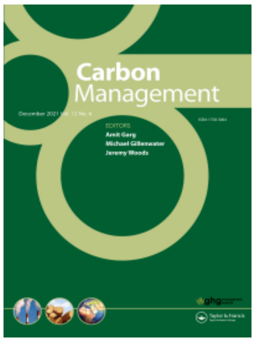

Carbon Management

ISSN: 1758-3004 (Print) 1758-3012 (Online) Journal homepage: www.tandfonline.com/journals/tcmt20

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To cite this article: Rohan Kumar, Kent Salo, Fabien Yao, Sebe Maxime, Recuero Vitro Laura, Dennis Booge, Christa A. Maradino, Shams Al-Hajjaji, Nele Matz-Luck & Anna Rutgersson (2025) Charting the course to cleaner shipping routes: emission inventory for Baltic Sea shipping and green fuel potential, Carbon Management, 16:1, 2523919, DOI: 10.1080/17583004.2025.2523919

To link to this article: https://doi.org/10.1080/17583004.2025.2523919

Published online: 30 Jun 2025.

CARBON MANAGEMENT
2025, VOL. 16, NO. 1, 2523919
https://doi.org/10.1080/17583004.2025.2523919

Charting the course to cleaner shipping routes: emission inventory for Baltic Sea shipping and green fuel potential

Rohan Kumar[a], Kent Salo[b], Fabien Yao[c], Sebe Maxime[c], Recuero Vitro Laura[c], Dennis Booge[d], Christa A. Maradino[d], Shams Al-Hajjaji[e], Nele Matz-Luck[e] and Anna Rutgersson[a]

[a]Department of Earth Sciences, Uppsala University, Uppsala, Sweden; [b]Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden; [c]Management Research Centre, i3-CRG Ecole Polytechnique, Palaiseau, France; [d]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany; [e]Walther Schücking Institute for International Law, University of Kiel, Kiel, Germany

ABSTRACT

This study presents a high-resolution shipping emission inventory for the Baltic Sea, assessing the environmental impacts of four fuel-based scenarios under a projected threefold increase in gross tonnage by 2050. The study evaluates how regulatory changes and alternative fuels, such as hydrogen and ammonia, can reduce emissions and advance sustainability in shipping. The study uses a bottom-up approach, combining activity data, fuel data, and emission factors to estimate tank-to-wake emissions. Comparative analysis indicates improved emissions prediction across all pollutants. While use of liquefied natural gas (LNG) and scrubber-equipped ships reduce sulphur oxides (SO_x) emissions, they incur notable environmental trade-offs. By 2050, significant reductions in particulate matter (99%) and carbon dioxide are projected, while SO_x emissions are expected to approach zero using hydrogen, ammonia, and methanol fuels. These reductions are helped by the decline in traditional fuels and technological progress. The current transition to cleaner marine fuels is insufficient to meet the IMO's 2030 and 2050 carbon reduction targets. While tank-to-wake contributes significantly toward emissions reduction, a broader focus on the well-to-wake approach is also critical for achieving net-zero emissions by 2050. Policy efforts should accelerate the adoption of green fuels and address challenges such as methane slip from LNG-powered ships.

ARTICLE HISTORY
Received 6 March 2024
Accepted 18 June 2025

KEYWORDS
Shipping emissions; decarbonisation; emission inventory; alternative fuels; emission pathways

Introduction

The maritime transport sector's contribution to global emissions has gained substantial attention due to its significant impact on climate change and air quality [1,2]. Quantifying and projecting shipping emissions accurately is essential, such a baseline serves as the foundation for developing strategies to reduce the industry's environmental footprint [3,4]. Continual monitoring and updates to emission inventories are crucial to maintain the accuracy of this information and source for development of strategies [4]. Shipping emissions can vary depending on a variety of factors such as fuel types, vessel designs, and operational practices [5,6]. Accurate projection of shipping emission inventories enables policymakers to assess the impact of various scenarios, providing valuable insights into the effectiveness of potential interventions. This, in turn, facilitates informed decision-making and promotes sustainable shipping practices [7]. Furthermore, emission inventory projections assist industry stakeholders in anticipating future regulatory requirements and technological advancements, thereby facilitating long-term planning and investment decisions [3].

As part of efforts to reduce the impact of shipping emissions, the IMO and European Parliament established the Baltic Sea Region as an ECA (Emission Control Area). This area sees heavy shipping activity, accounting for 22% of the gross tonnage share within European seas. Previous work conducted over Baltic Sea predominantly used AIS data mainly covering the period around 2015 [8–14]. Due to IMO regulations, the BALTIC SEA REGION has witnessed significant changes in recent years. These changes include the introduction of abatement technologies, shifts in fuel usage dynamics, the operation of new ships using

CONTACT Rohan Kumar rohan.kumar@geo.uu.se; Anna Rutgersson Anna.Rutgersson@met.uu.se Department of Earth Sciences, Uppsala University, Uppsala, Sweden

alternative fuels, and an improved understanding of emission factor values for different pollutants associated with various fuel types. Incorporating recent developments in understanding present and future emission trends is crucial for assessing the effectiveness of existing policies and designing new measures to achieve emission reduction targets.

The shipping emissions inventory is essential for climate modelling as it provides detailed data on emissions from the maritime sector, enabling precise simulations of shipping's impact on climate change and air quality. It helps assess the radiative forcing effects of emissions, model different regulatory scenarios, and evaluate the effectiveness of mitigation strategies. Being a high-resolution inventory, it supports regional and global impact assessments, guiding policy decisions and climate strategies. This study aims to estimate the recent tank to wake shipping emissions and implications of different fuel pathways on shipping emission inventory over the Baltic Sea Region. By bridging the gap between research and policy through different pathways, this study seeks to contribute to the development of effective strategies and measures for reducing shipping emissions and achieving a more sustainable maritime transport industry. One primary scientific objective of developing a shipping emission inventory is to quantify the various pollutants and greenhouse gases released into the atmosphere by ships over a short term and long term. This involves estimating the amounts of carbon dioxide (CO_2), sulphur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM) including sulphate particles a significant contributor to aerosol formation, volatile organic compounds (VOCs), and other harmful substances emitted by different types of vessels with different fuel types. This understanding forms the basis for assessing the severity of environmental problems associated with shipping emissions and identifying areas where interventions are needed.

The outline of this study is as follows: a brief background to emphasize the relevance of developing a shipping emission inventory, highlighting the need for mitigating harmful pollutants and carbon emissions in the shipping industry. The regulations, climate change targets, available fuel combinations, abatement technologies, and expected future fuels are discussed as strategies for emission mitigation through various scenarios. The methodology explains the steps taken to develop the shipping emission inventory, along with the required data for implementing these steps. The results predominantly focus on the estimated emission projections for different pollutants and the pathways through which emission reduction targets could be achieved. The gridded shipping emission reduction inventory maps for 2050 are then compared and discussed in relation to the baseline emission inventory prepared for 2019. The conclusion section offers a critique of scenarios, considering various fuel combinations and abatement technologies. It emphasises the pivotal role of the inventory in arriving at these conclusions.

Regulations and initiatives

Studies have shown that shipping emissions of greenhouse gases (GHG) such as CO_2 and methane (CH_4) as well as air pollutants like SO_x, NO_x, and particulate matter (PM), have adverse effects on the climate and environment [15–17]. The combustion of fossil fuels in ship engines leads to CO_2 emissions, contributing to global warming [2,18–20]. Additionally, SOx and NOx emissions contribute to air pollution and have localised environmental and health impacts [21–25].

The Paris Agreement (2015) aimed at combating climate change by limiting global temperature rise to well below 1.5 °C above pre-industrial levels [26,27]. The shipping sector is an integral part of global trade but contributes to greenhouse gas emissions. Reducing shipping emissions aligns with several Sustainable Development Goals SDGs, including Goal 13 on climate action [28], Goal 7 on affordable and clean energy, and Goal 9 on industry, innovation, and infrastructure. By addressing shipping emissions, countries can contribute to the global efforts to mitigate climate change, protect the environment, and promote sustainable development.

The Paris Agreement emphasises the role of the International Maritime Organization (IMO) in regulating and reducing shipping emissions to align with the agreement's goals [29]. International regulations and initiatives have been developed to reduce shipping emissions, including those of NOx, SOx, and PM. The most significant of these is the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, which sets aims to reduce emissions of SOx and NOx from ships [30–32]. The regulations apply to ships operating in designated both globally and in Emission Control Areas (ECAs) and require the use of low-sulphur fuels, alternative fuels such as liquefied natural gas (LNG) or exhaust gas cleaning systems(EGCSs) [33].

The IMO has also developed the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), which aim to improve the energy efficiency of new and existing ships [34,35]. The EEDI sets minimum requirements for the energy efficiency of new ships, while the SEEMP provides a framework for improving the energy efficiency of existing ships [36,37]. The EEDI has the potential to reduce CO_2 emissions from new ships by up to 30% by 2025 [38]. In addition, the convention includes regulations for the use of alternative fuels, such as LNG, which emit lower levels of pollutants than traditional marine fuels [39]. Several initiatives have been launched to reduce shipping emissions. For example, the Global Maritime Energy Efficiency Partnerships (GloMEEP) project, which is led by the IMO and funded by the Global Environment Facility (GEF), aims to promote energy efficiency and reduce GHG emissions from the shipping industry [28]. The Getting to Zero Coalition, which is a partnership of over 120 organizations, aims to accelerate the transition to zero-emission shipping by 2030 [40], while the recent IMO GHG Strategy has the ambition to reach net-zero by 2050 [41]. The 2023 IMO GHG Strategy, adopted at MEPC 80, emphasises reducing tank-to-wake emissions, which focus on GHGs produced during ship operations, while also integrating the more comprehensive well-to-wake approach that accounts for emissions across the fuel lifecycle. Tank-to-wake reductions remain critical in the short term, particularly through energy efficiency measures, regulatory compliance, and the adoption of low-carbon and zero-emission fuels like hydrogen and ammonia [41,42]. While the IMO is shifting toward a broader well-to-wake perspective, tank-to-wake emission reductions are essential for meeting the strategy's intermediate 2030 and 2040 goals and driving progress toward net-zero by 2050 [41]. This approach provides a measurable way to reduce operational emissions and aligns with current regulatory frameworks, making it a vital component of the IMO's decarbonization roadmap [43,44].

The European Union (EU) has implemented various regulations aimed at reducing emissions from shipping. The FuelEU Maritime Regulation promotes the use of alternative clean energy technologies by setting and progressively decreasing the authorised maximum GHG intensity for ships over 5000 gross tonnage calling at European ports [45]. The EU Sulphur Directive sets limits on the sulphur content of fuels used by ships operating in EU waters. The Directive requires ships to use fuels with a maximum sulphur content of 0.10% in ECA, and 0.50% while at sea [46]. In addition, the EU has established the European Maritime Safety Agency (EMSA), which provides technical assistance and support to Member States in implementing and enforcing EU regulations related to maritime safety, security, and the environment. EMSA also conducts inspections of ships to ensure compliance with EU regulations [47]. The EU Monitoring, Reporting, and Verification (MRV) Regulation requires ships calling at EU ports to monitor and report their CO_2 emissions [48]. The EMSA inspection regime could be effective in improving compliance with EU regulations on SOx emissions [49]. The EU's Emission Trading System (EU ETS) includes maritime transport in its scope, encouraging emissions reductions through market-based mechanisms [50]. To advance sustainable development in shipping, collaborative efforts have emerged between the IMO, the EU, and other stakeholders. Initiatives such as the Green Shipping Program, the European Sustainable Shipping Forum, and the Maritime Technology Cooperation Centre (MTCC) Network facilitate knowledge sharing, capacity building, and the adoption of sustainable practices [51].

Technological emissions mitigation strategies

Various technological advancements and operational practices to reduce shipping emissions are suggested and discussed. These include improving vessel design, adopting energy-efficient technologies, optimising ship operations, and exploring alternative fuels such as LNG, biofuels, and hydrogen. Furthermore, wind-assisted propulsion systems and the use of advanced monitoring and data analytics have shown potential in enhancing fuel efficiency [39,52–55].

One of the most effective ways to reduce emissions from ships is to use alternative fuels producing fewer emissions than traditional fossil fuels. These include biofuels, hydrogen, and ammonia, which are being developed and tested by the industry [56–59]. However, the adoption of new fuels in the shipping industry, while aimed at reducing emissions, presents potential new environmental risks [60]. These risks may include the potential for introducing novel pollutants or by-products into the environment due to incomplete combustion or unanticipated chemical reactions of the new fuels. Moreover, the sourcing, production, and transportation of these fuels might carry their own environmental footprint [61]. Consequently, a comprehensive assessment of these potential risks is imperative to ensure that the transition to new fuels genuinely results in a net reduction in environmental impact. There is also a risk that new fuels may not perform as expected and could lead to engine damage or other operational issues [62]. LNG is a cleaner-burning fuel than traditional marine fuels and is becoming increasingly popular as a fuel for ships. LNG propulsion systems can reduce emissions of SOx, NOx, and PM [63]. While LNG propulsion systems can reduce certain emissions, the release of unburned CH_4, known as methane slip, poses a greater threat [64]. This is significant due to methane's high global warming potential, which is 86 times that of carbon dioxide over 20 years and 25 times over 100 years [64,65].

The use of abatement technologies such as exhaust gas cleaning system (scrubbers) is another approach that has been adopted to comply with the regulations and reduce emissions such as SOx from shipping. The operation of Exhaust Gas Cleaning Systems (EGCSs) leads to an increase in fuel consumption, which can subsequently result in elevated carbon emissions [66]. This rise in emissions may offset the environmental benefits these systems provide in reducing SOx. Wet scrubbers are systems that remove SOx and other pollutants from the exhaust gas emitted by ships, by spraying the exhaust gas with a scrubbing solution. Scrubbers are classified into open-loop, closed-loop, and hybrid systems. Open-loop systems release seawater directly, closed-loop systems utilize alkaline-dosed freshwater in a recirculation process, and hybrid scrubbers offer the capability to operate in either mode [67]. The use of scrubbers has been allowed under the IMO regulations as an alternative to switching to low-sulphur fuel. However, concerns have been raised about the discharge of wash water from scrubbers, which is acidic and may contain pollutants such as heavy metals, into the sea [68]. The Selective Catalytic Reduction (SCR) system is used to reduce NOx emissions from ships by the use of urea in order to convert them into harmless nitrogen and water. These systems use a catalyst to promote the chemical reaction that converts NOx into nitrogen and water [69]. SCR systems consumes urea and require the use of a catalyst, which can be expensive and may need to be replaced regularly. There is also a risk that SCR systems may not perform as expected in certain operating conditions, which could lead to increased emissions [70,71].

Improving emission inventories for effective shipping regulations

The regulations and initiatives discussed have shown promising results in reducing emissions from shipping. However, to effectively monitor and reduce emissions, accurate and up-to-date emission inventories are needed. This is particularly important given the complexity of shipping emissions, which can vary depending on factors such as vessel type, fuel type, and operating conditions. Inaccurate emission inventories can lead to flawed policy decisions and ineffective mitigation measures, as well as hinder the assessment of progress towards emission reduction targets. Additionally, developing new emission inventories feed with constantly improving information in terms of emission factors, ship density, fuel mix and abatement technologies introduced in the ships, which directly facilitate the emission accuracy and can help to assess the effectiveness of these new policies and technologies and guide their implementation. Overall, the development of new shipping emission inventories is crucial for accurately monitoring and reducing emissions from the shipping industry and achieving global climate targets. This study provides a fine-resolution i.e. 1×1km, scenario driven, and technology-differentiated tank-to-wake emission inventory for the Baltic Sea. It fills crucial knowledge gaps left by CAMS, EMEP, and previous AIS-based inventories by offering a detailed assessment of current technologies, future fuel transitions, and policy impacts essential for supporting regional and international climate targets in the maritime sector. It also directly addresses the gap between current trends and the IMO's carbon reduction goals, providing the evidence base needed to inform more effective and forward-looking maritime decarbonisation strategies.

Methodology

Various methods are used to develop shipping emission inventories. The activity-based approach estimates emissions from ship activities, such as fuel use and operating hours, but may suffer from reduced accuracy due to underlying assumptions [72]. The bottom-up approach gathers detailed data on individual ships for more precise estimates but can be labour-intensive and face challenges with data availability across different regions. The top-down approach relies on atmospheric measurements to estimate emissions, which can be less accurate due to environmental variables affecting the data [13]. Finally, the hybrid approach integrates elements of multiple methods to enhance accuracy but can be more complex and dependent on the quality of the data used [73]. To increase the accuracy and reliability of the inventory, it is important to use multiple sources of data. This could include data on vessel characteristics, fuel consumption, operating conditions, and environmental conditions, among others. In this study, three key data sources are utilised to conduct the simulations, drawing on the available data for the Baltic Sea region. These sources are explained as follows:

Emission factors: The accuracy of emission estimates is highly dependent on the precision of emission factors employed in the inventory. We conduct a comprehensive review to choose the appropriate fuel consumption and emission factors, considering their specificity to the type of fuel, engine technology, and operational conditions of the vessels [74–78]. The inventory encompasses all pertinent emissions, covering those from main engines and auxiliary engines. Due to a lack of specific data, boilers are not explicitly included in the current shipping emissions study, which is a limitation. It is assumed that their energy consumption and emissions are covered within the estimates for auxiliary engine usage. Using shipping fuel emission factors in emission inventories has limitations, including variability in fuel quality and operational conditions, which can lead to inaccuracies. Geographical, temporal, and regulatory differences further complicate emissions estimates. The static nature of emission factors overlooks real-time changes and non-exhaust emissions, resulting in deviation from actual ship emissions [10,12,19].

The Automatic Identification System (AIS) data: It is transmitted by ships, providing valuable information about the vessel's location, speed, heading, and other operational characteristics. This rich dataset enables more accurate estimates of emissions and covers a vast number of ships, making it a cost-effective option. AIS data plays a crucial role in estimating fuel consumption and emissions along shipping routes. However, its accuracy can be affected by issues such as data gaps or errors in transmission. Consequently, we conduct thorough validation processes to ensure the accuracy and consistency of AIS data, particularly for speed, heading, and location coordinates, before utilizing it in inventory simulations. AIS data of all the ships are interpolated at high resolution (1 min interval).

Ship Characteristics: All 8084 IMO referenced ships entering into the area are covered by this dataset, which contains essential information such as IMO/MMSI numbers, ship types, main engine capacity, and type of fuel used, manufacturing dates, gross tonnage, and more. Either the IMO or MMSI number is utilized to track the corresponding ship within the AIS data. Fuel types are used for identifying the pollutants emitted by the ships, and they are matched with corresponding emission factors. Ship engine loads i.e. power demand of the engine, are determined by the maximum operating speed and instantaneous speed, with the maximum load not exceeding 80% of the engine load. Ship speed and port activity data are used to categorize ships as cruising, manoeuvring, or at berth. The methodology for developing both the baseline and scenario-based emissions inventory is detailed in Figure 1. In the case of scenario-based emissions inventory, ship characteristics and fuel mix are modified as explained in the following paragraph.

Emissions projections for different scenarios are based on current fuels and potential future fuels for shipping. We project four different scenarios, developing their inventories over the baseline emission inventory of 2019, which relies on actual AIS data and ship characteristic data. The 2019 inventory is compared with Copernicus Atmosphere Monitoring Service-global-emission-inventory (CAMs) and European Monitoring and Evaluation Programme emission inventory (EMEP). CAMs provides gridded distributions of global anthropogenic and natural emissions compiled by CAMs. It covers emissions from fossil fuel use on land, shipping, and aviation, as well as natural emissions from various sources [79]. The data, used in CAMs forecast models, ensures consistency in emissions of greenhouse gases, reactive gases, and aerosol particles. EMEP data comprises national aggregates, sector-specific details, and gridded emission data utilized in EMEP/MSC-W and EMEP/MSC-E reports. The emission data provided here are based on officially reported figures to the extent possible; however, some of the reported data have undergone corrections and/or gap-filling procedures [80]. It is assumed that shipping routes remain unchanged while extrapolating the gross tonnage-based engine capacity for both

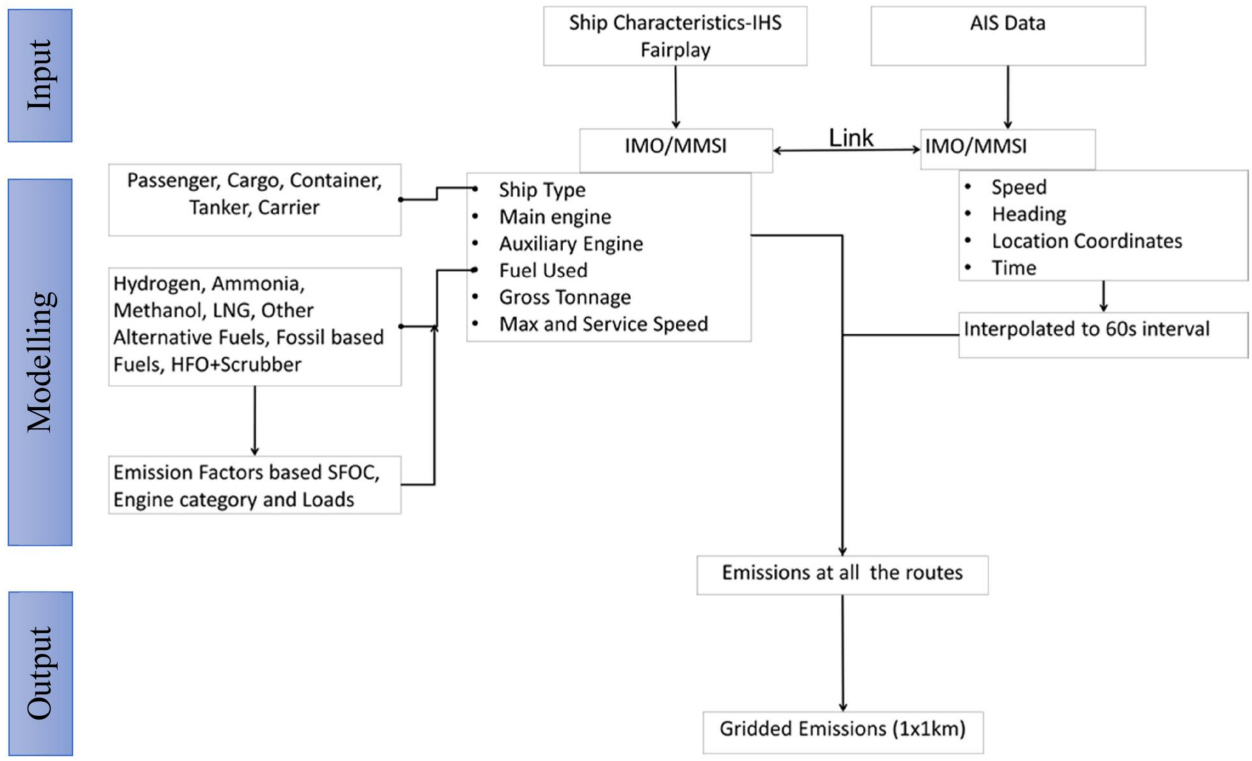

Figure 1. **Flow chart showing the steps involved to develop the gridded shipping emission inventory.**

the near and long term to account for the growing trade and ship sizes. This approach allows us to preserve the 2019 AIS data routes and effectively apply shipping load projections to all routes and ship types.

Fuel mix scenarios: It is developed for allocating fuel types to different ships operating in the Baltic Sea for projected years. The scenarios, explained in the Fuel Mix section, present projections for the anticipated fuel mix in 2030 and 2050 [81]. Fuel allocation in each scenario involves distributing fuels in a manner that: i) ensures the percentage fuel mix of Scenario1 to Scenario 4 is representative of all ships, and ii) maintains the same percentage across different ship categories, including Passenger, Cargo, Container, Tank, and Carrier. Additionally, this allocation introduces new fuels such as hydrogen, ammonia, and methanol progressively into different scenarios while simultaneously phasing out or increasing the use of currently employed fuels.

While this study presents a high-resolution, scenario-driven shipping emission inventory for the Baltic Sea, it is important to acknowledge several limitations. The accuracy of emission estimates is subject to uncertainties in emission factors, which can vary depending on vessel engine type, operational profiles, and fuel characteristics. Furthermore, projections of future fleet developments are based on assumptions regarding the adoption of alternative fuels, the pace of technological innovation, and the enforcement of environmental regulations. Key uncertainties include the timeline and scalability of hydrogen and ammonia integration, the effectiveness of methane slip mitigation in LNG-powered vessels, and the overall rate of fleet transition. Recognizing these limitations is crucial for contextualizing the findings and underscores the need for ongoing refinement of activity data, emission parameters, and scenario assumptions in future modelling efforts.

Results

Projections

Amidst rising trade volumes, the demand for increased cargo capacity is projected to be met primarily through a substantial increase in vessel gross tonnage, rather than an expansion in fleet numbers [68]. This assumption reflects current industry trends, where larger and more fuel-efficient ships are replacing older, smaller vessels. According to UNCTAD data, although the number of ships in Europe has declined over the past five years, a longer-term trend (10-year analysis) indicates a modest overall increase, reinforcing the shift toward larger vessel sizes rather than numerical fleet growth. For our projections of gross tonnage to 2030 and 2050, we use ship-type-specific growth rates derived from Equasis statistics (2010–

2019). These historical trends offer a consistent and data-driven basis for estimating future capacity, while the assumption of a constant fleet size (relative to 2019) ensures a conservative approach that avoids overestimating emissions through excessive fleet growth. Instead, emissions growth is linked more directly to increases in ship size and activity levels, in line with global fleet modernization trends. This approach aligns with efficiency-driven policies and technological advancements aimed at reducing per-unit transport emissions without necessarily expanding the number of operating vessels. The IHS 2019 data for all IMO referenced ships, including gross tonnage and main engine details, serves as our baseline. Initially, we estimate gross tonnage for 8,084 ships and then apply the gross tonnage projection for the respective years to estimate the corresponding main engine size [82]. The auxiliary engine's capacity is considered as a percentage of the corresponding main engine's capacity. A graphical representation of the varying gross tonnage for respective ships illustrates the shipwise gross tonnage trend from 2019 to 2030 and 2050 (Figure 2). The significant increase in gross tonnage corresponds to larger engine sizes (Figure 2, bottom). Notably, industry has already witnessed an 80 MW RT-Flx96C marine diesel engine [83], suggesting the possibility of engine sizes reaching approximately 150 MW by 2030 and around 250 MW by 2050. Considering the increase in ship density, there is a potential for a 2–3-fold increase in gross tonnage along shipping routes and related engine capacities in 2030–2050, reflecting a similar trend.

Anticipated high-volume trade forecasts a future marked by intensified shipping activity, resulting in increased fuel consumption. Ultimately, this heightened shipping activity has a direct impact on emissions, particularly related to the types of fuels utilized by ships.

Fuel mix

Scenarios for short-term and long-term changes in the fuel market are developed through a comprehensive qualitative and quantitative analysis. This analysis considers five key influencing factors: Energy mix, fuel and technology availability, technology maturity, fuel prices, and regulation & incentives [81]. The factors (1) have been projected based on a literature review determining mainly three future trends (two of them serving as lower and upper bounds), and (2) their mutual influence and consistency have been assessed for the determination of the scenarios: for example, banning a given technology (regulation) cannot be associated with an increase of its market penetration (technology maturity). The scenarios were then discussed with stakeholders from multiple backgrounds, including representatives from national maritime organisations, shipping and shipbuilding companies, and maritime cluster. The stakeholders' inputs, gathered through an online questionnaire and a focus group, addressed the likelihood of the scenarios and the potential challenges that might hinder their realisation [81].

The scenarios are designed to assess changes in emission inventories, considering regulatory and technological advancements aimed at mitigating climate change and achieving sustainable development goals. In these scenarios (Figure 3), we allocate the respective shares of different fuel types for the short term (2030) and long term (2050) to all IMO ships entering the Baltic Sea Region. The distribution is carefully planned to ensure that the fuel percentage satisfies both the overall allocation and the ship-wise allocation of fuel types.

Globally we are already facing a challenge of limiting global warming to 1.5 degrees Celsius above pre-industrial levels. The complexities of both accepting and implementing new technologies and the potential for a longer transition period further intensifies the challenge of limiting global warming. The extended transition period is reflected in the acceptance and growth of sustainable fuels, as depicted in the scenarios presented in the Figure 3. By 2030, most scenarios show an increasing acceptability of alternative fuels, but the percentage of fossil fuels remains significantly high. Therefore, the possibility of acceptance and growth is shown is substantially supported by 2050 in scenario 1 (S1) and to a certain extent in scenario 2 (S2). However, in the absence of strong technological development and regulatory mechanisms, the possibilities of wide-scale fossil fuel use with abatement methods, as opted for in scenarios 3 (S3) and scenario 4 (S4), cannot be ignored.

Comparison

We developed a novel high-resolution inventory over the Baltic Sea Region shipping emissions for the baseline year of 2019 and 2050 scenarios comprised in Figure 3 with detailed information on IMO ships. The inventory covers a large number of pollutants, including PM and Hydrocarbons (HC). To validate the estimated emissions, both the

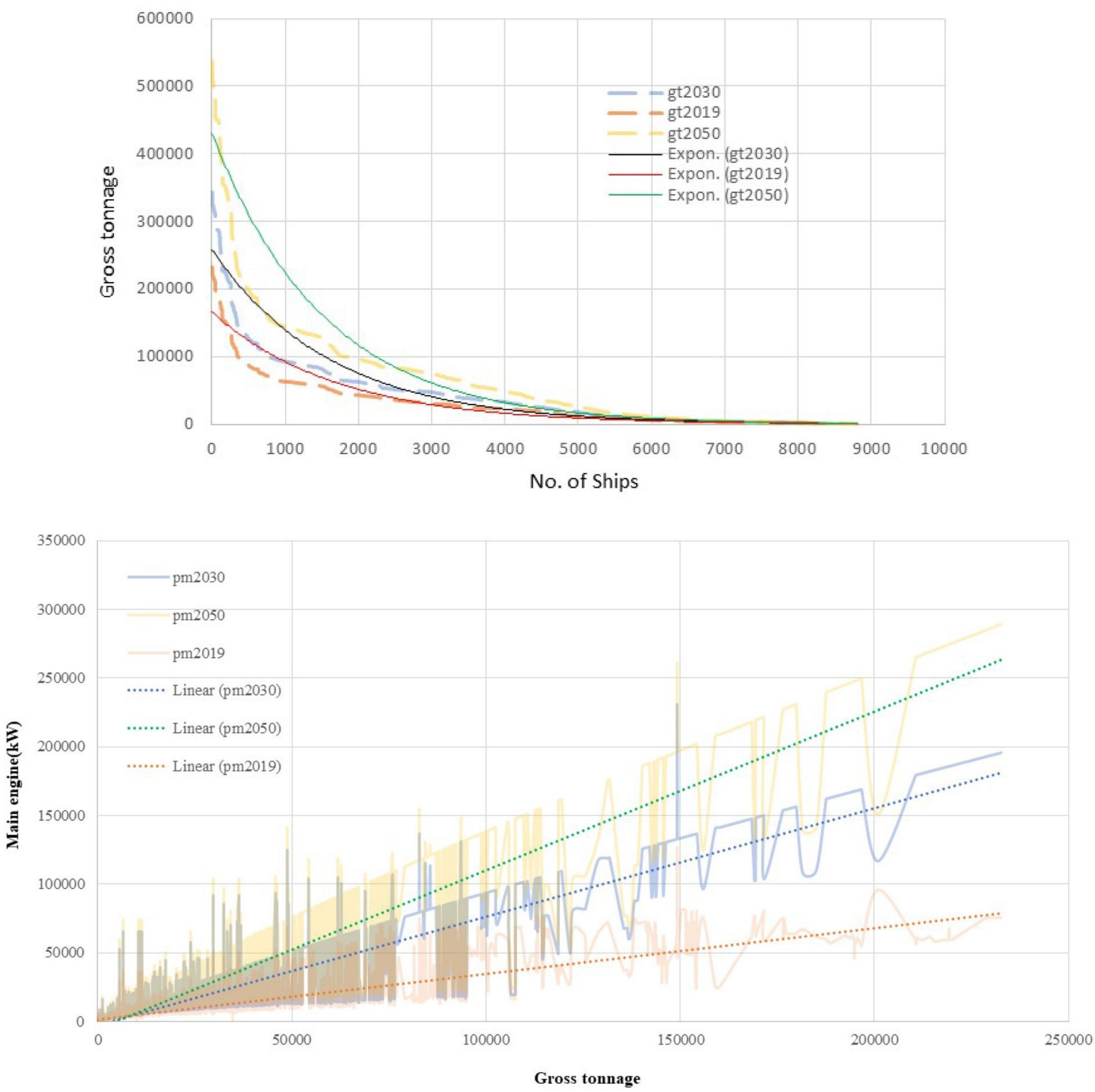

Figure 2. Projection for gross tonnage (top) and corresponding engine sizes (bottom) for respective ships in 2030 and 2050, with the base year set at 2019.

cams-global-emission-inventories (CAMs) for 2019 and the high-resolution inventory is compared against the EMEP Centre on Emission Inventories and Projections (EMEP) emissions data for the year 2019 (Figure 4). It is observed that all the pollutants such as carbon monoxide (CO) and black carbon (BC) within our analysis have lesser error than the CAMs emission inventory projected for year 2019. However, the amount of non-methane volatile organic compounds (NMVOCs) emitted are significantly overpredicted by both the inventories, although the high-resolution inventory's prediction error is around one fourth of the prediction error of CAMs.

There are only five pollutant types that overlap between the three emission inventories. However, the significant discrepancy in NMVOCs prompted us to compare the remaining pollutants only against CAMs. Although the emission gaps between CAMs and the high-resolution inventory are less than 50%, a notable difference in SO_4^{2-}, CH_4, and NMVOCs raises concerns as shown in Figure 5. This not only questions the accuracy of the inventory but also reflects changes in the fuel market and the evolving knowledge related to quantifying associated emissions and the adaptability of internal combustion engine technology on ships to different fuel types.

Emissions projection

Although LNG as a fuel is gradually increasing its share in the marine fuel mix, the methane slip from LNG-powered ships remains a

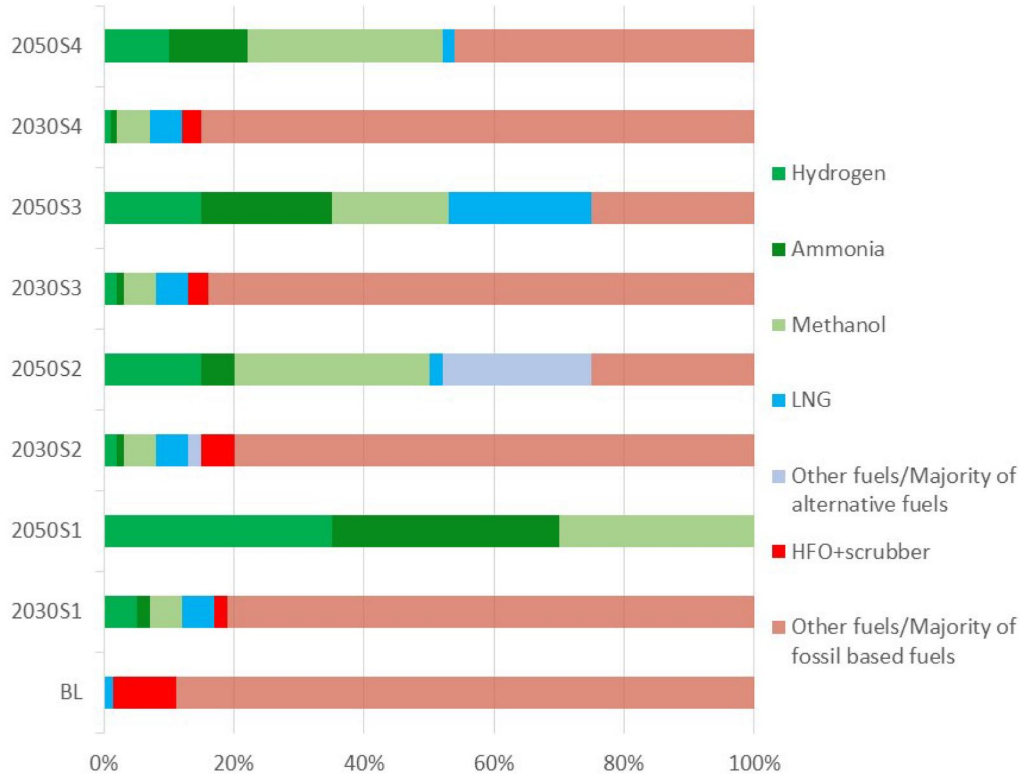

Figure 3. Scenarios projecting fuel combinations for the years 2030 and 2050, involving the reduction of fossil fuels, with Scenario 1 (S1) being the most environmentally friendly. The Baseline fuel mix (BL) represents the fuel combination used by the 8084 IMO ships operating in the Baltic Sea Region in 2019 [81].

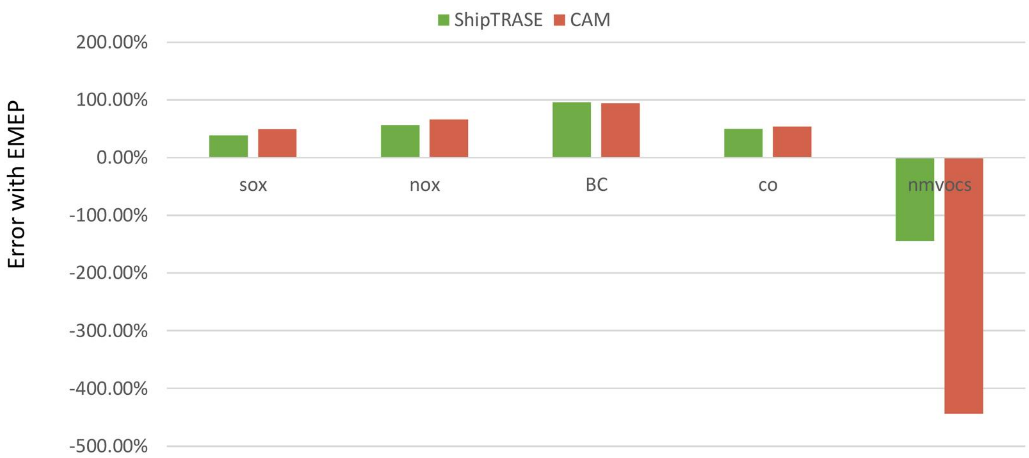

Figure 4. Percent variation of different pollutant emissions: CAM model and present study against the 2019 EMEP data.

significant concern [84,85]. Hydrogen and ammonia driven ships are expected to be introduced in coming years [86], but it could take a couple of years for their acceptance, growth, and efficient engine technologies. In all the scenarios depicted in Figure 6, it is observed that by 2040, the measures implemented for green shipping begin to exhibit a steady reduction in emissions. The trade-intensive shipping, which will lead to a significant rise in emissions due to the year-by-year increase in ships' gross tonnage from 2019 to 2040, will start to exhibit a steep decline in emissions.

One of the key aspects of this study is to explore a realistic pathway to control NOx and SOx emissions. The Baltic Sea region falls under the Emission Control Area, where priority is given to reducing or eliminating NOx and SOx emissions. Sulfur dioxide (SO_2) accounts for approximately 95% of SOx emissions from the combustion of fossil fuels. This toxic gas poses direct threats to both human health and plants. [87]. Another consequence of SOx emission is the creation of sulfate aerosols, extremely fine airborne particles that, according to the WHO [88,89], contribute to elevated annual mortality rates in Europe.

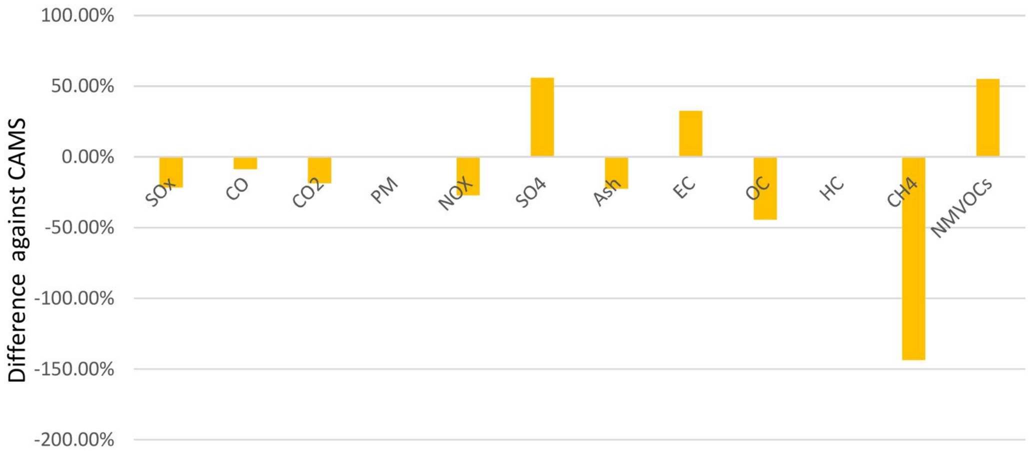

Figure 5. **Comparing CAMs and the present study results for ship-emitted pollutants.**

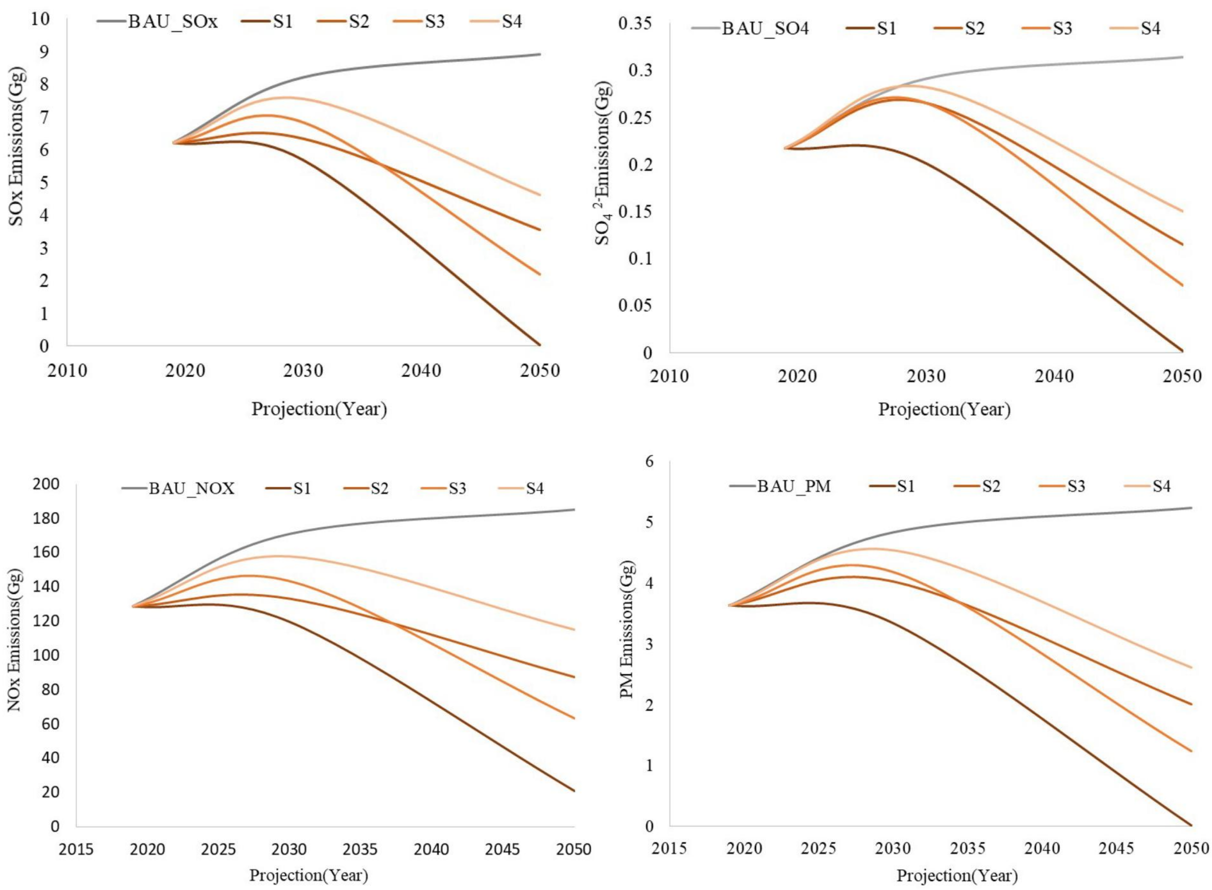

Figure 6. **Emissions pathways for different pollutants based on scenarios presented in Figure 3.**

Additionally, the well known outcome of SOx emissions is the generation of acid rain, formed when sulfur oxides, water, and oxygen combine to create sulfuric acid in clouds. NOx emissions have consequences with respect to eutrophication of marine and coastal ecosystems [90]. It also contributes to the formation of PM-nitrate, a secondary aerosol, produced through the photochemical oxidation of NO_2 to gaseous nitric acid (HNO_3) [87]. It is observed that a significant reduction in SOx emissions can be achieved through most of the scenario presented in Figure 6. Emission reduction involve either using an abatement technology or the replacement of HFO and distillates with alternative and green fuels in all IMO ships entering the Baltic Sea Region. Smaller ships with AIS, such as fishing, tug, dredging, diving, and towing boats, contribute less than 2% of the Baltic Sea Region (BSR) shipping emissions to differentiate referred as smaller non-IMO ships. It is assumed that these smaller non-IMO ships, primarily operating locally, might continue to use distillates while the focus would primarily be on regulating larger ships. The mitigation of pollutant emissions through various scenarios is discussed as follows:

Sulphur species

In S1, driven by the sustainable fuel combination of hydrogen, ammonia, and methanol, SOx emissions and associated sulphate aerosols will be reduced to zero by 2050 (Figure 6). Technological advancements in energy efficiency measures, along with changes in the shipping fuel mix, provide a significant buffer during the initial transition phase. When applied to S1, the emissions reach much earlier, around 2030.

Although LNG serves as a transitional fuel in decarbonisation efforts, it continues until 2050 in Scenario 3 (S3) and facilitates the reduction of SOx emissions. However, the presence of fossil fuels like distillates in S3 still adds 4Gg of SOx and 0.12 Gg of sulphates to the atmosphere. In the business-as-usual scenario (BAU), where no definitive interventions occur, SOx emissions increase by 44%. Distillates with 0.1% sulphur content contribute the majority of SOx emissions due to their larger share of the fuel mix, approximately 80% in BAU. The rest comes from ships using scrubbers as an abatement measure with Heavy Fuel Oil (HFO), which can capture approximately 90% of SOx exhaust emissions into the atmosphere. However, this 90% of SOx captured by scrubbers is either discharged into the sea through open-loop scrubbers or disposed of at onshore facilities by hybrid/closed-loop scrubbers.

As scrubber discharge is acidic, concerns have been raised about its release into the sea. Therefore, a detailed study is needed to quantify this discharge and understand its long-term consequences in the Baltic Sea.

NOx

NOx emissions are primarily determined by engine technology and are categorized into Tier I, II, and III, with Tier III engines having the lowest NOx emissions. The introduction of newer ships and increased demand for ships driven by greener fuels will directly address this issue. NOx emissions are not dependent on specific fuel oil consumption, so reduction measures primarily focus on the engine. The pace of adoption and growth of sustainable fuels will drive NOx mitigation efforts. The replacement of fossil fuel-based engines and ships will lead to the introduction of newer engines and ships that fall under Tier III emission standards, resulting in lower NOx emission factors. Scenario 1, which completely migrates to methanol, hydrogen, and ammonia fuels from present fossil fuel options, leads to the highest rate of replacing old ships and introducing advanced engines. Therefore, it achieves the maximum reduction in NOx emissions among all scenarios, bringing down NOx emissions from approximately 129 Gg to about 21 Gg, a significant 84% reduction (Figure 6).

Abatement technologies like selective catalytic reduction (SCR), which can reduce exhaust NOx emissions by more than 90%, could facilitate the complete removal of NOx. However, such abatement methods are more crucial in cutting down NOx emissions in Scenarios 3 and 4, where the share of traditional fuel oil ships with older engines is significantly high.

PM

The decline in the share of traditional fuels, i.e. HFO and distillates, directly impacts the reduction of particulate matter (PM), as it mainly consists of organic carbon (OC), elementary carbon (EC), ash, and sulphate. The reduction in OC alone accounts for more than 60% of the overall 99% PM emission reduction by 2050 (Figure 6). Reductions of more than 98% are also observed for other PM constituents, namely EC and ash. According to the IMO Fourth Greenhouse Gas Emissions report in 2020 [91], PM2.5 is derived from PM10. PM2.5 emissions have reduced by 98.5% from annual emissions of 3.34–0.05 Gg, with a significant contribution coming from the reduction in sulphate emissions.

In 2019, an estimated 1030 Gg of CO_2 emissions were recorded in the BALTIC SEA REGION shipping routes. It was observed that, to comply with the 0.1% sulphur mix fuel regulations, ships switched from HFO to distillates. However, a significant number of HFO-powered ships continued to operate in the region by adopting exhaust scrubber systems, which allowed them to control sulphur emissions. While switching to distillates facilitated SOx reduction, they produced approximately 3%–4% higher CO_2 emissions per kWh of energy generation compared to HFO. Considering the step changes in sulphur content from 0.5% to 0.1% in 2015 and 2021, the rapid transition to distillates has increased the possibility for higher CO_2 emissions by ships. Additionally, there was approximately a 2% increase in specific fuel oil consumption (SFOC) for HFO-driven ships to

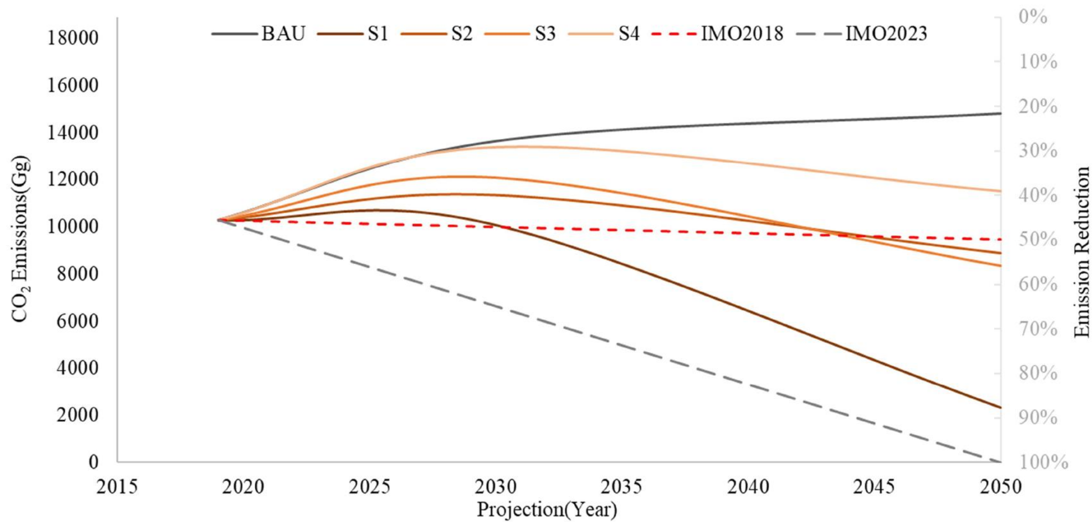

Figure 7. CO_2 **shipping emission pathways for all scenarios compared with the target set by IMO in 2018 and revised in 2023.**

support exhaust scrubber systems, resulting in a 2.2% increase in CO_2 emissions from HFO-driven ships.

CO_2

The IMO's 2008 target of a 50% CO_2 reduction [92] with fuel changes alone can be achieved in the near term through Scenario 1 (S1) and by 2050 through the adoption of Scenarios 2 (S2) and 3 (S3) [93] (Figure 7). The recently revised IMO 2023 target of net-zero carbon emission reduction can be achieved through the hydrogen and ammonia-intensive S1 scenario. In S1, CO_2 emissions are reduced by 88% through the use of the fuel mix alone, without the need for additional support mechanisms such as carbon capture abatement technologies or carbon trading. The remaining approximately 10% of CO_2 emissions can be easily offset through the Emission Trading System (ETS) by trading carbon certificates at mandatory (compliance) market prices, accounting for the same amount of emissions. Each credit represents one ton of carbon dioxide reduction or its equivalent in other greenhouse gases. An additional share of 1.5% from non-IMO ships can be addressed at the national level through regulations.

Industry has proposed carbon capture, utilisation, and storage (CCUS) integrated with scrubber systems, capable of capturing more than 90% of carbon dioxide emissions [94,95]. Although not applied in the present study, the application of CCUS could significantly contribute to reducing CO_2 emissions in Scenarios S2, S3, and S4, potentially offsetting a major portion of these emissions. This approach could make net-zero targets, through trading mechanisms more achievable. Additionally, proposed technologies for future such as CCUS if integrated successfully with LNG and methanol-driven ships in Scenario S1, could achieve carbon-free shipping routes by removing the most of the remaining 12% of CO_2 emissions [96,97].

Ship category wise emissions

Emissions from all 8084 IMO ships, accessed through SP Global 2019 data, are tracked for the Baltic Sea Region. These ship emissions are further categorized based on ship types provided in the data, broadly defined into 5 categories: Passenger, tanker, container, general cargo, and carrier. Each category consists of several subcategories, such as passenger (cruise) ships, passenger/ro-ro cargo ships, passenger/general cargo ships, and passenger ships combined to form the passenger ship category. The rest are smaller non-IMO ships operating locally.

Approximately 40% of emissions of all pollutants come from passenger ships (Figure 8). The higher share of passenger ships using LNG as their fuel contributes to methane emissions accounting for more than 50% of the total. Methane emissions from smaller non-IMO ships, where LNG is not utilized, remain minimal, amounting to just 0.002 kT. Following passenger ships, general cargo ships have the highest emissions, followed by container and tanker ships.

Seasonal

Emissions are directly correlated with shipping density, where areas with higher ship density exhibit higher emissions. Ship mobility is more active during the summer months, particularly

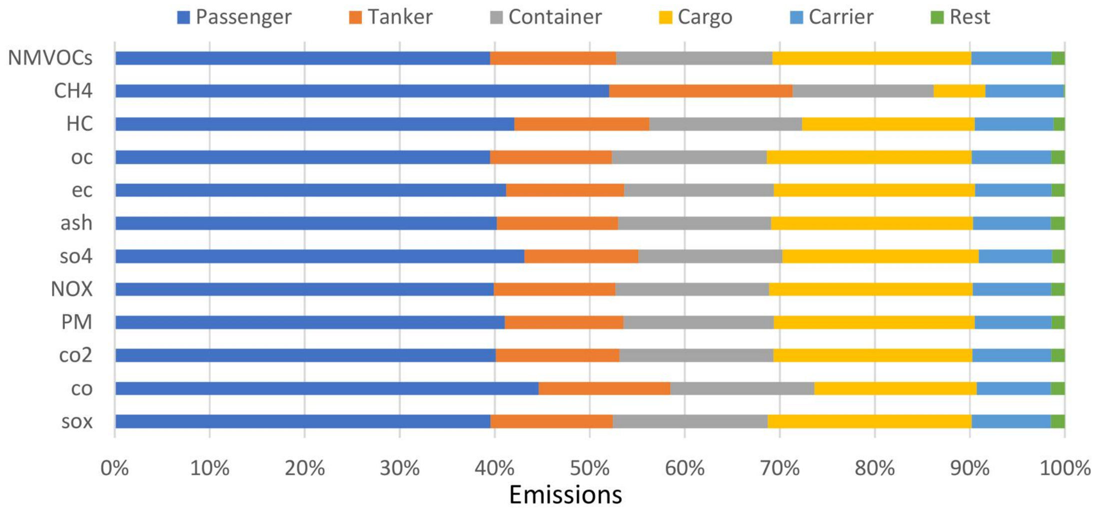

Figure 8. Emission share of different ship types for various pollutants, as defined in the IHS toolkit data 2019.

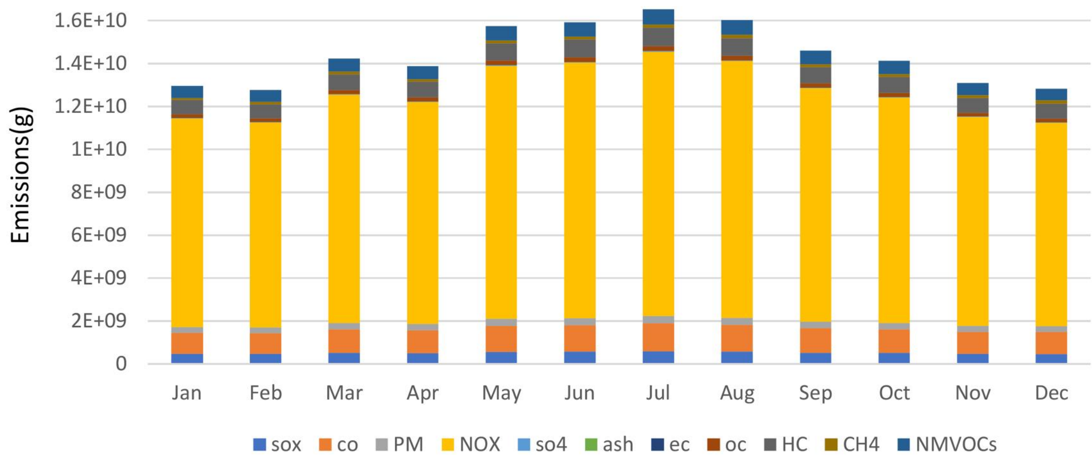

Figure 9. Emissions contribution for all the pollutants by month.

from May to August, leading to significantly higher emissions compared to the winter months, which occur from November to February (Figure 9). Emissions during the autumn and spring months fall in between those of summer and winter. Notably, emissions of NOx gases are significantly higher, primarily due to older ships equipped with Tier I and Tier II engine types. The implementation of abatement technology such as SCR is necessary to mitigate atmospheric NOx emissions. Additionally, a higher share of emissions of CO (carbon monoxide) and HC could be addressed by transitioning to greener fuel types.

Emission maps

The line emissions along all the shipping routes are modelled to assess the spatial and temporal variations of pollutants emitted with different fuel types. This is the final step in developing inventory maps used in climate model simulations. Gridded emissions are estimated by summing up all the pollutants emitted by ships for each grid cell, typically about 1 × 1 km with a 1-minute interval.

The focus is primarily on CO_2, NOx, SOx, and PM emissions. The 2019 emission map is compared with the greenest fuel mix scenario (S1) to evaluate the reduction in emissions of different pollutants along the routes, at ports, and in densely populated coastal areas (Figure 10). The map illustrates the percentage reduction at each grid cell by adopting the hydrogen-driven scenario (S1). A significant impact is observed, with a complete removal of HFO and distillates leading to emissions being controlled up to 100% on longer routes. In high-density regions like around Denmark, some emissions are still noticeable. However, emission reductions in these regions are still above 50% of baseline emissions for CO_2. NOx emissions are reduced by 50% of baseline emissions across almost the entire Baltic Sea Region and up to 75% on prominent longer routes, due to the introduction of new ships and engines falling under the TIER III emission category. Emissions near coastal

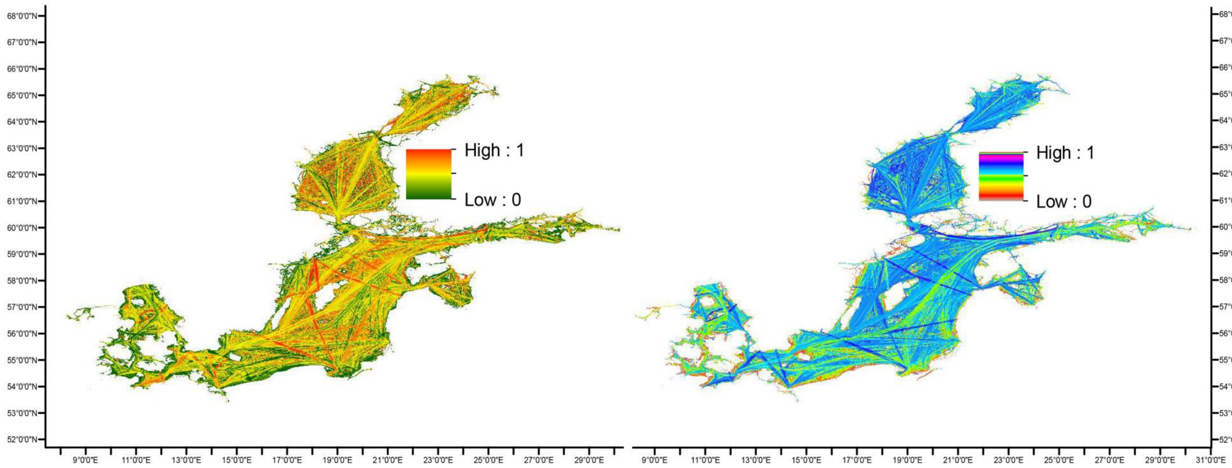

Figure 10. CO_2 (Left) and NOx (Right)emission reduction along different shipping routes in the Baltic Sea under the alternate fuel-intensive 2050 S1.

areas are primarily associated with smaller IMO ships, which are assumed to operate under weaker regulations than larger IMO ships.

PM

In the year 2019, the amount of PM emissions exhibited relatively elevated levels within the geographic areas encompassing the Kattegat basin, Arkona basin, and Belt Sea, with subsequent increments evident in the north-eastern sector of the Gulf of Finland (Figure 11). A discernible decrease in PM emissions was observed across various scenarios due to the expanded utilization of alternative fuels. Notably, scenarios characterised by a heightened reliance on hydrogen and ammonia as primary energy sources demonstrated a comprehensive elimination of PM emissions, achieving substantial reductions ranging from 95% to 100% along all specified maritime routes. Nonetheless, residual PM emissions are still within regions proximate to busy maritime ports, such as the coastal region of Stockholm. These residual emissions are emitted primarily from non-compliant vessels, which do not fully adopt sustainable fuels and technologies sanctioned by the IMO.

Discussion and conclusion

Shipping emissions inventories are essential for climate modelling as they provide precise data on emissions from the maritime sector, including CO_2, NOx, SOx, and particulate matter. This data is integrated into climate models to simulate shipping's contribution to greenhouse gases and air pollutants, aiding in the assessment of climate forcing and atmospheric composition. By modelling various fuel mix scenarios, influenced by multiple factors such as regulatory changes and technological advancements, these inventories help predict future emissions and assess the impact on global warming. High-resolution inventories also allow for regional assessments, such as the Baltic Sea, and support the development of targeted mitigation strategies by policymakers. These models guide decision-making, improve regulations, and track compliance with emission reduction targets. Therefore, a high-resolution emission inventory, focusing on the Baltic Sea region at approximately 1x1km spatial resolution, has been developed. It utilizes 2019 AIS data and vessel-specific characteristics for the same year. The primary purpose of this inventory is to develop the inventory using latest data for the region to evaluate the impact of recent regulatory changes and the evolving fuel landscape within the shipping industry. The study explores the potential for emission reductions through the adoption of green fuels like hydrogen and ammonia, in addition to evaluating the emissions associated with traditional fossil fuels and alternative options. Various emission pathways related to different fuel types are presented across four distinct scenarios and a business-as-usual (BAU) case, encompassing all shipping routes within the Baltic Sea.

The study projects a threefold increase in gross tonnage in the Baltic Sea by 2050, alongside a corresponding enlargement of engine sizes, which will substantially elevate fuel consumption and the associated emissions. Comparative analysis of the emission inventory results, derived from an activity-based model, reveals a closer alignment with EMEP data in contrast to CAM (Chemical Transport Model) results. Higher percentages of variation are observed in pollutants such as sulphate (SO_4^{2-}), NMVOCs, and CH_4, potentially attributed to the introduction of more LNG (Liquefied

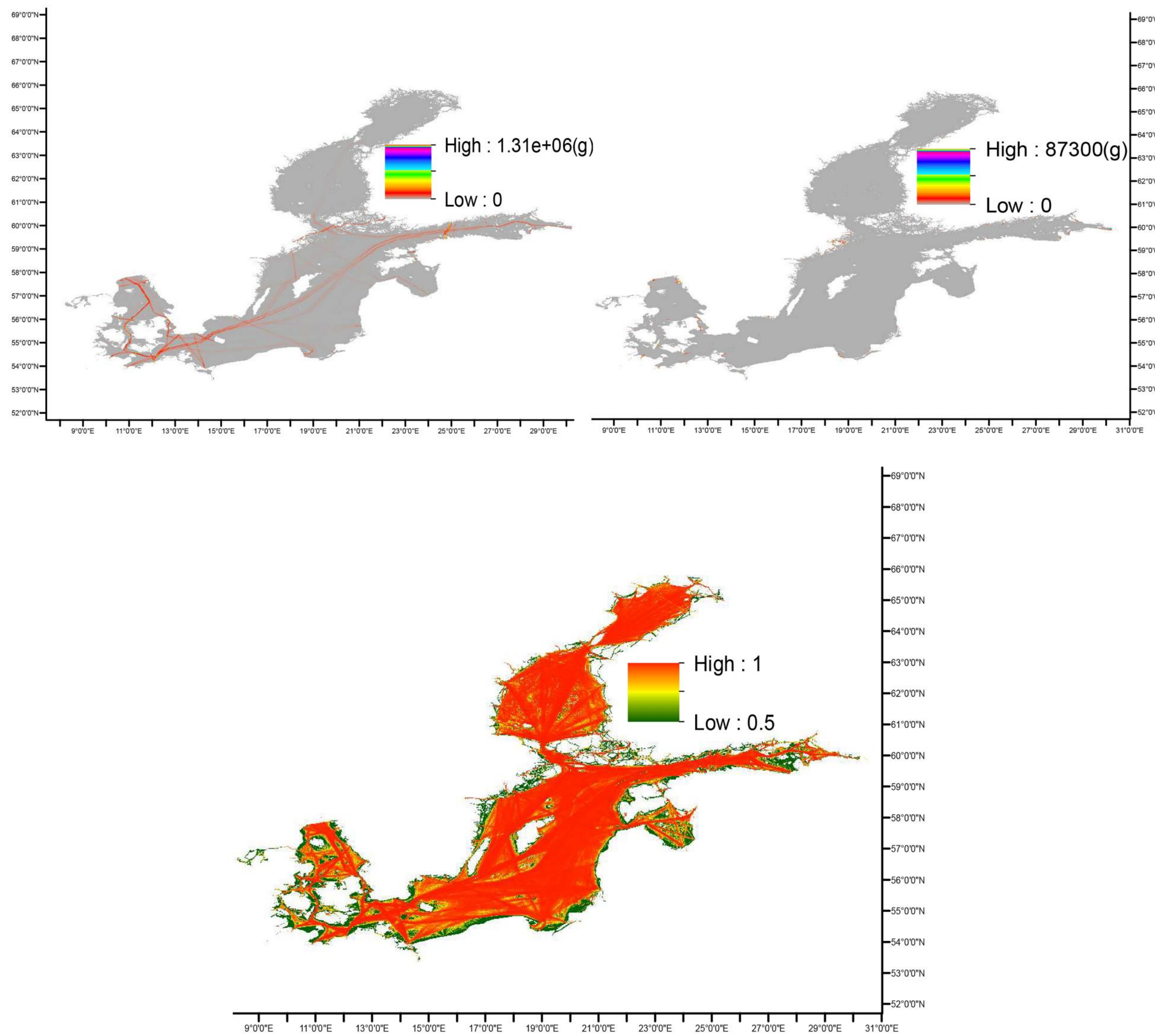

Figure 11. Comparing the PM emission for baseline emissions (top left) and 2050 S1(top right), and the emission reduction (bottom centre) along the different shipping routes in the Baltic sea.

Table 1. Policy matrix for maritime emission reductions in the Baltic sea region, outlining short- and long-term actions aligned with emission scenarios and regulatory targets.

Policy area	Short-term actions	Long-term actions
Fuel Strategy	Conditional use of LNG as a transitional fuel with mandatory methane slip control technologies.	Mandate hydrogen and ammonia for new vessels; phase out fossil-based marine fuels entirely.
Green Fuel Adoption	Incentivize pilot projects for hydrogen and ammonia; initiate infrastructure at key Baltic ports.	Scale up hydrogen/ammonia supply chains; develop port-wide bunkering and handling capabilities.
Regulation & Compliance	Enforce IMO 2030 carbon targets (tank-to-wake); establish monitoring and reporting protocols.	Adopt well-to-wake emissions accounting, with tank-to-wake as a main element; align regional policies with IMO 2050 net-zero ambitions.
Emission Inventory Accuracy	Improve vessel-specific data quality; update emission factors; strengthen AIS-based bottom-up inventories.	Integrate real-time emission monitoring and adaptive inventories using evolving ship tech data.

Natural Gas) and scrubber-equipped ships in the Baltic Sea. Continual enhancement in emission factors, facilitated by the ongoing investigation and availability of shipping data, contributes to improved accuracy. The introduction of LNG-powered vessels and the emerging concern regarding methane slip necessitate further in-depth investigation to determine the future role of LNG as a shipping fuel. Nevertheless, LNG's status as a transitional fuel remains contingent upon addressing the issue of methane emissions. Among the scenarios, Scenario 1 (hydrogen) is the most effective for emission reduction, achieving over 90% tank to wake reductions and to facilitate the revised 2023 carbon targets. Scenarios 2 and 3, while reducing pollutants, offer a weaker contribution toward achieving the IMO's 2050 carbon targets.

It is observed that the current transition to cleaner fuels is inadequate to meet the carbon reduction targets set in 2018 and revised in 2023 through tank to wake approach but it could potentially lead the way to the broader well to wake approach to achieve net-zero emission targets by 2050. Particularly for intermittent targets of 2030 and 2040 set by the IMO, could see a bigger role of limiting wake to tank emissions. However, there is a critical need to accelerate the adoption of green fuels to achieve significant emission reductions. Without stronger policy frameworks, targeted investment in port infrastructure, and technological breakthroughs, the scalability of hydrogen and ammonia in the Baltic shipping sector by 2050 remains ambitious. While LNG helps reduce SOx and particulate matter, it should be used cautiously as a transitional fuel due to the risk of methane slip i.e. unburned methane with a high global warming potential that can undermine climate benefits. This serves as an important lesson for adopting hydrogen and ammonia fuels, where potential challenges such as NOx emissions from hydrogen combustion and ammonia's toxicity to marine ecosystems must be carefully managed. Therefore, evaluating these secondary impacts alongside direct emissions is essential to ensure a truly sustainable transition in shipping. Policy measures should prioritize promoting the adoption of hydrogen and ammonia while carefully monitoring their life-cycle emissions and those of other prospective green fuels to effectively reduce emissions and meet regulatory targets.

This research provides a detailed high-resolution emission inventory specific to the Baltic Sea, offering valuable insights into regional emissions and fuel impacts. It evaluates multiple fuel pathways and their potential to meet emission reduction targets, with a particular emphasis on hydrogen as a highly effective option. The study also offers evidence-based recommendations for fuel policies and regulatory strategies. The accuracy of emission estimates depends on the availability and quality of vessel-specific data, which may vary across regions. Additionally, the feasibility of scaling up green fuel adoption and addressing methane slip remains uncertain.

Future research should focus on addressing the issue of methane slip from LNG-powered ships and exploring advanced technologies that may impact emission factors and compliance with Tier III standards. Long-term studies are also needed to assess the effectiveness of implemented policies and technologies in achieving emission reduction targets. To meet emission reduction targets, policies should support the rapid adoption of hydrogen and ammonia technologies. Strategies should also be developed to mitigate methane emissions from LNG-powered ships. Improving data collection and accuracy will further enhance the reliability of emission inventories and the effectiveness of regulatory measures. The recommended actionable policy steps that could help achieve both short-term and long-term goals are summarized in Table 1.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Belmont Forum.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Kumar, R., upon reasonable request.

Acknowledgement

We sincerely acknowledge Belmont Forum, FORMAS and Trafikverket for funding this research. We would like to acknowledge the computations and data handling were enabled by resources in project [NAISS 2024/22-1127] [NAISS 2024/23-506] provided by the National Academic Infrastructure for Supercomputing in Sweden (NAISS) at UPPMAX, funded by the Swedish Research Council through grant agreement no. 2022-06725.

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