and Systematic Assessment of Vessel Emissions – SAVE (Olmer *et al*. 2017 a and b). These models use detailed data about ship activities such as real-time location, speed and draught for individual ships from AIS matched with each individual ship-specific technical characteristic from Information Handling Services (IHS) and Global Fishing Watch (GFW) databases. Moreover, such models can produce and distribute ship emissions with high spatial and temporal resolution and therefore are especially useful in air pollution and environmental impacts modeling.

For the purpose of this study, we use a simplified approach with a set of assumptions for emission estimates. We consider, for instance, only main engine cruise ship's propulsive needs (no auxiliary engines), a use of only heavy fuel oil (HFO), that is exploited with scrubbers and a combination of emission estimation methods depending on data availability, taking mainly 2018 and 2019 MRV database for fuel consumption and the emission calculation of our model Ro-Pax ship and regular domestic voyage between continent and Corsica. The proposed method may be further extended, and applied to a full bottom-up database for estimation of a pollutant discharge by scrubber.

Emission factors for metals and PAHs are based on the available literature. The EFs are converted, where necessary, either to energy-based or fuel-based factors using specific fuel consumption of a ship (SFC, in g fuel/kWh) according to the following formula:

$$EF_f = \frac{EF_e}{SFC} \quad (5)$$

Whereas, emission factors for certain pollutants are directly related to the SFC and less dependent of type of engine and others depend more on the type of engine and combustion conditions. In the open literature, there are substantial differences in how emissions factors are assessed. In many ship emission inventory reports, including Third IMO GHG Study (Smith *et al*. 2015), most of energy-based emission factors used were from Cooper and Gustafsson (2004). These authors carried out an extensive study of pollutant emission factors, including metals and PAHs for a number of engine types and fuels (mainly HFO and MDO). We will update their emissions factors to the newest available literature in the following sections. It is also noticed that eventual changes in emission factors according to the ship generation are now taken by specific fuel consumption SFC, which includes the generational efficiencies of a ship (Faber *et al*. 2020). In the following sections we will shortly cover the EFs by indicating what approach was used in setting EFs for each of the studied pollutant, including examples of certain empirical equations for EFs of SO_x, PM and BC as selected ship main air pollutants.

However, high quality data on emission factors is generally still missing especially for not regulated emissions of many pollutants, such as metals and PAHs. In some ways, this is because maritime transport is one of the least regulated sectors. Furthermore, the experimental scientific devices setting and testing on board, in real-life seagoing various vessel conditions is very demanding. Finally, most of the emission factors do not provide thorough insight into particulate and gaseous emission speciation. All these elements are leading to the potential additional uncertainty in emission estimates.

The specific fuel consumption SFC baseline (noted also as SFOC), expressed as mass of fuel per unit of energy demand by the engine (g/kWh), varies according to engine age and type, where the later is assigned for marine diesel engines as slow speed (< 300 rpm, SSD), medium speed (300 – 900 rpm, MSD) and high speed (> 900 rpm, HSD). Most of modern cargo ships use slow to medium speed, two and four stroke diesel engines, whereas high speed engine are mainly used at small ships and fishing fleet. The SFC_{BE} baseline refers to an engine's most efficient ship load, which usually is around 80 % of the maximum engine power (Faber *et al*. 2020). In this study, we use the reference values of baseline SFCs, for marine diesel main engines, shown in Table 1.

Engine type and age	Before 1983	1984-2000	Post 2001
SSD	205	185	175
MSD	215	195	185
HSD	225	205	195

Table 1. Baseline SFCs given in g/kWh for different marine diesel main engines and ship generation (Smith et al. 2015; Faber et al. 2020)

The main engine SFC varies with loads. At low loads, below 20 %, the SFC tends to be at its highest level corresponding mainly to ship maneuvering phase. The empirical equation for main engine *SFC* as a function of a given engine load was proposed, using baseline SFC, as follows (Faber *et al.* 2020):

$$SFC_{ME} = SFC_{BE} * (0.455 * Load^2 - 0.710 * Load + 1.280) \ (6)$$

In the present example we use SFC_{ME} only for fuel consumption of our selected, random Ro-Pax model ship calculation and baseline SFC *i.e.* for most cruise phase calculation at 0.8 load factor, that is optimal low fuel consumption of diesel engines. The different SFC_{BE} were also reported for other MDO and LNG fuels, as well as for auxiliary and boiler engines (see in Faber *et al*. 2020). These values are useful for studies considering comparison of emissions of ships operating now with alternative distillate and low sulphur fuels or with the scrubbers (Comer *et al*. 2020).

2.3 Input data

European Union MRV database was used for 2018 and 2019 fuel consumption statistics for selected model vessels. The MRV refers to EU regulation 2015/757 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, amending Directive 2009/16/EC. The MRV system is based on the precise fuel consumption records reported by shipowners. The examples of data used are given in the Appendix 1.

Amount of wash water discharged globally by EGCS was recently estimated by Osipova *et al*. (2021) This report provides washwater mass, in tons, discharged by all ships with scrubbers installed or planned to be installed by 2020. The washwater discharges for each vessel were calculated as follows (Georgreff *et al*. 2019):

$$D = TED \times r \ (7)$$

Where: *D* is discharged water mass in tons (t), *TED* assigns total energy demand per ship, in megawatt hours (MWh) and *r* is scrubber washwater flow rate in t/MWh. For global assessment, the energy demand per ship in MWh was calculated with the SAVE model, using AIS data and ship characteristics from IHS database (Olmer *et al*. 2017). The washwater flow rate of 45 t/MWh, was that from IMO guidelines for EGCS (MEPC.259(68).4). In practice, many ships adjust the flow rate depending on operational conditions (fuel sulphur content, the alkalinity of seawater and pH of the washwater, exhaust gas flow etc.). Very often the average open-loop discharge rates are higher than 45 t/MWh and therefore reported estimates of scrubber's washwater discharge are relatively conservative (Comer *et al*. 2020, Osipova *et al*. 2021, Schmolke *et al*. 2020).

We have used the estimated mass of washwater discharged into the French EEZ and into the Gulf of Lion and the Ligurian Sea basins as well as in French Mediterranean ports for the calculations of pollutant discharged in these areas. The emission discharge factors for PAHs and selected metals were also revised and calculated
.

3 Example of single model-vessel fuel consumption and pollutant emissions

In this section estimates of pollutant emissions and theoretical range of its concentration in EGCS washwater are calculated for the random single Ro-Pax model vessel selected for this exercise from MRV database (Table 2). The fuel consumption and pollutant emissions are estimated using IMO's methodologies and the resulting fuel consumption is also compared to MRV database for the model ship. The vessel is supposedly fitted with an open-loop (OL) scrubber (or hybrid scrubber operating in OL mode). The concentrations of pollutant washwater are calculated for a range of different flowrates as well as for a range of different EGCS pollutant removal efficiencies. This allows also to calculate scrubber discharge water emission factors normalized to the recommended 45 t/MWh flow rate. This approach for pollutant emission estimates entering seawaters with EGCS discharged washwaters is thus analogous to the commonly accepted inventories of pollutant shipping exhaust gas emissions to air.

Model ship	**Specifications**
IMO Tier	0
Engine type	MSD
Construction year	1999
Fuel type	HFO, Sulphur 2,6%
Main engine power (kW)	23050
Washwater flow rate range (t/MWh)*	25 -160
SFC_{BE} (g/kWh)	195

**Assumed range of flowrates for scrubber open loop operation.*

Table 2. Model ship's main technical specifications (Ro-Pax ferry GT 30144)

3.1 Fuel consumption estimation

Main technical specifications of Ro-Pax ferry model ship are given in the Table 2. The ship operational profile is also given in Appendix 1 (Table 1; ship N° 6). The ship uses HFO with 2.6 % sulphur content and is supposed to operate with open loop scrubber. The hourly fuel consumption along a range of ship loads were calculated using the equation 6 where baseline specific fuel consumption is corrected by the load correction factor (CF_L) and power demand of ship at specific load. The results of this calculation are given in the Table 3.

ME load	SFC_{BE}	CF_L	W_i	SFC_{ime}	FC_i
%	(g/kWh)		(kW)	(g/kWh)	(kg/h)
0	195	1,28	0		0
10	195	1,214	2305	237	545,66
20	195	1,156	4610	225	1039,19
30	195	1,108	6915	216	1494,05
40	195	1,069	9220	208	1921,96
50	195	1,039	11525	203	2335,02
60	195	1,018	13830	199	2745,39
70	195	1,006	16135	196	3165,20
80	195	1,003	18440	196	3606,59
90	195	1,01	20745	197	4085,73
100	195	1,025	23050	200	4607,12

Table 3. Hourly fuel consumption results for the model ship at different main engine loads.

The annual fuel consumption for our model ship may be calculated on the base of annual time spent at sea reported in MRV database. 2018 and 2019 data for our model ship are shown in Table 4. The estimated annual fuel consumption is also reported, and it was within 6% difference of the MRV database, indicating relatively accurate estimation. These results show that selected ferry Ro-Pax model ship in normal operational conditions will burn between 14 to 16 kt of heavy fuel oil per year. This is further used in pollutant emission calculation exercise.

Model ship MRV data	**2018**	**2019**
MRV time at sea (h)	4454,6	4966,1
MRV FC annual (tons)	13375,9	15072,7
MRV annual distance (n-m)	76841,8	87514,7
FC annual estimated (tons)*	14165,8	15792,7
Difference MRV FC and estimated FC (%)	5,6	4,6

**Annual fuel consumption estimated from the data reported in the Table 2 and time spent at sea, MRV data.*

Table 4. MRV data and estimated annual fuel consumption (FC) for the model ship

3.2 Pollutant fuel-based emission factors calculation

Here are illustrated only emission factors (EFs) for particulate matter PM_{10}, polycyclic aromatic hydrocarbons $\sum PAH_{16}$ (summed EPA 16 PAHs) and vanadium V (see Table 9 for EF references). Emission factors significantly increase when engine loads are low. Low loads adjustment factors were used for loads below 10% (Faber *et al*. 2020). At these low loads the emissions factors for PAH, V and PM_{10} are indeed much higher, however at very low loads (usually below 5%) fuel consumption is set as nil.

Load	**EF_e**			**SFC_{BE}**	**EF_f**		
(%)	$\sum PAH_{16}$ (g/kWh)	V (g/kWh)	PM_{10} (g/kWh)	HFO (g/kWh)	$\sum PAH_{16}$ (g/g HFO)	V (g/g HFO)	PM_{10} (g/g HFO)
0	3,28E-03	2,07E-02	1,40	195	3,56E-04	4,92E-04	5,23E-02
10	3,28E-03	2,07E-02	1,40	195	3,67E-05	1,30E-04	9,91E-03
20	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03
30	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03
40	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03
50	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03
60	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03
70	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03
80	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03
90	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03
100	3,28E-03	2,07E-02	1,40	195	1,68E-05	1,06E-04	7,18E-03

Table 5. PAHs, V and PM10 energy- and fuel-based emission factors

These data were used for the present exercise of emission calculation for the random Ro-Pax model ship. Additional discussion on the emission factors of metals and PAHs will be given later (see 4.1).

3.3 Emission calculation

Annual emissions of pollutants are estimated using previously presented results (fuel consumption estimations, emission factors) as well as MRV data on fuel consumption and time spent at sea for the model ship (Table 4 and 5). Because of the difference of hourly fuel consumption throughout engine loads shown in the Table 3 and higher emissions factors at loads below 20%, the annual emission estimation will depend on the operational profile of the ship. The MRV data allow to estimate, for the model vessel, that time spent in ports in 2018 was about 10% and in 2019 was about 4%. Whereas estimated time of the model vessel with main engine loads below 20% was about 6%. The rough estimate shows also that annual fuel consumption with low load below 20 % was about 1.7% and pollutants emissions roughly about 3% of the total emissions. These results provide only rough estimates of what portion of total emission would be in the coastal and harbors areas when vessels are in low loads maneuvering phase. However, more precise ship operational information would be needed to calculate accurately share of coastal and harbor emissions.

	2018		2019	
Pollutant	**Based on FC MRV**	**Based on FC estimated**	**Based on FC MRV**	**Based on FC estimated**
PAH	225	238 (8)	253	265 (9)
V	1422	1506 (50)	1603	1680 (56)
PM_{10}	96031	101703 (3353)	108214	113383 (3758)

Table 6. Annual emission of selected pollutants in kg from the model ship; in brackets are estimates of emissions at main engine loads below 20%

3.4 Pollutant concentrations in EGCS washwater

The pollutant concentrations in EGCS washwater will vary with flowrates and will depend on pollutant emissions factors and pollutant washing out (trapping - removal) efficiency from exhaust gas. For this example, pollutant concentrations are calculated as 100 % trapping efficiency, for a given energy emission factors as well as for specified range of flow rates between 25 to 160 t/MWh (Table 7). The range of proposed flowrates fairly well cover reported scrubber practice (Buhaug *et al.* 2006 Schmolke *et al.* 2020, Teuchies *et al.* 2020, Osipova *et al*. 2021), and further conversion to higher or lower flowrates is straightforward. The pollutant concentrations are calculated by division of emission factors by specified flowrates for our model vessel. The results of this estimation are shown in the Table 7.

	EFe (g/kWh)	**FW = 25 t/MWh**	**FW = 45 t/MWh**	**FW = 100 t/MWh**	**FW = 160 t/MWh**
		Concentration (µg/L and mg/L for PM)			
∑PAH16	3,28E-03	131,20	72,89	32,80	20,50
V	2,07E-02	829,56	460,87	207,39	129,62
PM_{10}	1,40	56,00	31,11	14,00	8,75

Table 7. Calculated concentrations of selected pollutants in scrubber washwaters at different flowrates

The obtained range of concentrations is roughly plausible in respect of determined pollutant concentrations in washwaters (Celo, *et al.*, 2015, Agrawal, *et al.*, 2008a and b, Sippula, *et al.*, 2014, Moldanová, *et al.*, 2009, Kjolholt *et al*. 2012; Teuchies *et al*.2020; Schmolke *et al*. 2020; EGCSA and Euroshore 2018, Lunde-Hermansson *et al*. 2021). However, our estimated concentrations represent the upper limit for a given pollutant emission factor, with respect to exhaust derived pollutants. This is because 100% scrubber pollutant trapping efficiency should be considered as overestimation even for metals and particulate matter *i.e.* pollutants generally considered as being efficiently washed out from exhaust gas by scrubbers (Celo, *et al.*, 2015, Lehtoranta, *et al.*, 2019). On the other hand, higher concentrations of vanadium in washwaters were also already reported (Kjolholt *et al*. 2012; Teuchies *et al*.2020, EGCSA and Euroshore 2018). This, in turn, may be explained by its higher emission factor that is strongly dependent on vanadium content in fuels, which consequently is strongly variable from oil to oil (Celo, *et al.*, 2015). Calculated range of PAH concentrations is high regarding the IMO limit of 50 µg/L at 45 t/MWh flowrate and much lower concentrations reported in a few studies (Kjolholt *et al*. 2012; Teuchies *et al*.2020; Schmolke *et al*. 2020; EGCSA and Euroshore 2018, Lunde-Hermansson *et al*. 2021, Du *et al*. 2022). It might be so that trapping of PAH by scrubbers is low, however this technical information is principally missing. It is recognized that two and three-ring molecular light PAHs are better dissolved in scrubbing process, and these compounds are indeed major homologues typically determined in washwaters (Winnes *et al*. 2018, EGCSA 2018, Linders *et al*. 2020, Ushakov *et al*. 2020, Schmolke *et al*. 2020). Whereas 4 to 6 rings (or more) higher molecular weight compounds would be mainly associated with particulate matter (Kjolholt *et al*. 2012). Furthermore, we presume also that PAH determination in washwaters might be strongly underestimated (Linders *et al*. 2019, Du *et al*. 2022). This is mainly related to difficulties of their accurate analysis in the water phase and analyses done on whole not filtered waters, that is without separation of particles and water phase for their analysis (Linders *et al*. 2019). Our estimated concentrations of PM_{10} in model-vessel washwater seem also to be high. The most studies were looking at remaining PM in exhaust gas and not in scrubbers washwaters (Lehtoranta, *et al.*, 2019, Winnes *et al.*, 2020). These studies indicate high trapping efficiency of PM by scrubbers, while rather rare determinations of suspended particulate matter in washwaters seem to be fairly inconsistent (Schmolke *et al*. 2020). This high variation of PM concentration determined in washwaters might be expected with varying main engine operational regime conditions and would probably require long term large volume sampling to be representative of discharge washwater volumes. Such large volume sampling for accurate PM determination in washwaters will also be needed for the determination of particulate pollutants discharged by scrubbers.

4 Comparison of pollutant concentrations in washwaters and calculation of emission discharge factors

Fairly limited number of studies determined metal and PAH concentrations in scrubber washwaters sampled before their discharge. A few recent reports reviewed the determined concentration ranges (Linders *et al*. 2019, Comer *et al*. 2020, Hassellöv *et al*. 2020, Lunde-Hermansson *et al*. 2021) showing very high variation in the published data. Certain comments pointed out at scarcity of the thorough peer-reviewed scientific literature data comparatively to a number of reports coming from maritime industry and organizations, which generally do not go through peer-review approval (Linders *et al*. 2019, Comer *et al*. 2020, Hassellöv *et al*. 2020). Furthermore, only one review study (Comer *et al*. 2020), proposed the air and water emission/discharge factors of main pollutants for the ships equipped with scrubbers. In this work, the authors provide the relative air emissions change after the scrubber when using HFO (2.6% S). For the black carbon the emission change is shown additionally for the two different diesel engines (Table 8).

Pollutant	**SO_2**	**CO_2**	**PM_{10}**	**$PM_{2.5}$**	**NO_x**	**CO**	**BC (SSD)**	**BC (MSD)**
HFO (2,6% S)	-98%	+2%	-79%	-79%	0%	-11%	-9%	-11%

Table 8. Relative emissions change after the scrubber when using HFO 2.6% S (from Comer et al. 2020).

It appears that scrubber trapping and removal efficiency from exhaust gas of particulate matter ($PM_{10 \text{ and } 2,5}$) may be high, almost 80%, and thus all contaminants associated with PM will be likewise discharged with the scrubber washwaters. It is also shown that CO_2 emissions of ships with scrubbers will be slightly higher (+2%) that is in accordance with increased power consumption and scrubber specifications given by certain manufactures. Comer *et al*. (2020) also compared the relative emission changes for a ship using HFO with scrubber with emissions of a ship using low sulphur and distillate fuels, showing that the emissions of ships with scrubbers will be significantly higher for PM and BC than ships using alternative fuels (about +70 % of PM compared to MGO and more than 80 % of BC depending on engine). There is almost none information about scrubber trapping efficiency of metals and PAHs. It is frequently assumed that metals removal is high (Linders *et al*. 2020). However, Kjølholt *et al*. 2012 estimated nickel and vanadium scrubber removal to be 14 to 23% and 26 to 39 % respectively. These results suggest relatively low scrubber trapping efficiency of both metals. On the other hand, best to our knowledge, none of the studies determined both pollutant concentrations in the scrubber wash water and those remaining in the exhaust and compared the results to the calculated total emissions. This mass balance approach should be developed.

4.1 Pollutant concentrations in washwaters

In this section, we compare calculated pollutant concentrations in scrubbers washwater, assuming their 100 % removal efficiency, with concentrations determined by chemical analysis in scrubber washwaters. A few studies were selected as examples, for a number of vessels fitted with scrubbers and for which pollutant concentrations and ship characteristics were reported (Kjolholt *et al*. 2012; Teuchies *et al*.2020 ; Schmolke *et al*. 2020 ; EGCSA and Euroshore 2018).

The metals emissions factors used for their concentration estimation in washwaters, are given in Table 9. These data are from several publications reporting metal levels in HFO (Moldanova, *et al.*, 2009; Agrawal, *et al.*, 2010; Cooper and Gustafsson, 2004; Linak and Miller, 2000; Corbin, *et al.*, 2018; Huffman, *et al.*, 2000, Lunde Hermansson *et al*. 2021). Depending on the fuel used and determination protocols, emission factors for metals may be highly variable (Celo *et al*. 2015). For our set of selected data, the relative standard deviation of emission factors of vanadium and nickel is 57 and 21 % respectively, and for a number of trace metals it is even higher (Table 9). High variability of PAH emission factors is also reported in the literature. The selected data set presented here show relative standard deviation is 95 % of emission factors for ΣPAH_{16}. The wider range of variation of metal and PAH EFs was similarly reported in the recent paper of Lunde-Hermansson *et al*. 2021 (relative standard deviation for vanadium 112%, nickel 74% and PAH 204%).

	EF_m (g kg_{HFO}^{-1})				EF_p (g kWh^{-1}, SFOC = 0.195 (kg_{HFO} $(kWh)^{-1}$)			
Contaminant	**Mean**	**SD**	**Min.**	**Max.**	**Mean**	**SD**	**Min.**	**Max.**
V	1,20E-01	6,90E-02	3,50E-02	2,20E-01	2,34E-02	1,35E-02	6,83E-03	4,29E-02
Fe	1,90E-02	4,40E-03	1,30E-02	2,50E-02	3,71E-03	8,58E-04	2,54E-03	4,88E-03
Ni	2,90E-02	6,10E-03	1,70E-02	3,50E-02	5,66E-03	1,19E-03	3,32E-03	6,83E-03
Pb	1,70E-03	2,00E-03	1,00E-04	4,50E-03	3,32E-04	3,90E-04	1,95E-05	8,78E-04
Zn	2,30E-02	3,50E-02	1,00E-03	7,40E-02	4,49E-03	6,83E-03	1,95E-04	1,44E-02
Cd	4,60E-04	2,60E-04	1,30E-05	6,00E-04	8,97E-05	5,07E-05	2,54E-06	1,17E-04
Hg	7,70E-05	4,70E-05	3,00E-06	1,20E-04	1,50E-05	9,17E-06	5,85E-07	2,34E-05
As	3,10E-04	3,00E-04	1,00E-04	8,50E-04	6,05E-05	5,85E-05	1,95E-05	1,66E-04
Cr	1,10E-03	9,30E-05	9,60E-04	1,20E-03	2,15E-04	1,81E-05	1,87E-04	2,34E-04
Cu	1,80E-03	1,40E-03	5,60E-04	3,50E-03	3,51E-04	2,73E-04	1,09E-04	6,83E-04
ΣPAH_{16}	1,68E-02	1,59E-02	2,25E-03	5,13E-02	3,28E-03	3,11E-03	4,38E-04	1,00E-02

Table 9. Fuel-based and energy-based emission factors of metals and PAHs from selected literature data: Moldanova, et al., 2009; Agrawal, et al., 2010; Cooper and Gustafsson, 2004; Linak and Miller, 2000; Corbin, et al., 2018; Huffman, et al., 2000, Zhang et al. 2018; Zhao et al. 2019; Zhao et al 2020; Agrawal et al. 2008a and b, Agrawal et al. 2010.

It appears thus that the choice of reference value of EF will greatly influence the estimated contaminant concentration in washwaters. It also indicates a need for further work to derive commonly accepted range of EF values for metals and PAHs, including uncertainty calculation, like for GHGs and main ship pollutants (Faber *et al*. 2020). EF values used in our calculation were selected from the limited database, narrowing the range of variation (Table 9). Metals and PAH concentrations determined in the OL scrubber washwater are given in Figure 2 and Table 10.

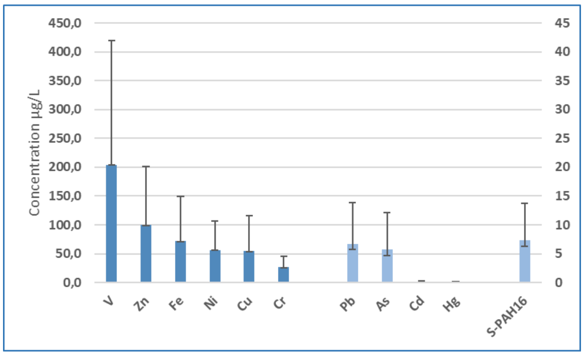

Figure 2. Metals and PAH concentrations (µg/L) determined in open-loop scrubber washwater; The principal axis is used for V, Zn, Fe, Ni, Cu and Cr concentrations while the secondary axis is used for Pb, As, Cd, Hg and ΣPAH16 concentrations.

The highest overall mean concentrations of metals were found for V (204 ± 215 µg/L), Zn (100 ± 101 µg/L), Fe (72 ± 78 µg/L), Ni (57 ± 51 µg/L) and Cu (55 ± 61 µg/L). Cr (27 ± 19 µg/L) show intermediate levels. About 10 times lower mean concentrations than nickel, were determined for Pb (6.7 ± 7.2 µg/L), As (5.7 ± 6.4 µg/L) and ΣPAH_{16} (7.3 ± 6.4 µg/L), whereas the trace level elements, such as mercury and cadmium, were in most cases well below detection limit of the analytical methods. It is noticed that, Fe was analyzed only in one study (Schmolke *et al*. 2020). The wide range of concentrations were determined for all analyzed metals and PAHs. The reported levels are given here for only a few selected studies for which ship operational conditions were described (Table 2 Appendix 1), so that discharge flow rates of OL scrubbers at given main engine power loads were known. Finally, only a few outlier data for Cr, Pb and Zn (singular very high concentrations) were excluded from descriptive statistics in Table 10.

The comparison between estimated and determined mean concentrations of contaminants in the OL scrubber washwater is presented in Figure 3, for the selected set of data (Tables 10 and 11). The estimated concentrations were much higher for PAHs (10 times higher) and for two trace level metals, Cd and Hg (17 and 4 times higher respectively, Table 11). V and Ni estimated mean concentrations were more than two times higher, whereas those of Fe, Zn and Pb were in same range of concentrations. Finally, the estimated mean concentrations of Cu, Cr and As were lower than those determined in the set of selected studies (Table 11). The various factors contribute to these differences. As previously mentioned, PAHs and also trace levels metals may not be well determined in washwaters and their determined concentrations are probably significantly underestimated in a number of studies (Du *et al*. 2022).

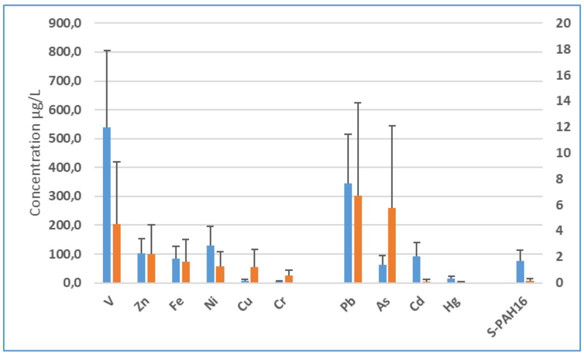

Figure 3. Metals and PAH concentrations (µg/L) estimated (blue) and determined (orange) in open-loop scrubber washwater; secondary axes only for Pb, As, Cd, Hg

On the other hand, the scrubber removal efficiency for main metals such as V and Ni were reported to be below 50% (Kjolholt *et al*. 2012). Whereas, emission factors for Fe, Zn and Pb used here might be too low. Finally, in a number of studies, the determined concentrations of Cu in inlet waters were frequently reported higher than concentrations determined at scrubber outlet in discharged washwaters (Teuchies *et al*.2020 ; Schmolke *et al*. 2020 ; EGCSA and Euroshore 2018). The contamination by certain metals from ship domain (anti-fouling paints, plumbing, various lubricants) may potentially result in significant additional contamination of the scrubber washwater (Linders *et al*. 2019). The reason of higher concentration of As and Cr is not well recognized and the emission factors of these elements should probably be further revised.

The estimated concentrations of contaminants are dependent on their emission factor and washwater flow rate. The power function of this relationship is shown in Figure 4. Such correlation is however not observed for metals and PAHs determined in scrubber discharged washwater. As discussed above determined pollutant concentrations in washwater, will depend on one hand on scrubbing trapping process efficiency and on the other hand on a number of factors including: washwater sampling representativeness, sample contamination, elements and compounds speciation in washwater as well as overall methodology and its precision and accuracy.

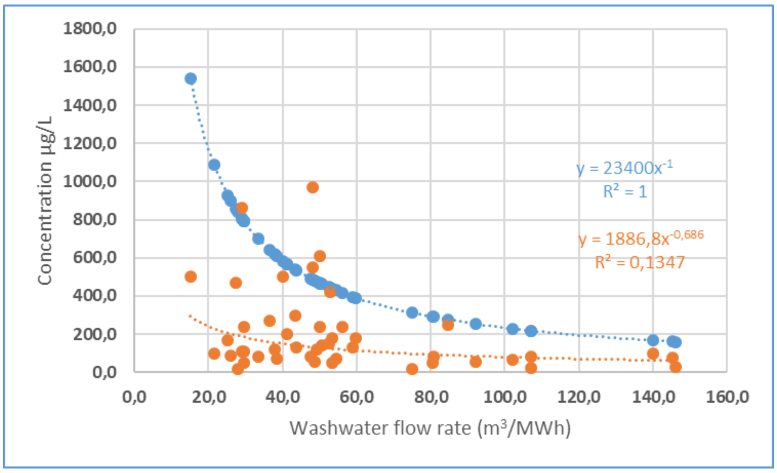

Figure 4. Vanadium concentrations (µg/L) estimated (blue) and determined (orange) in open-loop scrubber washwater as function of washwater flow rate (t/MWh).

Therefore, the initial approach for scrubber pollutants discharge assessment, could be based on the estimates only, that is, using their emissions factors, washwater volume and flow rate and estimated scrubber trapping efficiency. Inventories of GHG and main pollutant air emissions from shipping are not done on the basis of determined pollutant concentrations in the exhaust gas, but on the basis of their estimated air emissions, using emission factors and energy and fuel consumption by shipping fleet.

	Study (number of ships with operational conditions) *											
	A (4)			**B(5)**			**C(5)**			**D(34)**		
	Minimum, maximum and mean concentrations (µg/L)											
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Vanadium (V)	25	180	83,75	30,0	970,0	351,0	15,0	250,0	96,8	20,0	860,0	213,3
Iron (Fe)							30,0	210,0	72,1			
Nickel (Ni)	9,1	43,0	22,8	14,0	180,0	74,6	7,0	60,4	26,1	20,0	240,0	63,0
Lead (Pb)	3,6	21,0	8,6	2,1	17,0	8,6	0,1	1,1	0,4	8,0	20,0	14,0
Zinc (Zn)				88,0	270,0	179,6	2,3	66,7	18,0	20,0	330,0	100,8
Cadimum (Cd)	0,1	0,1	0,1	0,1	0,5	0,2						
Mercury (Hg)	0,1	0,1	0,1									
Arsenic (As)	0,5	1,8	0,8	6,3	21,0	12,1	1,2	5,0	3,3			
Chromium (Cr)				6,5	62,0	24,1				1,7	60,0	27,3
Copper (Cu)	110,0	260,0	167,5	9,4	100,0	40,9	2,1	15,3	8,3	6,4	140,0	46,6
ΣPAH_{16}	1,0	1,8	1,4	2,1	6,1	3,5	4,5	31,4	13,7	0,5	24,0	7,7

** Reference study: (A) Kjolholt et al. 2012 ; (B) Teuchies et al.2020 ; (C) Schmolke et al. 2020 ; (D) EGCSA and Euroshore 2018.*

Table 10. Metal and PAH concentrations (µg/L) determined in open loop scrubber washwater; data from a selected number of studies with given ship operational conditions (see also Table 2, A1.)

	Study (number of ships with operational conditions)											
	A (4)			**B(5)**			**C(5)**			**D(34)**		
	Minimum, maximum and mean concentrations (µg/L), except PM (mg/L)											
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Vanadium (V)	218,7	437,4	328,1	160,1	485,6	337,8	167,1	312,0	247,8	289,8	1541,0	636,0
Iron (Fe)	34,6	69,3	51,9	25,3	76,9	53,5	26,5	49,4	39,2	45,9	244,0	100,7
Nickel (Ni)	52,9	105,7	79,3	38,7	117,3	81,6	40,4	75,4	59,9	70,0	372,4	153,7
Lead (Pb)	3,1	6,2	4,6	2,3	6,9	4,8	2,4	4,4	3,5	4,1	21,8	9,0
Zinc (Zn)	41,9	83,8	62,9	30,7	93,1	64,8	32,0	59,8	47,5	55,5	295,4	121,9
Cadimum (Cd)	0,8	1,7	1,3	0,6	1,9	1,3	0,6	1,2	0,9	1,1	5,9	2,4
Mercury (Hg)	0,1	0,3	0,2	0,1	0,3	0,2	0,1	0,2	0,2	0,2	1,0	0,4
Arsenic (As)	0,6	1,1	0,8	0,4	1,3	0,9	0,4	0,8	0,6	0,7	4,0	1,6
Chromium (Cr)	2,0	4,0	3,0	1,5	4,5	3,1	1,5	2,9	2,3	2,7	14,1	5,8
Copper (Cu)	3,3	6,6	4,9	2,4	7,3	5,1	2,5	4,7	3,7	4,3	23,1	9,5
ΣPAH_{16}	30,7	61,3	46,0	22,4	68,1	47,4	23,4	43,7	34,7	40,6	216,0	89,1
PM	13,1	26,2	19,6	9,6	29,1	20,2	10,0	18,7	14,8	17,3	92,2	38,1

** Reference study: (A) Kjolholt et al. 2012 ; (B) Teuchies et al.2020 ; (C) Schmolke et al. 2020 ; (D) EGCSA and Euroshore 2018.*

Table 11. Metal, PAH and particulate matter concentrations estimated in open loop scrubber washwater for a selected number of studies with given ship operational conditions (see also Table 2 A1.)

4.2 Pollutant water emission discharge factors

The IMO scrubber guidelines relate pollutant concentrations in washwater to a normalized washwater flow rate (MEPC 2015). PAH concertation IMO limit is 50 µg/L at 45 t/MWh flow rate, that is resulting in the maximum allowable discharge under the IMO guidelines equivalent to 2250000 µg/MWh. Accordingly, PAH concentrations vary with washwater flow rates so that their emission discharge factor (DF) remain constant (Table 12, Figure 5). Comer *et al*. (2020) provides a short review on IMO's scrubber guidelines history. This report and others pointed out that there is no clear scientific explanation on how the IMO's discharge limit for PAHs was established (Comer *et al*. 2020, Linders *et al*. 2020). It is also questionable whether IMO's current discharge limits are protective enough for the environment in terms of both pollutant amount input and environmental quality criteria (U.S. EPA 2011, Linders *et al*. 2020). It may be also guessed that PAH scrubber discharge limit (50 µg/L at 45 t/MWh flow rate) was established with PAH air emission factor of 2,25 g/MWh for marine diesel engines operating with HFO. Therefore, such PAH limit level will indeed be rarely exceeded in scrubber discharge waters. Furthermore, there is no IMO's discharge limit for heavy metals and this is strongly missing in current guidelines (Endres *et al*. 2018, Linders *et al*. 2020).

Comer *et al*. (2020) proposed for six metals and ΣPAH_{16} scrubber water emission discharge factors on the basis of their selected determined concentrations data in the washwaters, reported in the literature. The comparison of Comer's *et al*. 2020 rounded median values with our estimates is presented in Table 13. We compared also these values with metal and PAH emission factors with discharge level of pollutants of 100 % scrubber removal efficiency.

Scrubber flow rate (t/MWh)	PAH concentration (µg/L)
1	2250
2,5	900
5	450
11,25	200
22,5	100
45	50
90	25
100	22,5
125	18
150	15
160	14,1

Table 12. IMO’s PAH limit concentration (µg/L) in the scrubber washwater at different open-loop scrubber operational flow rates (t/MWh).

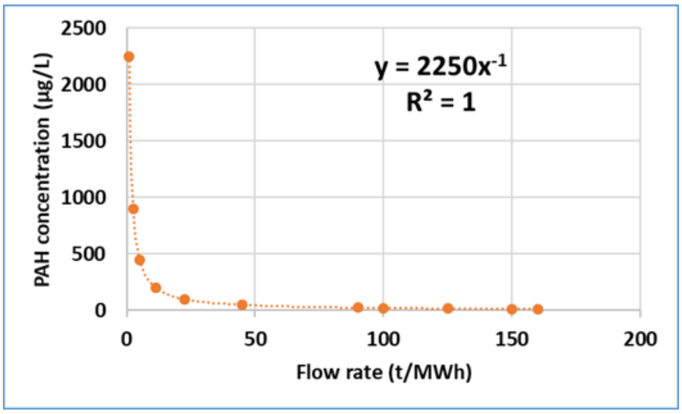

Figure 5. IMO’s PAH limit concentration (µg/L) in scrubber washwater as function of flow rate (t/MWh).

	$DF1_{ww}$	**$DF2_{ww}$**	**EF_e**	**Ratios**	
	This report	ICCT	This report	DF1/DF2	$DF1/EF_e$
	µg/MWh				
V	6857857	9310000	23400000	0,74	0,29
Fe	4282418		3705000		1,16
Ni	1906000	2590000	5655000	0,74	0,34
Pb	395870	519000	331500	0,76	1,19
Zn	3287061		4485000		0,73
Cd	5350	5000	89700	1,07	0,06
Hg	6072	7000	15015	0,87	0,40
As	383567		60450		6,35
Cr	1010824		214500		4,71
Cu	1304605	2180000	351000	0,60	3,72
S-PAH16	297303	119000	3280000	2,50	0,09

Table 13. Includes estimated scrubber water emission discharge factors DFs_{ww} in µg/MWh for each pollutant. $DF1_{ww}$ are estimated values in this report, $DF2_{ww}$ are estimated values in Comer’s *et al*. and EF_e pollutant energy-based emission factors, as proposed in this report.

Comer *et al*. 2020 water emission discharge factors for metals are generally higher than our estimates (about 13 to 26 % higher, except for Cd which is similar), whereas for PAH their median discharge factor is 2,5 times lower than our estimate. A number of water emission discharge factors calculated on the basis of pollutant determined concentrations in the scrubber washwaters are significantly lower than pollutant discharge calculated on the basis of their emission factors, suggesting that, as discussed above, low scrubber removal efficiency for instance for two main metals Ni and V (below 34%) and very low for PAHs (below 10%). DFs for Fe and Pb are close to their energy-based emission factors, whereas the DFs for As, Cr and Cu are much higher than their discharges calculated on the basis of their energy-based emission factors, indicating additional contamination from ship domain not related to ship propulsion fuel consumption.

The better understanding of pollutant discharged by scrubbers requires comprehensive water emission discharge factors, which if matched with detailed data about ship activities and characteristics, would provide useful spatial and temporal marine water pollution data (Linders *et al*. 2019, Comer *et al*. 2020, Hassellöv *et al*. 2020). However, presented records of comparatively large range of water emission discharge factors for metals and PAHs suggest inconsistent results. Furthermore, we remark also that all proposed scrubber washwater emission discharge factors were obtained on the basis of very limited sets of data. We believe that the more efforts and research work on the consensus values for metals and PAHs water emissions discharge factors should be recommended. Therefore, at present, the estimation of pollutant discharged by scrubbers using the energy-based and fuel-based emission factors elaborated for various ship marine engines, seems to be an appropriate solution.

5 Potential pollutant discharges by Ro-Pax shipping on regular journey example: France – Corsica

In this section, the case study assessment scenario of pollutants potential discharge by EGCS is proposed for the regional scale projection taken place in the Western Mediterranean, on the regular crossing journey of Ro-Pax maritime transport services between mainland France and Corsica. Eleven ships operating on this line were selected from EMSA Thetis-MRV database for 2019, providing among other annual fuel consumption records (total FC in tons and kg/nautical mile), ship time spent at sea and total CO_2 emissions (Table 14). The annual ship distance was calculated from these data. The gross tonnage (GT) of all ships was extracted via the VesselFinder website (https://www.vesselfinder.com/fr/) and the main engine power was estimated from GT data (EMEP/EEA 2019). Estimated emissions were thus based on both energy demand and fuel consumption, using pollutant emission factors given in Table 9. Energy demand estimation was done with assumption of 80 % load and annual time spent at sea. The potential discharge is thus assumed for ship as it would be fitted with scrubber operating in the OL mode and with 100 % pollutant removal efficiency (Table 15). The ship number 6 is our model ship also used for the previous presentation.

Ship N°	**Ship 1**	**Ship 2**	**Ship 3**	**Ship 4**	**Ship 5**	**Ship 6**	**Ship 7**	**Ship 8**	**Ship 9**	**Ship 10**	**Ship 11**
GT (t)	34694	22070	28338	29718	30144	29968	26024	36093	35760	41447	34419
Power est. (kW)	26122	18548	22412	23234	23485	23381	21012	26916	26728	29887	25965
Power 80% (kW)	20898	14838	17930	18587	18788	18705	16810	21533	21382	23910	20772
FC (t)	14849	7950	18925	11814	15073	15012	22918	24738	16084	16641	17519
Time (h)	4196	4044	4714	4056	4966	4435	4966	4584	4100	3572	5134
FC (kg /n-m)	216	133	221	172	172	200	239	256	220	240	198
FC (kg/h)	3538	1966	4014	2913	3035	3385	4615	5396	3922	4659	3412
Distance (n-m)	68821	59778	85501	68775	87515	75107	95737	96643	73008	69284	88698
CO_2 EM (t)	46375	24850	59063	36934	47061	46915	71456	77131	50227	51961	54613

Table 14. Selected Ro-Pax ships, mainly operating in the Western Mediterranean, between mainland France and Corsica, data from EMSA Thetis-MRV 2019 database including total annual fuel consumption (FC tons), time spent at sea (hours), amount average fuel consumption per shipping distance (kg/nautical mile) and CO2 emissions (tons). Ship hourly fuel consumption (kg/h) and annual distance (nautical miles) were calculated. Ship gross tonnage GT were obtained from https://www.vesselfinder.com/fr/ and ship power estimated from GT data.

5.1 Potential pollutant EGCS loads

All ships belong to the same Ro-Pax category and therefore their annual 2019 operational activity characteristics are of similar order of magnitude (Table 14). For instance, the average annual shipping distance is 78987 ± 15% nautical miles and the average annual time spent at sea is of 4433 ± 11% hours, resulting in mean ship speed of 17,8 knots. Higher range of variation was reported for total annual fuel consumption (± 28 %) this is because of ship number 2 with significantly lower fuel consumption. The estimated potential annual pollutant discharges are reported in Table 15. An example of the difference between energy-based and fuel-based estimation for each ship is shown for V (Figure 6). This difference is the same as for all pollutants, with relative standard deviation of ± 22 %, reflecting the variation in ship energy demand estimation and fuel consumption records. Whereas, this difference in the average of pollutant annual emission estimated by both methods is definitely leveled (Table 16 and Figure 7).

Ship N°		**Ship 1**	**Ship 2**	**Ship 3**	**Ship 4**	**Ship 5**	**Ship 6**	**Ship 7**	**Ship 8**	**Ship 9**	**Ship 10**	**Ship 11**
	GT	34694	22070	28338	29718	30144	29968	26024	36093	35760	41447	34419
	Power (kW)	20898	14838	17930	18587	18788	18705	16810	21533	21382	23910	20772
		kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
V	Energy	2052	1404	1978	1764	2183	1941	1953	2310	2052	1998	2496
	Fuel	1782	954	2271	1418	1809	1801	2750	2969	1930	1997	2102
Fe	Energy	325	223	314	280	346	308	310	366	325	317	396
	Fuel	282	151	360	224	286	285	435	470	306	316	333
Ni	Energy	496	340	478	427	528	469	472	559	496	483	604
	Fuel	431	231	549	343	437	435	665	717	466	483	508
Pb	Energy	29	20	28	25	31	28	28	33	29	28	35
	Fuel	25	14	32	20	26	26	39	42	27	28	30
Zn	Energy	394	269	380	338	419	372	375	443	394	383	479
	Fuel	342	183	435	272	347	345	527	569	370	383	403
Cd	Energy	8	5	8	7	8	7	7	9	8	8	10
	Fuel	7	4	9	5	7	7	11	11	7	8	8
Hg	Energy	1	1	1	1	1	1	1	1	1	1	2
	Fuel	1	1	1	1	1	1	2	2	1	1	1
As	Energy	5	4	5	5	6	5	5	6	5	5	6
	Fuel	5	2	6	4	5	5	7	8	5	5	5
Cr	Energy	19	13	18	16	20	18	18	21	19	18	23
	Fuel	16	9	21	13	17	17	25	27	18	18	19
Cu	Energy	31	21	30	26	33	29	29	35	31	30	37
	Fuel	27	14	34	21	27	27	41	45	29	30	32
ΣPAH_{16}	Energy	288	197	277	247	306	272	274	324	288	280	350
	Fuel	250	134	318	199	254	253	385	416	271	280	295

Table 15. Ship pollutant annual potential washwater emission discharge (in kg); energy-based and fuel-based estimations for 2019.

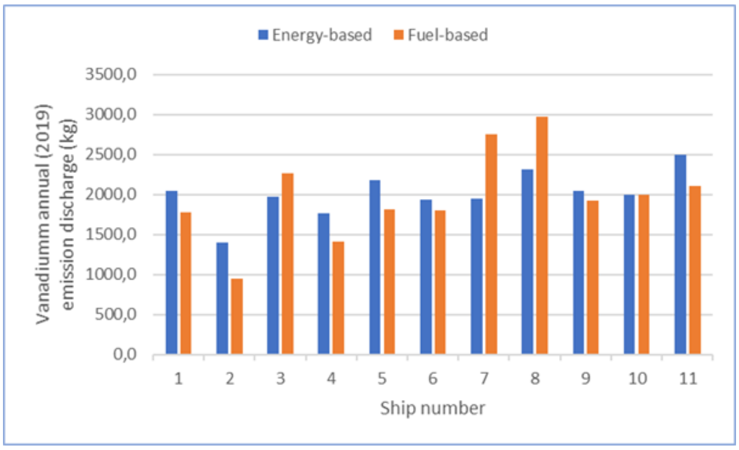

Figure 6. Vanadium annual 2019 potential water emission discharge (kg) per studied Ro-Pax ship; ships characteristics and data given in the Table 14.

In the context of the routine operational conditions in 2019 for our group of Ro-Pax ships, this provides rough estimation of an order of magnitude of potential amount of pollutant emission discharge by a single ship. The highest average emission discharge of about 2000 kg/y was determined for V, intermediate discharges are in order of hundreds of kilograms per year determined for Fe, Ni, Zn, and PAHs (range 277 – 486 kg/y) and from dozens to a few kilograms for Pb, Cd, As, Cr and Cu and about 1 kilogram for Hg (Table 16).

	ED (kg)	**SD**	**ED (kg)**	**SD**
	Energy-based	σ	Fuel-based	σ
V	2011,9	282,1	1980,2	560,5
Fe	319,0	44,7	313,5	88,8
Ni	486,6	68,2	478,6	135,5
Pb	28,5	4,0	28,1	7,9
Zn	386,0	54,1	379,5	107,4
Cd	7,7	1,1	7,6	2,1
Hg	1,3	0,2	1,3	0,4
As	5,2	0,7	5,1	1,4
Cr	18,5	2,6	18,2	5,1
Cu	30,2	4,2	29,7	8,4
ΣPAH$_{16}$	282,0	39,5	277,6	78,6

Table 16. Average annual emission discharge ED (kg) by one ship; standard deviation on basis of 11 ships (kg).

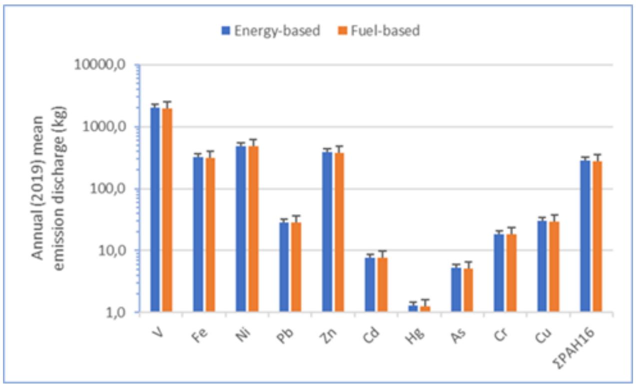

Figure 7. Average emission discharge (kg) by one ship; (y-axis log scale).

The summed emission discharges of metal and PAHs for our group of 11 Ro-Pax ships determine prospective pollutant loads into the Western Mediterranean (Table 17 and Figure 8). Because the ship operational characteristics are very similar, the resulting total emissions are about 11 times higher than a single ship average discharge. The difference between energy-based and fuel-based estimation is negligible. Very few studies are providing estimations of pollutant emission discharges by EGCS. Schmolke *et al*. 2020, in their recent report, provide metal and PAH annual washwater emissions discharged into the North and Baltic Seas for the different scenarios ranging from the current state (that is 81 ships with installed EGCS and operating in the study area) to the maximum installation scenario for 5885 ships accounted for a potential EGCS installations (Table 18). Their discharge estimations are also based on the determined and calculated pollutant washwater concentrations at different flow rates at open-loop mode of operation.

	ED (kg)	ED (kg)
	Energy-based	Fuel-based
V	22131,2	21782,5
Fe	3508,8	3448,9
Ni	5353,1	5264,1
Pb	314,0	308,6
Zn	4246,5	4175,0
Cd	84,8	83,5
Hg	14,2	14,0
As	57,2	56,3
Cr	203,3	199,7
Cu	332,0	326,7
ΣPAH_{16}	3102,1	3053,3

Table 17. Total summed annual 2019 emission discharge ED (kg) by 11 ships.

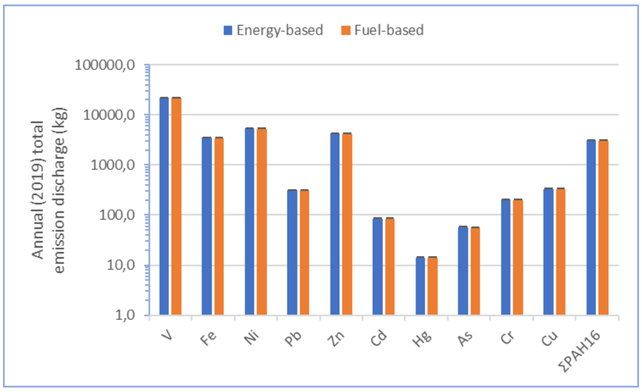

Figure 8. Total summed annual emission discharge (kg) by 11 ships; (y-axis is in log scale).

	GL Ro-Pax	CIS	MIS
	tons	tons	tons
V	22,0	3 - 151	26 - 1411
Fe	3,5		
Ni	5,3	1 -35	12 - 331
Pb	0,3	0,02 - 1	0,2 - 10
Zn	4,2	0,5-64	5 - 598
Cd	0,1	0,002 - 0,03	0,02- 0,3
Hg	0,01		
As	0,1	0,3 - 3	2 -31
Cr	0,2		
Cu	0,3	0,4 - 8	3 - 72
ΣPAH16	3,1	0,3 - 7	3 - 63

Table 18. Total annual washwater emission discharge of metals and PAHs estimated for the Gulf of Lion and Ligurian Sea by Ro-Pax shipping example (GL Ro-Pax) and for the North and Baltic Seas current state CIS and maximum installation scenarios MIS (from Schmolke et al. 2020).

It appears that the amount of pollutant potentially discharged by EGCS into the Gulf of Lion and the Ligurian Sea lay in the ranges estimated in the current state scenario for the Baltic and North Seas. This indicates that proposed methods for EGCS pollutant discharges assessment provide credible order of magnitude. The environmental importance of these pollutant's inputs will be also shortly appreciated below.

5.2 Amounts of washwater discharges

The amount of wash water discharged by the ships was also estimated using equation 7 that is calculated from the ship energy demand (in MWh) and OL scrubber flow rates (here, we chose for illustration 45, 90 and 140 t/MWh, Table 19). The total ship energy demand was obtained from two calculations, by means of the ship total fuel use and ship main engine specific fuel consumption (g/MWh) and also from ship main engine power (here at 80 % load) and ship annual total time spent at sea, both giving analogous results. The estimation of potential washwater discharged into Gulf of Lions and the Ligurian Sea by Ro-Pax ships operating between mainland France and Corsica are given in Table 19. Again, the difference between two method is negligible. These results show that if all selected Ro-Pax ships would be fitted with scrubbers the amounts of washwater discharges into the Western Mediterranean would attained levels of about 40 to 130 million of tons, depending on their real live operating conditions. However, these amounts would be just a fraction of whole ship fleet operating in the Mediterranean Sea if widespread scrubbers' installations would take place. The comparison of our mean Ro-Pax washwater discharges estimation (at 45 t/MWh) with the mean discharge of real-live 85 Ro-Pax ships with installed scrubbers (also with assumed operating average flow rate of 45 t/MWh), reported by Osipova *et al*. (2021) for global fleet, is remarkable close, indicating accurate estimation.

Ship N°	**TED**	**Washwater discharges by open-loop scrubber at different flow rates**						
		Estimated from ship energy demand				Estimated from ship power and shipping time		
	MWh	45 t/MWh	90 t/MWh	140 t/MWh		45 t/MWh	90 t/MWh	140 t/MWh
Ship 1	76148	3,4E+06	6,9E+06	1,1E+07		3,9E+06	7,9E+06	1,2E+07
Ship 2	40772	1,8E+06	3,7E+06	5,7E+06		2,7E+06	5,4E+06	8,4E+06
Ship 3	97050	4,4E+06	8,7E+06	1,4E+07		3,8E+06	7,6E+06	1,2E+07
Ship 4	60582	2,7E+06	5,5E+06	8,5E+06		3,4E+06	6,8E+06	1,1E+07
Ship 5	77296	3,5E+06	7,0E+06	1,1E+07		4,2E+06	8,4E+06	1,3E+07
Ship 6	76983	3,5E+06	6,9E+06	1,1E+07		3,7E+06	7,5E+06	1,2E+07
Ship 7	117526	5,3E+06	1,1E+07	1,6E+07		3,8E+06	7,5E+06	1,2E+07
Ship 8	126861	5,7E+06	1,1E+07	1,8E+07		4,4E+06	8,9E+06	1,4E+07
Ship 9	82480	3,7E+06	7,4E+06	1,2E+07		3,9E+06	7,9E+06	1,2E+07
Ship 10	85340	3,8E+06	7,7E+06	1,2E+07		3,8E+06	7,7E+06	1,2E+07
Ship 11	89839	4,0E+06	8,1E+06	1,3E+07		4,8E+06	9,6E+06	1,5E+07
Total WW		4,2E+07	8,4E+07	1,3E+08		4,3E+07	8,5E+07	1,3E+08
Mean WW RoPax		3,8E+06	7,6E+06	1,2E+07		3,9E+06	7,7E+06	1,2E+07
Mean Global RoPax		4,1E+06	8,3E+06	1,3E+07		4,1E+06	8,3E+06	1,3E+07

Table 19. Annual 2019 washwater discharge (tons) by Ro-Pax ships with scrubber open-loop at different flow rates. Total ship energy demand TED are calculated from amount of fuel used (tons) and engine specific fuel consumption (g/MWh). Total washwater discharge (total WW) summed volumes and mean for 11 Ro-Pax ships (Mean WW). Mean Global is the mean from 85 Ro-Pax ship fitted with scrubbers as reported by Osipova et al. 2021.

Taking the total amount of pollutants and total amount of washwater potentially discharged by 11 ships, the concentrations of pollutants in the washwater may again be calculated. These results give even more robust estimation of pollutant concentrations in washwaters because are based on larger totals (Table 20). The calculated concentrations are given for different flow rates. It indicates that estimated pollutant concentrations at 45 t/MWh flow rates (*i.e.* IMO's guideline flow rate) remain in the range of determined concentrations except for trace level metals Cd and Hg and As, Cr, Cu and PAHs. The difference of estimated and mean determined concentrations reflect previously discussed variation. In any case, the pollutant concentrations need to be normalized to scrubber flow rates and thus discussed as emission discharge factors (see above comments Table 13).

	Estimated concentrations			**Determined concentrations**	
	45 (t/MWh)	90 (t/MWh)	140 (t/MWh)	Mean	Range
	µg/L	µg/L	µg/L	µg/L	µg/L
V	524,2	262,1	168,5	168,4	15-970
Fe	83,0	41,5	26,7	72,1	30-210
Ni	126,7	63,4	40,7	48,0	7-180
Pb	7,4	3,7	2,4	7,5	0,1-21
Zn	100,5	50,3	32,3	115,6	2,3-330
Cd	2,0	1,0	0,6	0,1	0,01-0,5
Hg	0,3	0,2	0,1	0,1	0,05-0,1
As	1,4	0,7	0,4	5,7	0,5-21
Cr	4,8	2,4	1,5	31,2	6,5-62
Cu	7,9	3,9	2,5	53,3	2-260
ΣPAH16	73,5	36,7	23,6	7,0	0,5-31

Table 20. Pollutant concentrations (µg/L): estimated and determined in washwaters (see for reference studies in Table 10).

Global scrubber washwater discharges was recently estimated by the International Council on Clean Transportation ICCT (Osipova *et al*. 2021). The washwater discharges were calculated using normalized flow rate of 45 t/MWh for open-loop scrubbers and real-world ship activity in 2019 for all ships with scrubbers installed or planned to be installed by 2020. In this report, the SAVE model (Olmer *et al*. 2017a and b), which uses AIS, matched with each individual ship-specific technical characteristic allow to map and show distribution of washwater discharges. Interactive map showing scrubber washwater discharges can be accessed online (https://theicct.org/publications/global-scrubber-discharges-Apr2021) and the database provided discharges by ship types, in countries Exclusive Economic Zone (EEZ), territorial seas (TS), internal waters (IW) and their major ports is available online (https://theicct.org/publications/global-scrubber-discharges-Apr2021).

The contribution of the current annual (2019) washwater discharges in France are presented in Figure 9 and Table 21 (extracted on 13/09/21 from ICCT database). It appears that in France about 75 % of scrubber discharges occur beyond territorial sea waters of 12 nautical miles, whereas 15 % of washwaters is released in the territorial seas (TS), 6 % in internal waters (IW) and 4% in their ports. Around maritime Europe the scrubber washwater discharge hotspots occur in heavily trafficked regions, including the English-Channel, the Mediterranean Sea and Baltic Seas (Osipova *et al*. 2021).

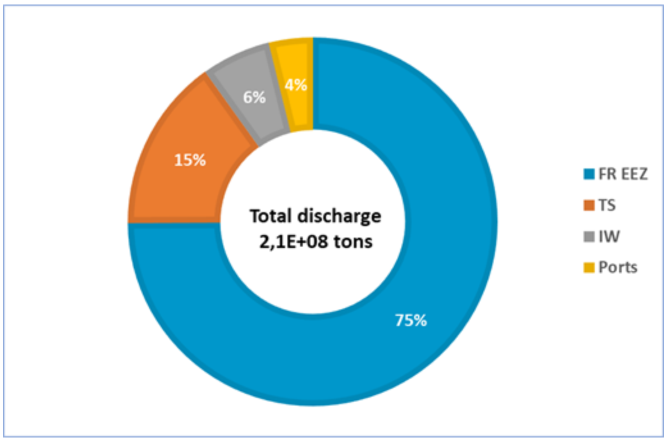

Figure 9. Current annual (2019) scrubber washwater discharges (%) in France.

Zones	**Washwater**	**Portion**
	Tons	%
FR EEZ	1,6E+08	75
TS	3,2E+07	15
IW	1,3E+07	6
Ports	8,0E+06	4
Total FR EEZ	2,1E+08	100

Table 21. Current annual (2019) scrubber washwater discharges (tons) in France; exclusive economic zone (200 nautical miles EEZ), territorial seas (12 nautical miles TS), internal waters (IW) and their ports.

The distribution of washwater discharges based on the 2019 shipping traffic in the Gulf of Lion and Ligurian Sea basins around Corsica is shown in Figure 11 (as extracted on 13/09/21 from ICCT site). This spatial distribution though shows that highest concentrations (*i.e.* if expressed in tons per square kilometer) of scrubber discharges may occur within 12 nautical miles of territorial seas, flanking also their ports, anchorage and waterfront areas.

In the Gulf of Lion zones around Marseille and Fos-sur-Mer ports and in the Ligurian Sea around Genova, Civitavecchia and Livorno, between 5 to 9 Mt of scrubber washwaters are annually discharged (Figure 10). The eastern coast of Corscia is more impacted than its western counterpart. Whereas, away from the shore, scrubber discharges occur along major shipping routes.

The distribution of pollutant loads will follows washwater discharges. Taking the previously estimated pollutants concentrations for RoPax ship washwaters (Table 20) and extracted data on totals of washwaters discharged into French Exclusive Economic Zone (EEZ) as well as in their ports, internal waters and territorial seas (Osipova *et al*. 2021), we estimated the pollutant annual inputs for the year 2019 in these maritime areas of France (Table 22). The total scrubber washwater discharge into the French EEZ of the Mediterranean Sea (Gulf of Lion and the Ligurian Sea basins) was also estimated at 75 Mt (Osipova *et al*. 2021) and this amount was similarly allocated into above marine zones allowing estimation of pollutant loads in these areas (Table 20).

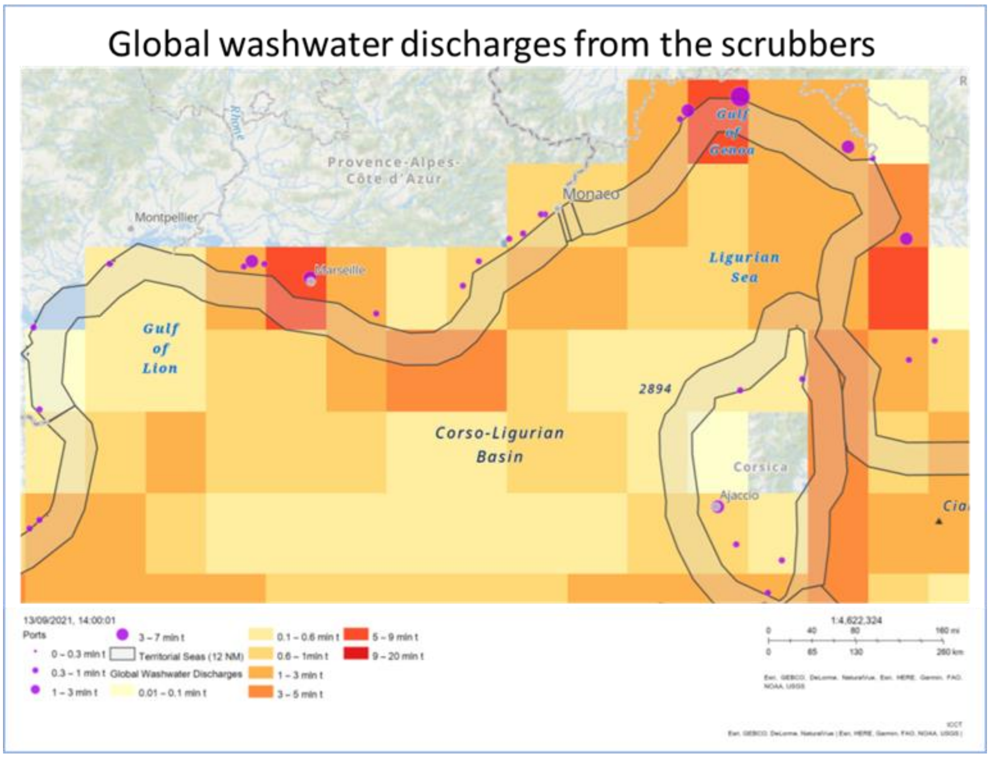

Figure 10. Distribution of the scrubber washwater discharges in the Gulf of Lion and the Ligurian Sea basins; Discharges in the ports of this region are also indicated as extracted on 13/09/21 from ICCT website (https://theicct.org/publications/global-scrubber-discharges-Apr2021).

	France				Mediterranean (Fr)			
	EEZ	TS	IW	Ports	EEZ	TS	IW	Ports
	kg							
V	81779	16592	6615	4208	29587	6008	2411	1522
Fe	12949	2627	1047	666	4685	951	382	241
Ni	19766	4010	1599	1017	7151	1452	583	368
Pb	1154	234	93	59	418	85	34	21
Zn	15679	3181	1268	807	5672	1152	462	292
Cd	312	63	25	16	113	23	9	6
Hg	47	9	4	2	17	3	1	1
As	218	44	18	11	79	16	6	4
Cr	749	152	61	39	271	55	22	14
Cu	1232	250	100	63	446	91	36	23
ΣPAH16	11467	2326	928	590	4149	842	338	213

Table 22. Total annual (2019) metals and PAHs discharges (kg) in France and in French Mediterranean Sea: exclusive economic zones (200 nautical miles EEZ), territorial seas (12 nautical miles TS), internal waters (IW) and their ports.

These estimates show that in 2019 almost 82, 20 and 12 tons of V, Ni and PAHs respectively were discharged by ships outfitted with OL scrubbers into the French metropolitan EEZ. Whereas, the estimated amount of pollutant loads into the French Mediterranean EEZ using the washwater volumes are equivalent to the load levels estimated as potential pollutant inputs coming from a fleet of 11 RoPax ships commonly operating between France and Corsica (Table 17). These results suggest that the total number of ships with installed scrubbers shipping in the French Mediterranean EEZ is still relatively limited, but this number of ships is already responsible of significant pollutant inputs in this region. The precise amounts of scrubber washwater volumes discharged in the Mediterranean French ports in 2019 allowed to calculate the pollutant discharges (Table 23). These annual pollutant inputs occurring in the ports represent about 4 % of total inputs in the MED-EEZ.

Port Name	**Washwater**	**V**	**Fe**	**Ni**	**Pb**	**Zn**	**Cd**	**Hg**	**As**	**Cr**	**Cu**	**ΣPAH_{16}**
	Tons	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
Port d'Ajaccio	6,0E+05	315,0	49,9	76,1	4,4	60,4	1,2	0,2	0,8	2,9	4,7	44,2
Marseille	4,8E+05	253,4	40,1	61,2	3,6	48,6	1,0	0,1	0,7	2,3	3,8	35,5
Fos	4,6E+05	242,2	38,4	58,5	3,4	46,4	0,9	0,1	0,6	2,2	3,7	34,0
Villefranche	2,5E+05	132,8	21,0	32,1	1,9	25,5	0,5	0,1	0,4	1,2	2,0	18,6
Toulon	2,5E+05	130,4	20,6	31,5	1,8	25,0	0,5	0,1	0,3	1,2	2,0	18,3
Bastia	2,1E+05	109,4	17,3	26,4	1,5	21,0	0,4	0,1	0,3	1,0	1,6	15,3
Port-De-Bouc	1,8E+05	93,0	14,7	22,5	1,3	17,8	0,4	0,1	0,2	0,9	1,4	13,0
Sète	1,7E+05	87,9	13,9	21,2	1,2	16,9	0,3	0,1	0,2	0,8	1,3	12,3
Cannes	1,6E+05	83,9	13,3	20,3	1,2	16,1	0,3	0,0	0,2	0,8	1,3	11,8
Porto Vecchio	1,1E+05	55,9	8,9	13,5	0,8	10,7	0,2	0,0	0,1	0,5	0,8	7,8
Saint-Raphaël	8,7E+03	4,5	0,7	1,1	0,1	0,9	0,0	0,0	0,0	0,0	0,1	0,6
Antibes	6,4E+03	3,3	0,5	0,8	0,0	0,6	0,0	0,0	0,0	0,0	0,1	0,5
Saint-Tropez	6,2E+03	3,2	0,5	0,8	0,0	0,6	0,0	0,0	0,0	0,0	0,0	0,5
L'Ile Rousse	4,2E+03	2,2	0,3	0,5	0,0	0,4	0,0	0,0	0,0	0,0	0,0	0,3
Port De Propriano	2,6E+03	1,4	0,2	0,3	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,2
Nice	2,5E+03	1,3	0,2	0,3	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,2
Bonifacio	2,4E+03	1,3	0,2	0,3	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,2
Port-Vendres	9,0E+02	0,5	0,1	0,1	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,1
Port Saint Louis Du Rhône	2,6E+02	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Port-La-Nouvelle	1,7E+02	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Total	2,9E+06	1522	241	368	21	292	6	1	4	14	23	213

Table 23. Annual (2019) scrubber discharges washwaters (tons), metals and PAH loads (kg) as estimated in the French Mediterranean ports.

5.3 Environmental significance of EGCS pollutant loads

The environmental importance of contaminants inputs from EGCS may be diversely assessed. Quantities amounting to hundreds and thousands of kilograms of main metals (V, Fe, Ni, Zn) and PAH discharged annually by a given fleet of 11 Ro-Pax into the Western Mediterranean Sea come into the same category as other large-scale environmental inputs and emissions of these compounds. For instance, the estimated annual EGCS potential loads to the Gulf of Lion and the Ligurian Sea (Table 22) compare to the amounts of V, Ni and ΣPAH_{16} spilled into the Bay of Biscay during the *T/V Erika* and the *T/V Prestige* oil spills. These oil spill inputs may be estimated to range from 1,7 to 3,4 tons for V, from 0,8 to 1,1 tons of Ni and from 18 to 19 tons of ΣPAH_{16} (Tronczynski *et al*. 2004). For PAHs, the Rhone river annual flux entering the GoL was also estimated in the range of 3,7 tons (Tronczynski *et al*. 2012), that is being at the same level of 11 RoPax ship estimated EGCS potential emissions. These figures clearly indicate that ship scrubber washwaters may represent significant source of pollutants entering the western Mediterranean Sea.

This also may be assessed in the context of annual air emissions of metals and PAHs in Europe per source category as reported through EMEP Centre on Emission Inventories and Projections (CEIP) database (website http://www.ceip.at) and through National Emission Ceilings (NEC) Directive Inventory (https://www.eea.europa.eu/data-and-maps/data/national-emission-ceilings-nec-directive-inventory-17). EU28, annual 2018, pollutant shipping exhaust emissions (metals and PAHs) are presented in Table 24. The $PM_{2,5}$ for EU28 and CO_2 for the whole Mediterranean Sea emissions are also given and provide references for comparison with our estimates for RoPax ship fleet operating between France and Corsica. This shows that the estimated portion of RoPax ship emissions is below 2 % for most of the contaminants, being about 1,2 % for the major indicators: Ni, PAHs, $PM_{2,5}$ and CO_2. This comparison for Pb, Zn, Cd, and Hg with EU28 shipping emissions, may suggest possible overestimation of our RoPax ship fleet emissions. V and Fe are not reported in European shipping air emission inventories database. Whereas, PAH shipping exhaust emissions are reported for only four compounds: benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene and indeno[*1,2,3*-cd]pyrene, used as indicators for the purpose of emission inventories under the CEIP/NEC. However, these compounds are more appropriate indicators for stationary large combustion sources and are poorly representative for shipping exhaust emissions. As proposed by Cooper and Gustafsson (2004) the conversion factors from “Total PAH-4” to “total PAH-16” for ship emission might be as high as 250 to 730 times, mainly due to the inclusion of lower weight PAHs strongly emitted by ship diesel engines.

	EU28 shipping (2018)	RoPax GL	RoPax GL
	Tons	Tons	%
V	-	22,0	-
Fe	-	3,5	-
Ni	462,7	5,3	1,1
Pb	4,3	0,3	7,2
Zn	28,7	4,2	14,7
Cd	0,4	0,1	21,0
Hg	0,5	0,0	2,9
As	10,8	0,1	0,5
Cr	11,0	0,2	1,8
Cu	26,3	0,3	1,3
ΣPAH_{16}	294 -857	3,1	0,4 -1,1
$PM_{2,5}$	120980	1324	1,1
CO_2 Med.	48344100	566586	1,2

Table 24. EU28 annual 2018 shipping pollutant air emissions (tons) as reported through Centre on Emission Inventories and Projections (CEIP) database and National Emission Ceilings (NEC); CO2 annual shipping exhaust emission (2011) in the Mediterranean taken from Jalkanen et al. 2016. ΣPAH16 converted from ΣPAH4 using 250 and 730 conversion factors (Cooper and Gustafsson 2004).

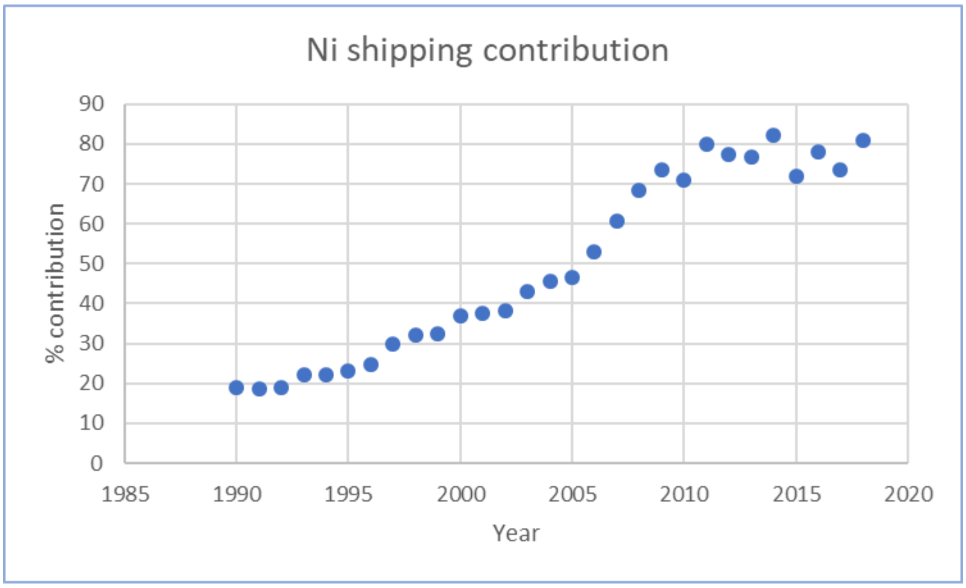

Figure 11. Nickel ship exhaust emissions historical contribution into the total nickel air emission from ship EU28 (EMEP/CEIP database).

The relative increase of shipping transport pollutant exhaust emissions in the total pollutant air emissions contribution is well illustrated by historical data of Ni (Figure 11). It is shown that Ni ship traffic emission contribution in the total of its air emissions in Europe has increased from around 20 % to about 80 % over the last three decades (1990 to 2020). The importance of ship pollutant discharges entering marine environment should thus be better appreciated. This includes several additional aspects of the environmental impacts of scrubber washwaters which might be related to the new IMO's regulation allowing global introduction of scrubbers in shipping industry.

6 Summary

1. The expertise aims to present a critical approach in the effort of EGCS pollutant discharge assessments and provide methodological proxy for pollutant emission/discharge estimations based on similar practice as used for shipping GHGs and main pollutants inventories;
2. The focus is given primarily to the estimation of scrubber emission discharges of heavy metals and polycyclic aromatic hydrocarbons (PAHs) that is two groups of ship exhaust contaminants, which were less studied and regulate, but other shipping pollutants may readily be added to the calculation;
3. The methodology proposed recognizes that ship pollutant emission with exhaust gas represents the basis for specified pollutant discharge estimation with washwater of the scrubber systems. The scrubber discharge is considered as a fraction of total emission of a given pollutant and therefore may be estimated;
4. The proposed approach is based on the estimates using pollutant emission factors, discharged washwater volumes and flow rates, estimated scrubber trapping efficiencies, ship fuel consumption and energy demand;
5. At present, the estimation of pollutant discharged by scrubbers using the energy-based and fuel-based exhaust gas emission factors elaborated for various ship marine engines, seems to be an appropriate solution. However, high quality data on emission factors is generally still missing especially for not regulated emissions of many pollutants, such as metals and PAHs;
6. The case study of the metals and PAHs discharge estimation is presented for the model Ro-Pax one ship scenario and its real-world operation between two ports Marseille and Ajaccio;
7. The larger scale projection, is also presented, of potential pollutant discharges by EGCS of 11 Ro-Pax ships also operating in the Gulf of Lion and the Ligurian Sea basins. Pollutant quantities amounting to hundreds and thousands of kilograms of main metals (V, Fe, Ni, Zn) and PAHs discharged annually by a given fleet of 11 Ro-Pax ships into the Western Mediterranean Sea come into the same category as other large-scale environmental loads of these compounds.
8. The amount of wash water discharged by the ships was also estimated from the ship energy demand at different OL scrubber flow rates. The results show that if all selected Ro-Pax ships would be fitted with scrubbers the amounts of washwater discharges into the Western Mediterranean would attained levels of about 40 to 130 million of tons, depending on their real live operating conditions. The comparison of mean Ro-Pax washwater discharges estimation with the mean discharge of real-live 85 Ro-Pax ships with installed scrubbers, reported by Osipova *et al*. (2021) for global fleet, is remarkable close, indicating accurate estimation.
9. Building on the global assessment of the mass of washwater discharges from vessels using scrubbers (Osipova *et al*. 2021) it appears that in France about 75 % of scrubber washwater discharges occur beyond territorial sea of 12 nautical miles, whereas 15 % is released in the territorial seas (TS), 6 % in internal waters (IW) and 4% in their ports. The distribution of pollutant loads follows washwater discharges.
10. The estimated annual EGCS potential loads to the Gulf of Lion and the Ligurian Sea compare to the amounts of vanadium, nickel and ΣPAH_{16} dumped with major oil spills or to the Rhone river annual flux of PAHs entering the Gulf of Lion. These estimates clearly indicate that ship scrubber washwaters may represent significant source of pollutants entering the western Mediterranean Sea. The estimation of EGCS pollutants discharge loads appears to be a prerequisite for a better appreciation of pollutant environmental impact assessments.

Appendix 1.

A1. Table 1. MRV database 11 Ro-Pax ship operating in the Gulf of Lion and the Ligurian Sea basins

Ship type	Period	Technical efficiency [gCO_2/tnm	Fuel cons. [mtons]	CO_2 emissions [m tons]	CO_2 within ports [m tons	Time at sea [hours	Fuel cons. [kg / nm]
Ro-pax ship 1	2018	3,69	14582,88	45425,95	171,05	4567,48	192,52
Ro-pax ship 2	2018	39,79	8576,93	26822,08	2451	4458,5	130,41
Ro-pax ship 3	2018	3,79	20616,14	64331,3	1087,91	4959,18	235,57
Ro-pax ship 4	2018	8,09	13129,68	41067,3	4158,71	4555,9	170,01
Ro-pax ship 5	2018	11,38	13375,85	41790,76	4173,55	4454,55	174,07
Ro-pax ship 6	2018	6,04	14348,17	44824,46	3561,26	4075,37	208,79
Ro-pax ship 7	2018	5,16	26318,74	82058,01	2305,34	5591,2	243,05
Ro-pax ship 8	2018	4,21	26556,72	82834,87	6713,26	4902,91	256,86
Ro-pax ship 9	2018	5,61	15997,23	49997,64	4928,29	4198	214,55
Ro-pax ship 10	2018	3,18	25099,39	78356,46	5955,97	4963,84	252,95
Ro-pax ship 11	2018	3,84	16024,4	49905,96	142,18	4838,83	196,67
Ro-pax ship 1	2019	3,69	14848,78	46374,53	5447,6	4196,41	215,76
Ro-pax ship 2	2019	6,92	7950,49	24850,11	2450,37	4043,93	133
Ro-pax ship 3	2019	3,79	18924,69	59063,12	90,4	4714,18	221,34
Ro-pax ship 4	2019	8,09	11813,51	36933,64	3587,01	4055,53	171,77
Ro-pax ship 5	2019	11,38	15072,65	47061,2	2044,99	4966,13	172,23
Ro-pax ship 6	2019	6,04	15011,72	46915,01	4309,1	4434,66	199,87
Ro-pax ship 7	2019	5,16	22917,55	71456,44	2633,09	4965,83	239,38
Ro-pax ship 8	2019	4,21	24737,83	77131,49	5203,95	4584,25	255,97
Ro-pax ship 9	2019	5,61	16083,63	50226,6	4132,19	4100,45	220,3
Ro-pax ship 10	2019	3,18	16641,38	51961,19	3929,63	3572	240,19
Ro-pax ship 11	2019	3,84	17518,66	54612,96	2985,25	5134,25	197,51

A1. Table 2. Reference studies operational ship and EGCS data.

Reference	Engine Power at load	EGCS Flow rate	EGCS Flow Rate	Fuel S content	SFC_{ME}	Fuel consumption
	MW	m^3/h	t/MWh	%	g/kWh	kg/h
Kjolholt *et al*. 2012	18,7	1000,0	53,5	2,2	188	3510,0
Kjolholt *et al*. 2012	9,3	1000,0	107,0	2,2	198	1850,0
Kjolholt *et al*. 2012	18,7	1000,0	53,5	1,0	180	3360,0
Kjolholt *et al*. 2012	9,3	1000,0	107,0	1,0	196	1830,0
Teuchies *et al*.2020	11,7	564,7	48,2	1,5	193	2261,6
Teuchies *et al*.2020	11,7	564,7	48,2	1,5	193	2261,6
Teuchies *et al*.2020	12,6	743,0	59,0	1,1	193	2431,8
Teuchies *et al*.2020	6,0	872,0	145,2	1,1	193	1159,2
Teuchies *et al*.2020	5,1	747,0	146,2	1,1	193	986,2
Schmolke *et al*. 2020	13,1	1203,0	92,0	3,2	210	2746,0
Schmolke *et al*. 2020	5,4	757,0	140,0	2,5	240	1297,7
Schmolke *et al*. 2020	9,0	918,0	102,0	2,7	240	2160,0
Schmolke *et al*. 2020	7,3	548,0	75,0	0,7	220	1607,5
Schmolke *et al*. 2020	11,8	1000,0	84,8	2,0	230	2713,9
EGCSA 2018	10,8	164,0	15,2	2,4	193	2084,4
EGCSA 2018	10,8	468,0	43,3	2,9	193	2084,4
EGCSA 2018	10,8	471,0	43,6	2,9	193	2084,4
EGCSA 2018	8,4	180,5	21,5	2,1	193	1621,2
EGCSA 2018	20,0	756,0	37,8	2,3	193	3860,0
EGCSA 2018	20,0	953,0	47,7	2,6	193	3860,0
EGCSA 2018	21,3	537,0	25,3	2,2	193	4101,3
EGCSA 2018	20,8	1092,0	52,5	2,5	193	4014,4
EGCSA 2018	20,8	1054,0	50,7	2,5	193	4014,4
EGCSA 2018	31,5	930,0	29,5	2,4	193	6079,5
EGCSA 2018	31,5	930,0	29,5	2,4	193	6079,5
EGCSA 2018	7,8	300,0	38,5	2,2	193	1505,4
EGCSA 2018	8,6	346,0	40,0	2,3	193	1667,5
EGCSA 2018	18,2	535,0	29,5	2,6	193	3504,9
EGCSA 2018	18,2	527,0	29,0	2,6	193	3504,9
EGCSA 2018	20,1	989,0	49,3	2,8	193	3873,5
EGCSA 2018	12,6	420,0	33,3	2,1	193	2431,8
EGCSA 2018	25,2	1332,0	52,9	2,6	193	4863,6
EGCSA 2018	10,8	870,0	80,6	2,1	193	2084,4
EGCSA 2018	10,8	872,0	80,7	2,1	193	2084,4
EGCSA 2018	15,6	850,0	54,5	2,4	193	3010,8
EGCSA 2018	31,5	821,0	26,1	2,6	193	6079,5
EGCSA 2018	31,5	876,0	27,8	1,0	193	6079,5
EGCSA 2018	20,8	1039,0	50,0	2,4	193	4014,4
EGCSA 2018	20,8	1044,0	50,2	2,4	193	4014,4
EGCSA 2018	11,5	336,0	29,2	2,6	193	2223,4
EGCSA 2018	11,5	315,0	27,3	2,6	193	2223,4

A1. Table 2 (continuation). Reference studies operational ship and EGCS data.

Reference	**Engine Power at load**	**EGCS Flow rate**	**EGCS Flow Rate**	**Fuel S content**	**SFC_{ME}**	**Fuel consumption**
	MW	m^3/h	t/MWh	%	g/kWh	kg/h
EGCSA 2018	8,6	315,0	36,5	2,6	193	1667,5
EGCSA 2018	8,6	356,0	41,2	2,6	193	1667,5
EGCSA 2018	8,6	356,0	41,2	2,6	193	1667,5
EGCSA 2018	8,6	356,0	41,2	2,6	193	1667,5
EGCSA 2018	11,6	694,0	59,8	2,5	193	2238,8
EGCSA 2018	11,6	651,0	56,1	3,1	193	2238,8
EGCSA 2018	11,6	565,0	48,7	1,2	193	2238,8

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