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Final Report

The potential for cost-effective air emission reductions from international shipping through designation of further Emission Control Areas in EU waters with focus on the Mediterranean Sea

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Abstract

This study explores the impacts of alternative emission control interventions for international shipping on the European Seas on relevant air pollutant emissions, examines their consequence on ambient air quality in Europe and the neighbouring regions, and explores the resulting improvements of human health. It estimates the costs of the various policy interventions, and compares them with monetized benefits on human health and other impacts.

It is found that further controls of SO_2 emissions, e.g., through SO_2 emission control areas, could deliver rather fast benefits, and avoid by 2030 up to 4000 cases of premature deaths annually, and 8000 in 2050. In the longer run, by 2050, application of Tier III NO_x standards could double the health benefits. Even when using the lower (most conservative) health valuation, all reduction measures examined in this report emerged as cost-effective, with monetized benefits exceeding emission control costs typically by a factor of 6 in 2030 and by a factor of 12 in 2050.

Designation of the Mediterranean Sea as an Emission Control Area could by 2030 cut emissions of SO_2 and NO_x from international shipping by 80 and 20 percent, respectively, compared to current legislation. These additional emission reductions could avoid 4,100 cases of premature deaths in 2030 and more than 10,000 annual premature deaths in 2050. Even with the most conservative assumptions for health valuation, monetized benefits are on average 4.4 times higher than the costs in 2030 and 7.5 times higher in 2050.

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Executive Summary

This study explores the benefits and costs of additional measures that could be taken to reduce shipping emissions to air, with a focus on the Mediterranean Sea

International maritime shipping is an important contributor to poor air quality in Europe. It has particularly large impacts in port cities, but through the long-range transport of pollutants it deteriorates also inland air quality affecting a large share of the European citizens.

After the adoption of the 2013 Clean Air Programme for Europe and the 2016 agreement on the EU National Emission Ceilings Directive, there is interest to explore the balance between the stringencies of the current emission control regulations for land-based sources in the EU versus those for the shipping sector, and to explore the feasibility and potential impacts of further emission reduction initiatives for the maritime sector.

This study explores the effects of additional measures that could be taken to reduce shipping emissions to air, with a focus on the Mediterranean Sea. While maintaining consistency with other recent studies, this report:

- updates the projections of the likely development of maritime transport activities,
- provides new assessments of costs of compliance with current legislation,
- improves the understanding of the role of emissions from vessels in ports, and the options for reducing these emissions,
- develops new scenarios of future emissions that would result from different policy interventions, including additional Emission Control Areas (ECAs) for SO_x (SO_x-ECAs or SECAs in this study) or for NO_x (NO_x-ECAs or NECAs in this study) or both, in the Mediterranean Sea and other European Sea regions,
- assesses their impacts on ambient air quality and resulting population exposure, and
- estimates the associated benefits to human health, and quantifies these benefits in monetary terms.

As a central tool, this report employs the GAINS (Greenhouse gas – Air Pollution Interactions and Synergies) model (Amann et al. 2011), complemented by more detailed computations with MET Norway's EMEP atmospheric chemistry-transport model (Simpson et al. 2012). Subsequently, EMRC's ALPHA-RiskPoll model (Holland et al. 2013) provided full benefit analyses. By employing the same methodologies and models that have been used for the Impact Assessment and the underlying reports of the 2013 Clean Air Policy Package (EC 2013) and, most recently, for the Clean Air Outlook of the European Commission (Amann et al. 2017), results are directly comparable with the above-mentioned studies.

While current IMO and EU regulations will cut SO_2 emissions from international shipping up to 2030, without further controls emissions will grow again after 2030. After 2030, NO_x emissions will exceed those from land-based sources in the EU.

The sulphur in fuel requirements that have been agreed by the IMO will cut SO_2 emissions by 50-80 percent up to 2030, but in the absence of additional regulations, emissions will rebound afterwards. CO_2 and NO_x emissions are expected to further increase without additional measures, and NO_x emissions will exceed emissions from all land-based emissions in the EU-28 after 2030 (Figure A-1).

Figure A-1: Projections of greenhouse gas and air pollutant emissions with current emission control regulations, international maritime shipping and land-based sources in the EU-28

Enhanced emission controls could cut emissions from international shipping in the European Seas by more than 90 percent

There is significant potential for further emission reductions from international maritime shipping in Europe. An extension of the sulphur in fuel controls to all European Sea regions could reduce SO_2 emissions by more than 90 percent, compared to 2015. These measures would also have co-benefits on primary PM2.5 and black carbon emissions and reduce them by 20 percent. In addition, particle filters could cut PM2.5 emissions further, up to 95 percent below the 2015 level in 2050. Tier III standards could lower NO_x emissions in the European Seas by up to 50 percent in 2050 (Figure A-2).

The exact potentials depend on the scope of application (i.e., spatial coverage of emission control areas), from when they would be phased in, and for NO_x whether existing vessels will be retrofitted.

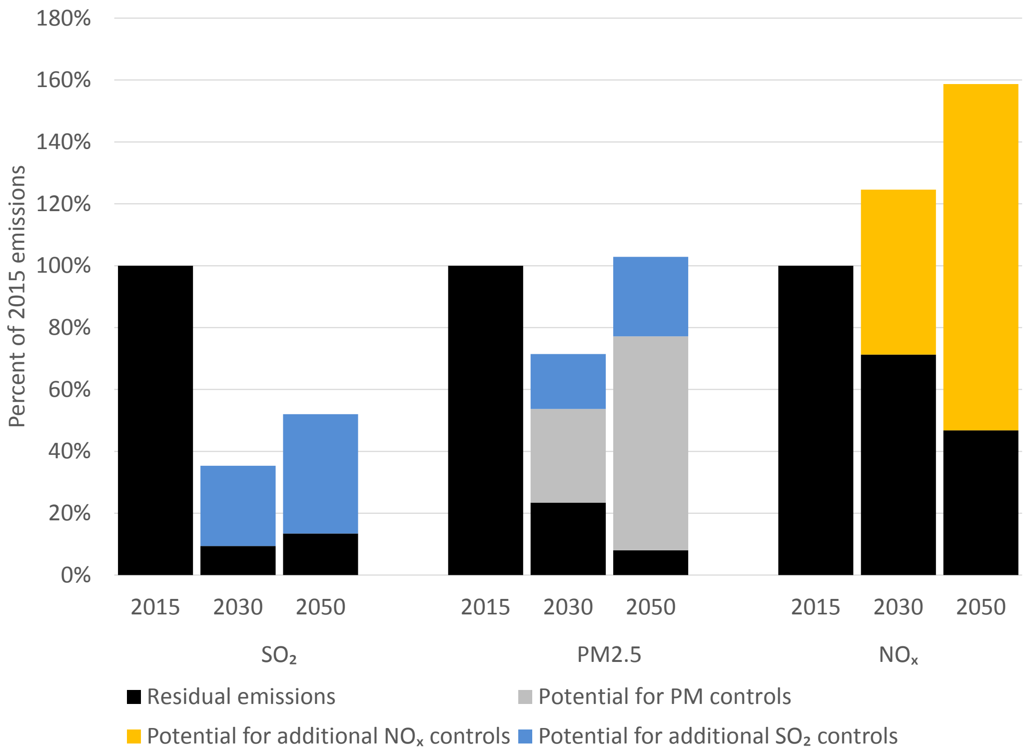


Figure A-2: Emission control potentials in the European Seas, for the baseline projection relative to the 2015 emissions

Climate policy measures, through their reduction of fuel consumption, have significant co-benefits on air pollutant emissions

The baseline projection of future shipping activities, reflecting current thinking on the evolution of economic growth, global trade volumes and fuel efficiency, indicates for 2050 a 130% increase in CO_2 emissions from international shipping in the European Seas. In contrast, in 2018 the IMO MEPC 72 has agreed on a target to reduce greenhouse gas emissions from international shipping by at least 50 percent in 2050. Measures to achieve such a deep reduction in greenhouse gases will deliver significant co-benefits on air pollutant emissions from shipping. As an illustration, a scenario that assumes climate measures that would stabilize CO_2 emissions by 2050 (but not achieve the 50 percent cut established by the IMO) would allow an additional 50 percent cut in SO_2, NO_x and PM2.5 emissions on top of the reductions achieved with the full set of emission controls in the baseline projection (Figure A-3).

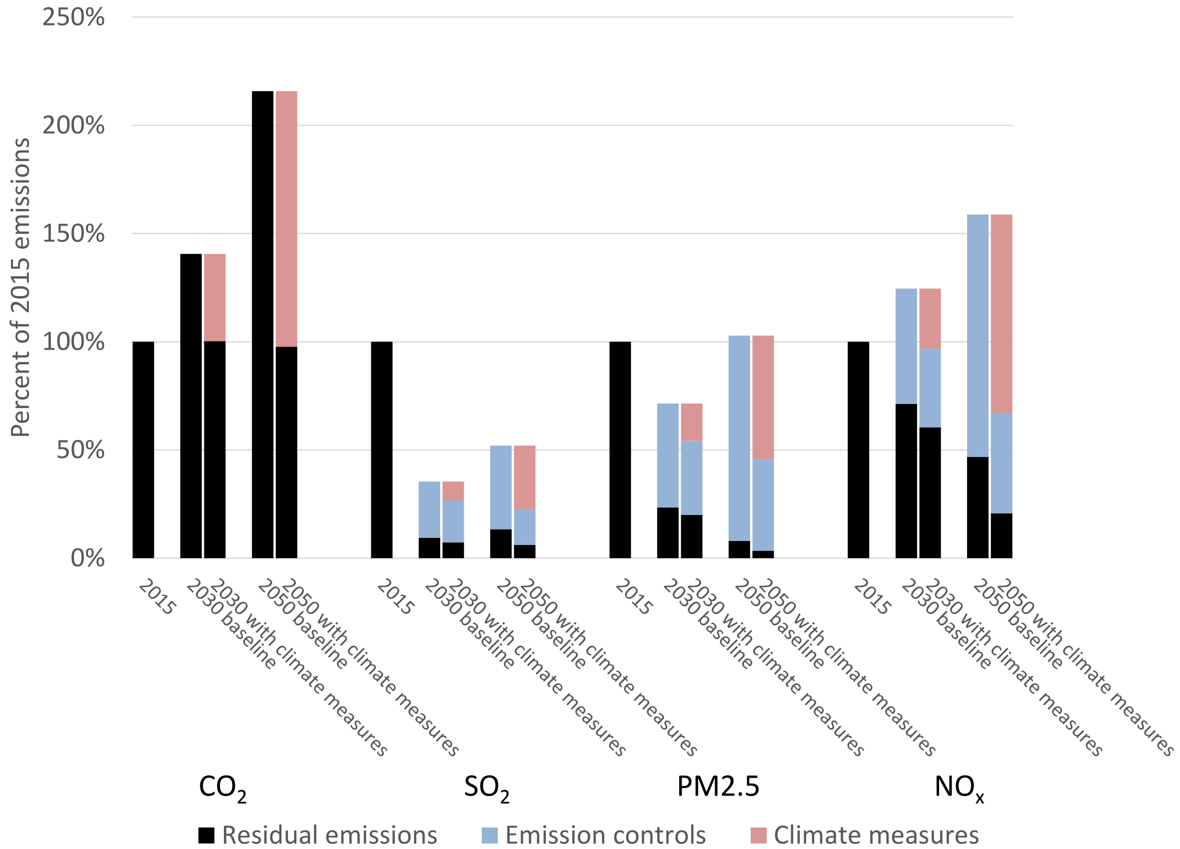


Figure A-3: Emission reductions from climate measures and pollution control legislation, all European Seas, relative to the 2015 levels

Further emission controls for international shipping would deliver important improvements for air quality throughout Europe, particularly in coastal areas

Further controls of emissions from international shipping could improve air quality for a large share of European population, given that about half of the EU population lives within 50 km distance from the Sea (Figure A-4). Largest improvements could occur along the coast of Mediterranean countries, and in particular along the North African coast. Here the concentrations of PM2.5 could decrease by up to 1.2 μg/m^3 in 2030 and up to 1.5 μg/m^3 in 2050 (Figure A- 5).

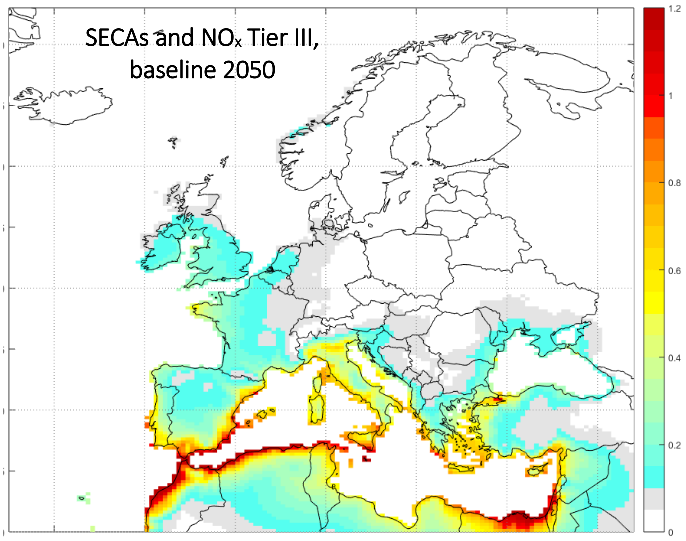


Figure A-4: Decrease of ambient PM2.5 concentrations (μg/m^3) in 2050 from implementation of SECAs and Tier III standards for NO_x (including retrofits) in all European Sea regions, for the baseline fuel consumption projection

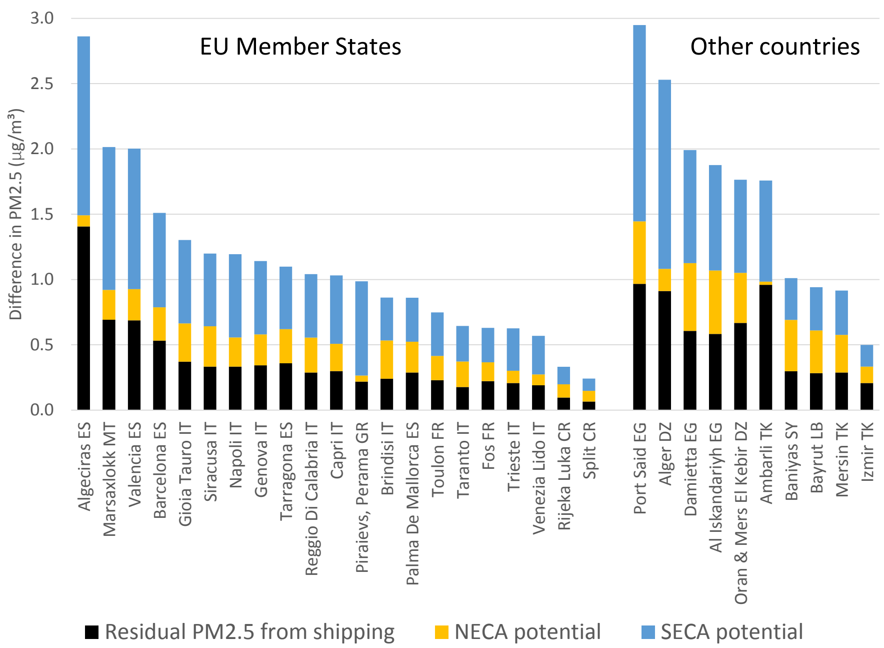


Figure A- 5: Reductions of ambient PM2.5 concentrations in port cities from SECAs and NECAs in the Mediterranean in 2050 (concentrations averaged across the 28*28km grid cell that contains the port city)

The air quality improvements of further ship emission controls could save up to 15,000 cases of premature deaths annually

The emission controls examined in this report could avoid up to 15,000 cases of premature deaths annually, about one third of them in the EU-Member States, and 50 percent in North Africa and the Middle East (Figure A-6). Until 2030, sulphur controls that can be introduced in the short term offer the largest potentials for fast improvements, and 40 percent of the full potential of the SECAs could be obtained with measures in the 12 nm zones. Tier III standards for NO_x will unfold their full benefits in the longer term, and could double the health benefits by 2050.

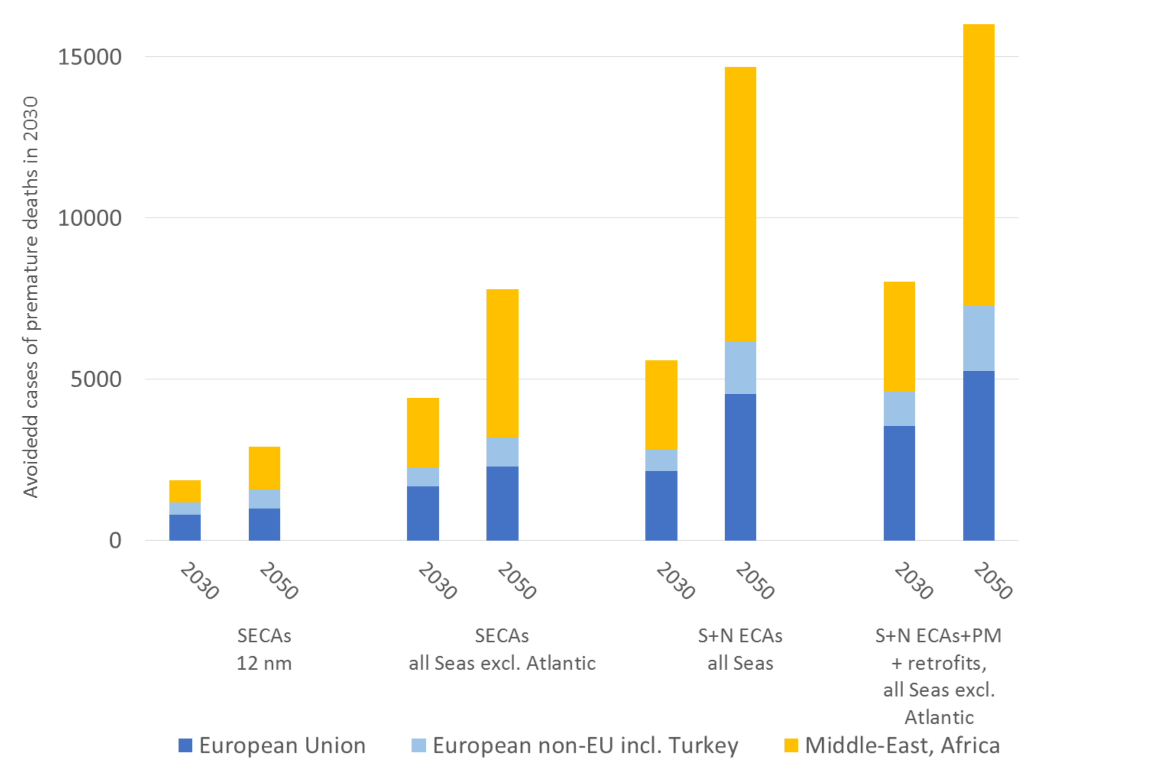


Figure A-6: Avoided cases of premature deaths from the control of shipping emissions in all European Seas in 2030 and 2050

Benefits of further emission controls for international shipping outweigh the costs by a wide margin

A comparison of costs and monetized benefits of further emission controls for international shipping clearly shows that benefits outweigh the emission control costs by a wide margin for all examined variants of policy interventions, scenario trends, assumptions on cost data and benefits evaluation methods. On average, the monetized benefits exceed costs by a factor of 6 in 2030 (Figure A-7) and by a factor of 12 in 2050.

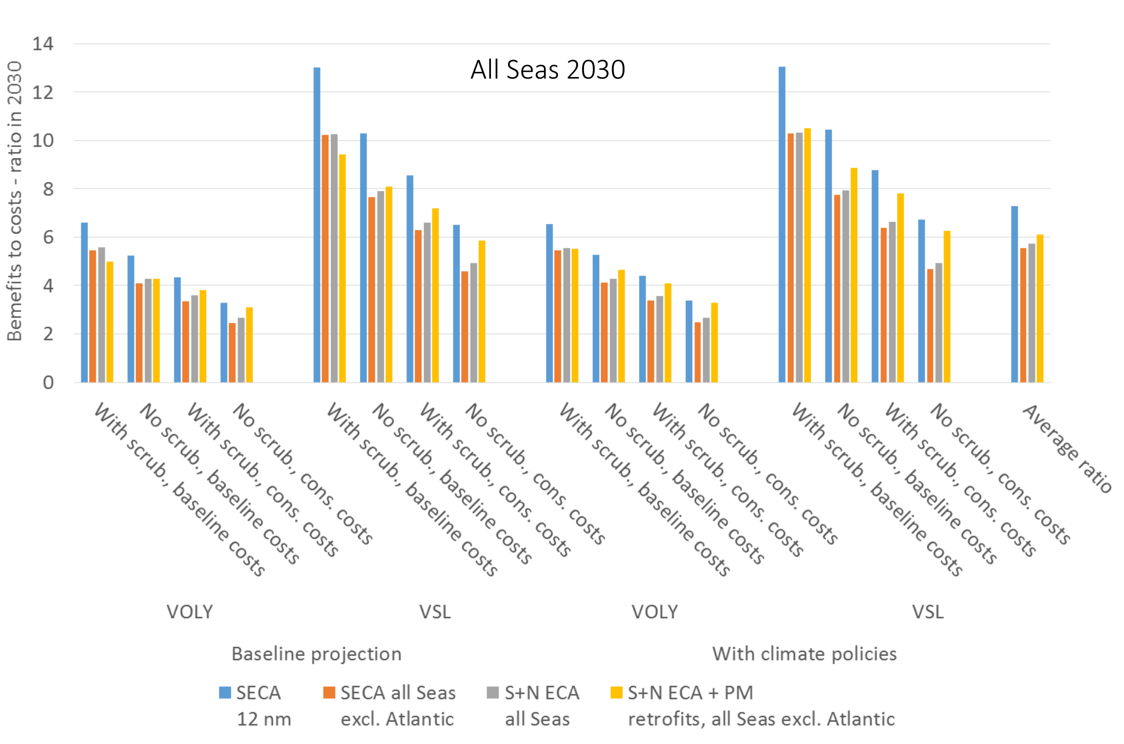
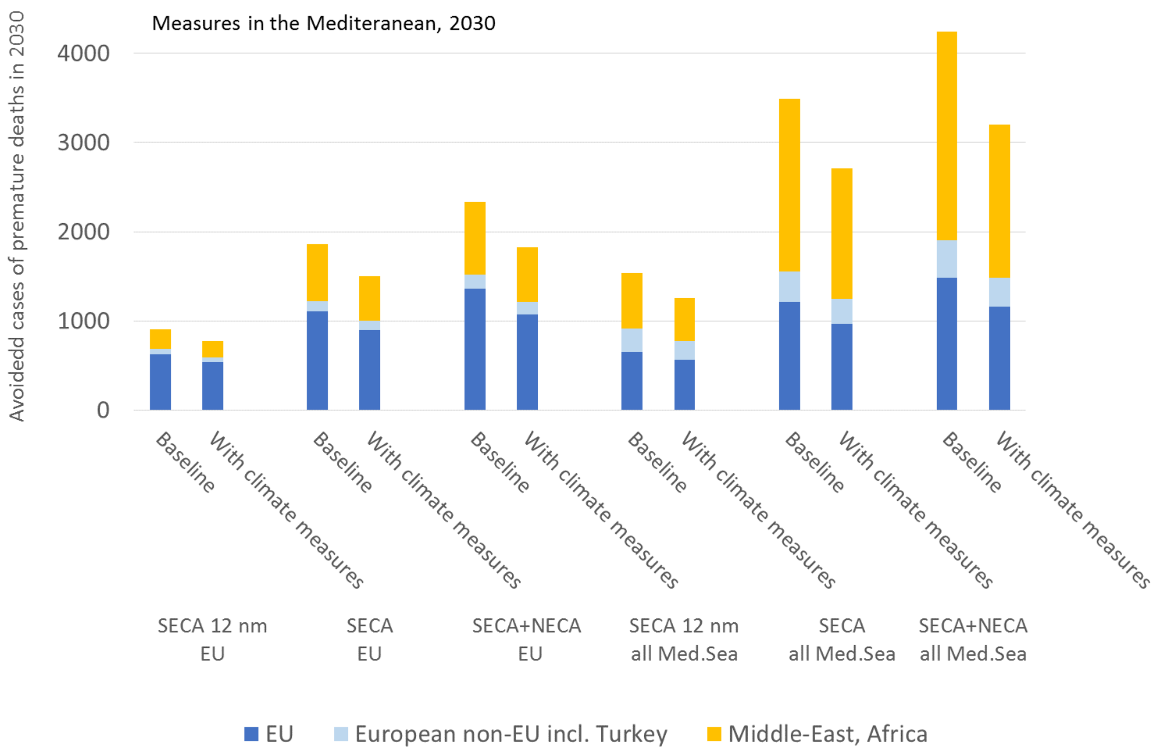


Figure A-7: Benefits-to-costs ratios for the emission control scenarios for all European Seas, 2030 (VSL – Value of Statistical Life; VOLY –Value of Life Year)

An ECA designation of the Mediterranean Sea could very cost-effectively save more than 4,000 cases of premature deaths annually already by 2030

Designation of the Mediterranean Sea as an ECA could by 2030 cut emissions of SO_2 and NO_x from international shipping by 80 and 20 percent, respectively, compared to current legislation. These additional emission reductions could avoid 4,100 cases of premature deaths in 2030 (Figure A- 8) and more than 10,000 annual premature deaths in 2050.

Figure A- 8: Avoided cases of premature deaths from the control of shipping emissions in the Mediterranean Sea in 2030



Even with the most conservative assumptions for health valuation, monetized benefits are on average 4.4 times higher than the costs in 2030 and 7.5 times higher in 2050.

Contents

List of acronyms

BC	Black carbon
ECA	Emissions Control Area
EMEP	European Monitoring and Evaluation Programme
IMO	International Maritime Organization
kt	kiloton = 10^3 tons
MARPOL	International Convention for the Prevention of Pollution from Ships
NECA	NO_x Emission Control Area (NO_x-ECA)
NH_3	Ammonia
nm	nautical mile
NO_x	Nitrogen oxides
PM2.5	Fine particulate matter with an aerodynamic diameter of less than 2.5 µm
REMPEC	Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea
SECA	SO_2 Emission Control Area (SO_x-ECA)
SO_2	Sulphur dioxide

The potential for cost-effective air emission reductions from shipping through designation of further Emission Control Areas in EU waters with focus on the Mediterranean Sea

1 Introduction

1.1 Context

In 2013, the European Commission adopted the Clean Air Programme for Europe, with specific measures to achieve the existing air quality targets as soon as possible, and proposals for additional legislation to reduce harmful emissions. In 2016, national emission ceilings for six air pollutants have been adopted in the National Emission Ceilings Directive (OJ L344/1, 2016). These initiatives focused on land-based sources within the European Union, but they do not address emissions from the maritime sector, which contribute significantly to air pollution in port cities and coastal areas in Europe and the neighbouring regions.

For international shipping, the Sulphur in Fuel Directive (2016/802/EU) transposes the 2008 revision of the sulphur in marine fuel requirements of Annex VI to the Marine Pollution Convention (MARPOL 73/78) of the International Maritime Organization (IMO) into EU law. It establishes SO_x Emissions Control Areas (SO_x-ECAs) in the Baltic, the North Sea and the English Channel, with a limit on the sulphur content in marine fuels of no more than 0.10 percent as of 1/1/2015. In October 2016, the IMO decided to lower the global sulphur limit in marine fuels to 0.50 percent by 2020 for ships sailing outside the ECAs, and to designate the Baltic, the North Sea and the English Channel as NO_x–Emission Control Areas (NO_x-ECAs, NECA in this study) as of 2021, introducing strict (Tier III) NO_x emission standards for new ships.

Given these recent policy agreements, there is interest to explore the balance between the stringencies of the current emission control regulations for land-based sources in the EU versus those for the shipping sector, and to explore the feasibility and potential impacts of further emission reduction initiatives for the maritime sector, for example through designations of additional ECAs in the Sea areas surrounding Europe, in particular in the Mediterranean Sea.

In addition, after completion of earlier studies which explored the costs and benefits of SECAs and NECAs in the Mediterranean Sea (Campling et al. 2013), new information has emerged on the quantities and locations of emissions from shipping, the likely trends of future land-based and shipping activities, and on compliance costs with recent legislation.

Recently the European Commission assessed the implementation of and compliance with the sulphur standards for marine fuels (EC 2018). It was found that the stricter standards – 0.10 percent S in SO_x-ECAs or SECAs in the North Sea and the Baltic Sea – delivered an important decrease of sulphur deposition in coastal zones of riparian states and improved air quality. Implementation of the NECA from 2021 will further improve air quality in these regions. The global sulphur standard of 0.5 percent sulphur content in marine fuel from 2020 will decrease negative impacts from shipping in coastal zones of non-SECA Seas. The Commission will continue to consider the potential for further reducing air pollution from ships, potentially also including other pollutants than SO_2.

1.2 Objectives of the report

This report aims to inform discussions at the international and regional levels on the health benefits and associated costs of designating additional Emission Control Areas (both for SO_2 and NO_x emissions) in the European Seas other than the Baltic and North Seas.

For this purpose, this report:

- updates the projections of the likely development of maritime transport activities,
- provides new assessments of costs of compliance with current legislation,
- improves the understanding of the role of emissions from vessels in ports, and the options for reducing these emissions,
- develops new scenarios of future emissions that would result from different policy interventions, including additional ECAs in the Mediterranean Sea and other European Sea regions,
- assesses their impacts on ambient air quality and resulting population exposure, and
- estimates the associated benefits to human health, and quantifies these benefits in monetary terms.

Importantly, by employing the same methodologies and models that have been used for the Impact Assessment and the underlying reports of the 2013 Clean Air Policy Package (EC 2013) and, most recently, for the Clean Air Outlook of the European Commission (Amann et al. 2017), results are directly comparable with the above-mentioned studies.

1.3 Structure of the report

Section 2 provides a brief introduction to the approach of this study and the tools that have been used for the analyses. The starting point of the assessment is an updated inventory of emissions from maritime activities in 2015, which is described in Section 3. Subsequently, Section 4 explores the future impacts of a range of alternative emission regulations (e.g., SECAs and NECAs) in various Sea regions on emissions of PM2.5 precursors, i.e., SO_2, NO_x, primary PM2.5 and black carbon (BC). Costs of these emission controls are discussed in Section 5, and their impacts on ambient air quality in Section 6. Section 7 quantifies the health benefits of these emission control variants in terms of premature deaths and estimates the associated monetized benefits. These monetized benefits are compared against the emission control costs in Section 8. Section 9 summarizes the findings and presents conclusions from the analyses.

2 Approach, method and tools employed for this study

2.1 Approach

This study explores the impacts of alternative emission control interventions for international shipping on the European Seas on relevant air pollutant emissions, examines their consequence on ambient air quality in Europe and the neighbouring regions, and explores the resulting improvements of human health. It estimates the costs of the various policy interventions, and compares them with monetized benefits of human health improvements and other impacts. For this purpose, the study develops alternative emission control scenarios with different assumptions on the spatial scope, stringency and timing of the introduction of specific emission controls. It employs a suite of well-established modelling tools to estimate for each of these scenarios the changes in emissions and the resulting impacts on air quality and human health, and to determine the costs of measures and the benefits in monetary terms.

2.2 Modelling tools

As a central tool, this report employs the GAINS (Greenhouse gas – Air Pollution Interactions and Synergies) model (Amann et al. 2011) developed by the International Institute for Applied Systems Analysis (IIASA). To distinguish the impacts of measures in various Sea regions (see Section 2.3) on population exposure to ambient PM2.5 concentrations across Europe and North Africa, the GAINS calculations were complemented by more detailed computations with MET Norway's EMEP atmospheric chemistry-transport model (Simpson et al. 2012). Subsequently, EMRC's ALPHA-RiskPoll model (Holland et al. 2013) provided full benefit analyses, with detailed estimates of all benefits that can be monetized. By employing the same methodologies and models that have been used for the Impact Assessment and the underlying reports of the 2013 Clean Air Policy Package (EC 2013) and, most recently, for the Clean Air Outlook of the European Commission (Amann et al. 2017), results are directly comparable with the above-mentioned studies.

2.3 Sea regions and zones distinguished in this study

The study distinguishes shipping emissions and air quality impacts in eight Sea regions around Europe (Figure 1). Each of these regions is subdivided into four zones, i.e., (i) ports and berth activities, (ii) within internal waters and the territorial Seas (12 nm from the internal waters boundary), (iii) within the exclusive economic zones (200 nm from the internal waters boundary), and (iv) outside the exclusive economic zones (high Seas). Where applicable, EU and non-EU waters are addressed separately (see Annex 1).

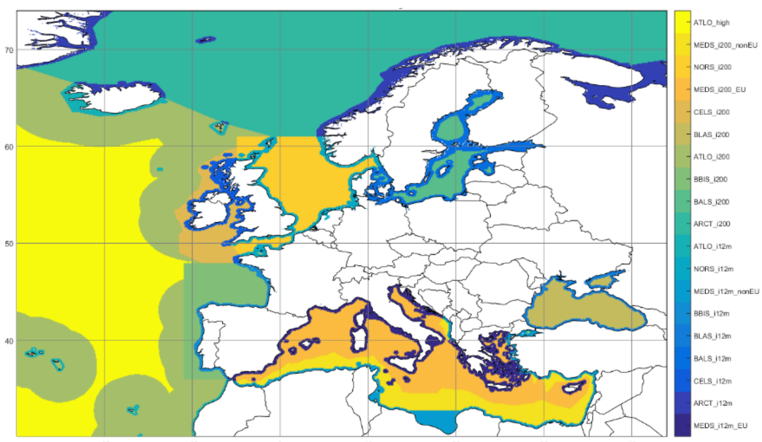


Figure 1: Emission source regions distinguished in this study. Definitions of the zones are provided in Annex 1.

3 An inventory of shipping emissions in 2015

As a starting point for the analyses of the effectiveness of further emission controls, a spatially resolved inventory of shipping emissions was compiled for the year 2015 that (i) takes into account most recent statistical data and information on emission factors, (ii) distinguishes the different categories of vessels to the extent that these are relevant for emissions and emission controls, and (iii) considers the Sea regions and zones defined in Section 2.3.

Emissions of air pollutants have been estimated based on the gridded inventory of CO_2 emissions (by vessel type) developed with the STEAM 3 model by the Finnish Meteorological Institute (Johansson et al. 2017), which employed AIS (Automatic Identification System) activity data for the year 2015. Assuming representative emission factors for CO_2, underlying fuel consumption volumes have then been derived for each of the 28 zones. For further analysis, the 11 vessel categories of the STEAM 3 model have been aggregated into seven types of ships: cargo, container, passenger vessels, RoPax, tankers, vehicle carriers, and others (fishing vessels, service ships, miscellaneous, and other/unknown vessels).

While the STEAM3 inventory includes data for all ship movements, regulations and reporting requirements are different for international shipping and for seagoing ships travelling between ports in the same country. EU emission regulations apply to the latter category, and countries have to report these emissions as part of their national emission inventories. In order to avoid double counting of emissions, fuel volumes used for national shipping have been estimated and subtracted from total fuel consumption, so that the resulting data represent the best estimates for international shipping (see Annex 2).

3.1 Fuel consumption

In 2015, fuel consumption by vessels operating in European Seas amounted to about 1.8 EJ, which corresponds to about 20 percent of the total diesel fuel consumption for road traffic in the EU-28. About 40 percent of the fuel was consumed in the Mediterranean Sea, 20 percent in the North Sea, and about 10 percent in the Gulf of Biscay, the Baltic Sea and the North East Atlantic (within the study domain), respectively (Figure 2). About one third of all fuel was consumed by container ships, 22 percent by tankers and 19 percent by cargo ships.

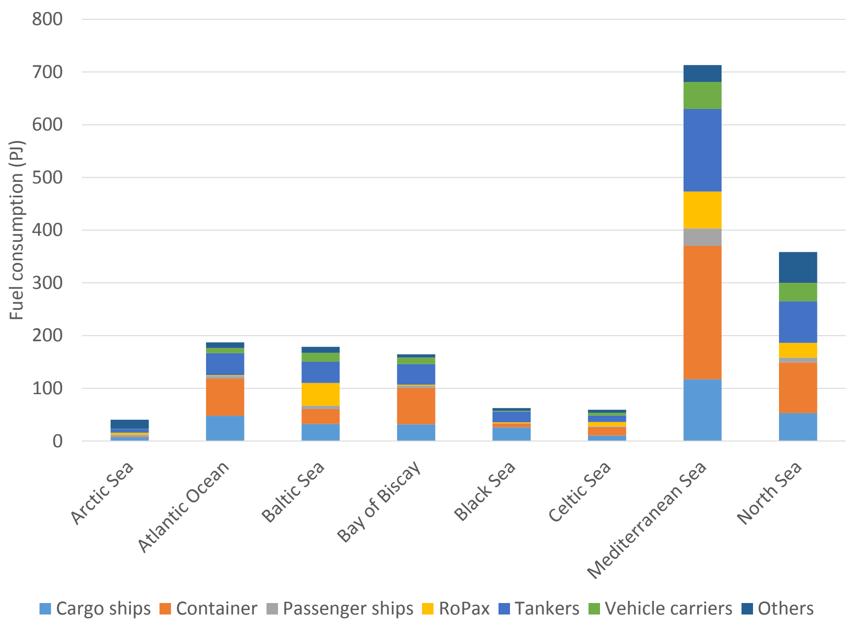


Figure 2: Fuel consumed by international shipping in 2015

3.2 Emissions in 2015

It is estimated that international shipping in Europe caused emissions of about 134 million tons of CO_2, 1,230 kt of SO_2, 2,830 kt of NO_x and 175 kt PM2.5. These quantities compare to 3.6 percent of land based CO_2 emissions in the EU-28, 44 percent of land-based SO_2, 36 percent of NO_x emissions, and 13 percent of PM2.5 emissions (Figure 3; tables are provided in Annex 2). Based on these data, gridded emissions have been computed for SO_2, NO_x and PM2.5 for the various vessel types.

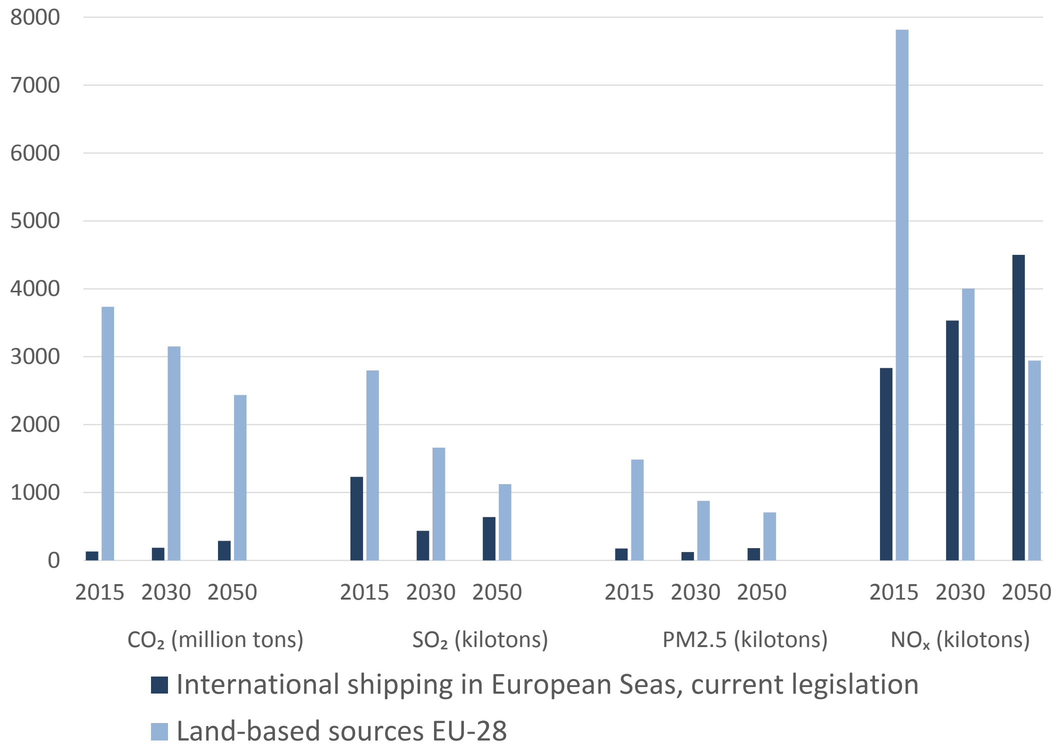


Figure 3: Emissions from maritime shipping in the European Seas and from land-based sources in the EU-28

The largest share of emissions emerges from container ships, followed by tankers and cargo ships (Figure 4).

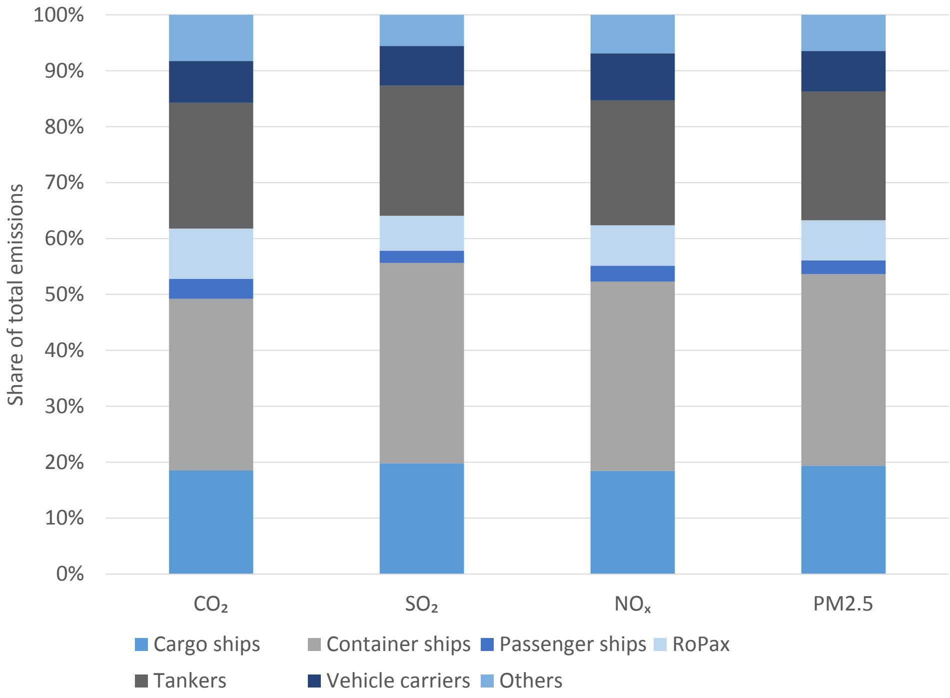


Figure 4: Emissions from international shipping in 2015, by vessel type

The spatial pattern of NO_x emissions mirrors closely the fuel consumption volumes, while for SO_2 and PM the emission controls in the SECA regions (Baltic Sea and the North Sea) cause large differences. Up to 57 percent of all emissions from international shipping in Europe occur in the Mediterranean Sea (Figure 5).

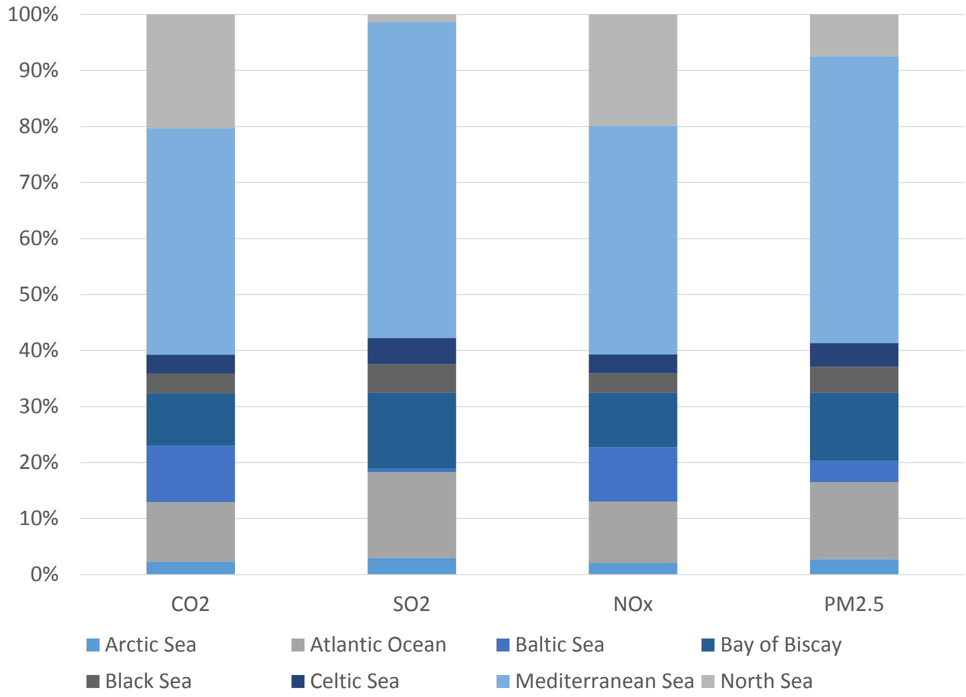


Figure 5: Emissions from international shipping in 2015, by Sea region

Up to one third of emissions is emitted in the 12 nm zones along the coasts, and about two thirds in the adjacent 200 nm zones, most of which in dedicated shipping corridors in variable distances to the coast. Berth or in ports activities account for only a few percent of all emissions from international shipping. In the Mediterranean Sea, about two thirds of emissions originate from the EU waters (Figure 6).

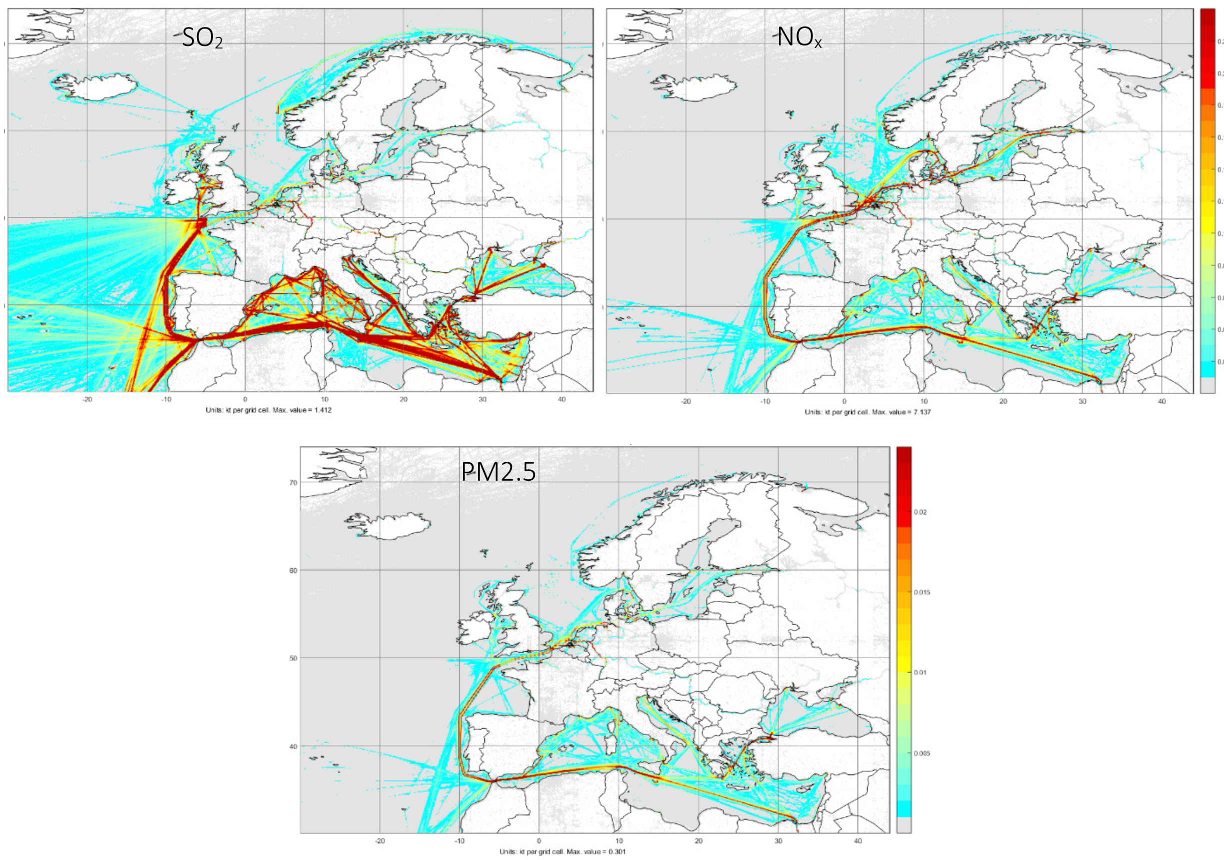


Figure 6: Gridded emissions of SO_2 and NO_x (upper panel) and PM2.5 (lower panel) in 2015, kt

3.3 Comparison with other inventories

In general, the emission estimates developed for this study compare rather well with the FMI inventory for 2015 (Johansson et al. 2017), which is not surprising given that the gridded FMI inventory for CO_2 was taken as the starting point for this analyses. Differences (less than 7 percent for fuel consumption and lower than 3 percent for SO_2 emissions) are explained by different estimates for national Sea traffic.

Also, for comparable domains, the estimated fuel consumption data are in close agreement (±2 percent) with the statistics developed by the European Maritime Safety Agency (EMSA), which were derived from recorded ship movement data. The EMSA inventory does not include the Atlantic and Arctic Oceans, which prohibits a complete comparison. However, notable differences for some Sea regions need further clarification.

The good agreements of the fuel consumption data are reflected by the NO_x estimates, and the differences to earlier studies are mainly explained by new information on emission factors. More details are provided in Annex 2.

4 Scenarios of future emissions

To explore the costs, health impacts and monetary benefits of additional controls of maritime emissions, this report develops a range of alternative scenarios of future emissions for different assumptions on the evolution of fuel demand, climate policies and emission controls.

4.1 Projections of fuel demand

Two alternative projections explore the interplay between the growth in shipping activities, trends in energy efficiency improvements, and climate policies. A baseline projection extrapolates current trends in economic growth, trade relations and fuel efficiencies, while a ‘with climate measures’ scenario illustrates the potential consequences of greenhouse gas reduction policies for maritime activities, and their knock-on effects on air pollutant emissions.

For these scenarios, future fuel consumption trends up to 2030 are derived from the ‘business as usual’ and ‘climate policy’ scenarios developed by COWI, CENIT and VITO (EC 2015), and follow thereafter the corresponding growth rates assumed in the 3rd IMO Greenhouse Study (Smith et al. 2015). With these assumptions, total fuel consumption for international shipping on European Seas increases in the baseline case from 1.8 EJ in 2015 to about 4.1 EJ in 2050. In contrast, with climate measures fuel consumption volumes would stabilize at a level below 2.0 EJ after 2030 (Figure 7). Notably, with a 5 percent increase of CO_2 emissions in 2050 relative to 2015, this ‘with climate measures’ scenario falls significantly short of the ambition of the 2018 IMO agreement reached at the MEPC 72 meeting, i.e., to reduce shipping's greenhouse gas emissions by at least 50 percent by 2050 (IMO 2018). Details are provided in Annex 3.

Trends vary across different vessel types, based on the projections developed by (Winnes 2015; Smith et al. 2015; Åström et al. 2018). These suggest a rapid expansion of container and dry cargo traffic, while for oil tankers, passenger vessels and other vessel types much lower increases or even declines are projected. This will lead to a distinct shift in the relative shares of different vessel types. By 2050, container ships would consume 48 percent of all fuel in the baseline case and 38 percent in the ‘with climate policy’ case, compared to 31 percent in 2015. Shares of other vessel types (e.g., tankers) are expected to decrease accordingly (Figure 7).

It is expected that liquefied natural gas (LNG) will play a greater role as a marine fuel, although the exact penetration rate remains open due to uncertainties about fuel supply infrastructure, LNG prices, and investment costs for vessels. This study adopts the global LNG trend of the NPS scenario of the IEA World Energy Outlook 2017 (IEA 2017), assuming that Europe will maintain its share in total global LNG use (11 percent) that has been projected for 2025 by (CE Delft 2016). Thereby, the share of LNG in the total fuel demand at European Seas would increase from less than 2 percent in 2020 to about 5 percent in 2030 and nearly 12 percent in 2050.

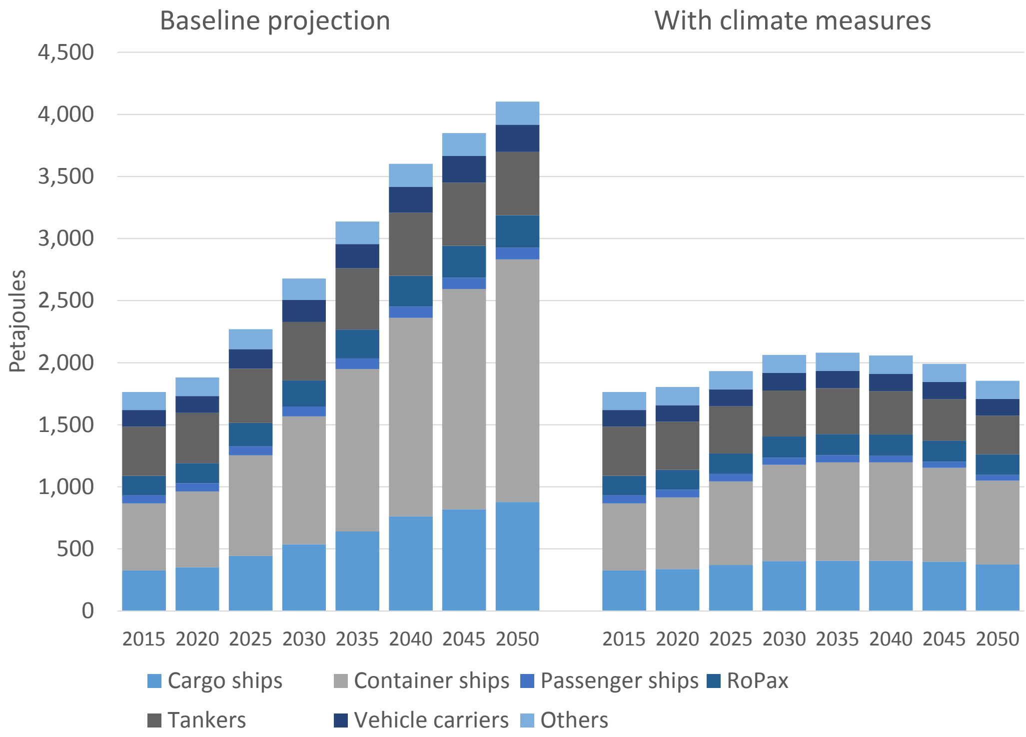


Figure 7: Assumed development of fuel consumption by vessel type

4.2 Emission controls

For the two projections listed above, this study develops three families of emission control scenarios:

- The **Current Legislation (CLE)** scenario illustrates the impacts of current policies and regulations for maritime emissions. In particular, it assumes full compliance with the IMO MARPOL Annex VI standards for fuel quality and for NO_x emissions. As of 2015, these required in the sulphur emission control areas (SECAs) in the Baltic Sea, North Sea and English Channel reductions of the sulphur content down to a limit of 0.1 percent. Fuels with higher sulphur content are allowed, but require flue gas desulfurization. From 2020 onwards, the sulphur content of marine fuels will be limited to 0.5 percent outside the SECAs. For national and international ships berthed and anchored in EU ports the sulphur content is limited to 0.1 percent by the EU Sulphur in Liquid Fuel Directive (2016/802/EU). In addition, vessels built after mid-2011 need to meet Tier II standards for NO_x emissions and, as of 2021, new vessels operating in NO_x emission control areas (NECAs) including the North Sea and Baltic Sea have to comply with Tier III NO_x emission standards. Corresponding emission factors are presented in Annex 4.
- Extended **SO_2 Emission Control Areas** (SECA) as of 2025, imposing a limit of 0.1 percent on the sulphur content of fuel (or equivalent emissions through scrubbers) for all vessels. The temporal introduction of scrubbers follows the assumptions of MECL, 2017 and IHS Markit, 2018 (see Annex 6). Variants

explore different target areas (12 mile zones only/all Sea regions/excluding the Atlantic Ocean outside the 12 nm zone).

- Extended **Tier III NO_x emission standards** as of 2025, for new vessels only (corresponding to the current requirements for NECAs) or including retrofits of existing vessels. Variants are computed for different Sea regions and earlier introduction (2021).

4.3 Emission projections

4.3.1 CO_2 emissions

With the quantitative assumptions described above, CO_2 emissions from international shipping increase in the baseline case by about 50 percent up to 2030 compared to 2015, and by a factor of 2.3 until 2050. In contrast, in the 'with climate measures' case they grow by 15 percent up to 2020, and decrease to the 2015 level thereafter (Figure 8). More than 40 percent of total CO_2 is emitted in the Mediterranean Sea.

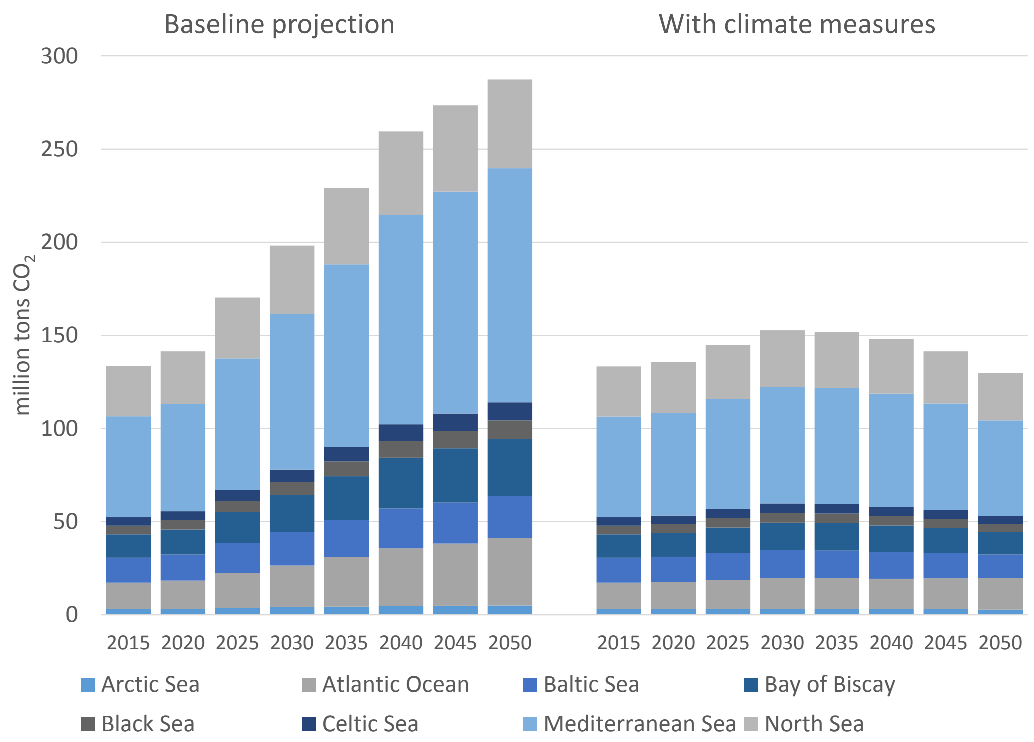


Figure 8: Emissions of CO_2 by Sea region, million tons

4.3.2 SO_2 emissions

Current legislation will lead to a clear decoupling of shipping volumes and SO_2 emissions, although future emission levels will be critically linked to the evolution of fuel consumption, which is likely to be strongly determined by greenhouse gas policies. In the baseline, fuel consumption is expected to grow by 50 percent in 2030 and 130 percent in 2050 relative to 2015. Current emission regulations will reduce SO_2 emissions in the European Seas by 65 percent in 2030 and by almost 50 percent in 2050 (Figure 9). Climate measures would effectively reduce fuel consumption and lead, as a side-effect, to a further decline of SO_2 emissions, by 73 percent in 2030 and by 78 percent in 2050. Declaration of all Sea regions as SECAs would cut SO_2 emissions in 2030 and beyond by 90-94 percent, depending on the ambition of climate measures.

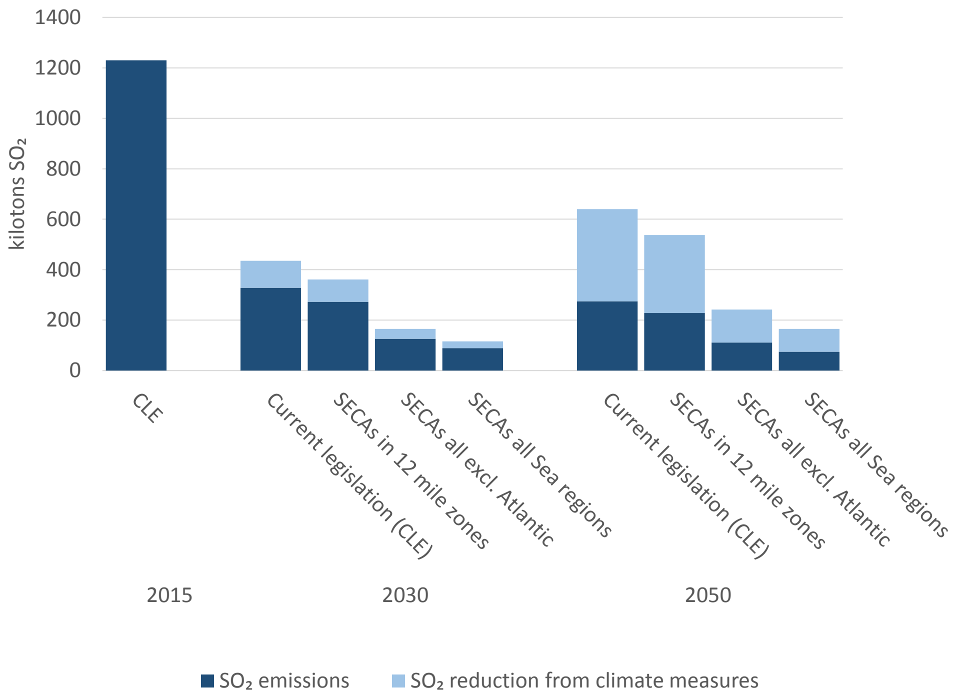


Figure 9: SO_2 emissions from international shipping in the European Seas, measures applied in all Sea regions. The total bars refer to the baseline case, while the light blue areas indicate the reduction from climate measures.

4.3.3 PM2.5 and BC emissions

The current emission standards will also affect trends of PM2.5 emissions, leading to 30 percent lower emissions in 2030, after which emissions rebound to current levels in the baseline in 2050. Greenhouse gas measures would decrease PM2.5 by about 50 percent as a side-effect (Figure 10).

An introduction of SECAs in all Sea regions would cut PM2.5 emissions further. They fall in the baseline case by about 45 percent until 2030. Thereafter, the continuing increase in traffic volumes lets PM2.5 grow again, but emissions will remain 25 percent below the 2015 level up to 2050. In contrast, SECAs combined with climate measures could cut PM2.5 emissions in 2050 by two thirds below today's level.

Installation of particle filters (PF) for ships could reduce PM2.5 emissions by up to 80 percent in 2030 and 97 percent in 2050.

As a side effect, emission controls for SO_2 will also influence trends of black carbon (BC) emissions, although to a lesser extent than those of PM2.5. In the baseline case, BC emissions grow after 2030 by up to 40 percent in 2050 (while fuel consumption is projected to increase by 130 percent). The climate measures would cut them by 37 percent in 2050 (Figure 11). SECAs and dedicated PM controls could deliver additional cuts, and reduce black carbon emissions by up to 87 percent in 2050.

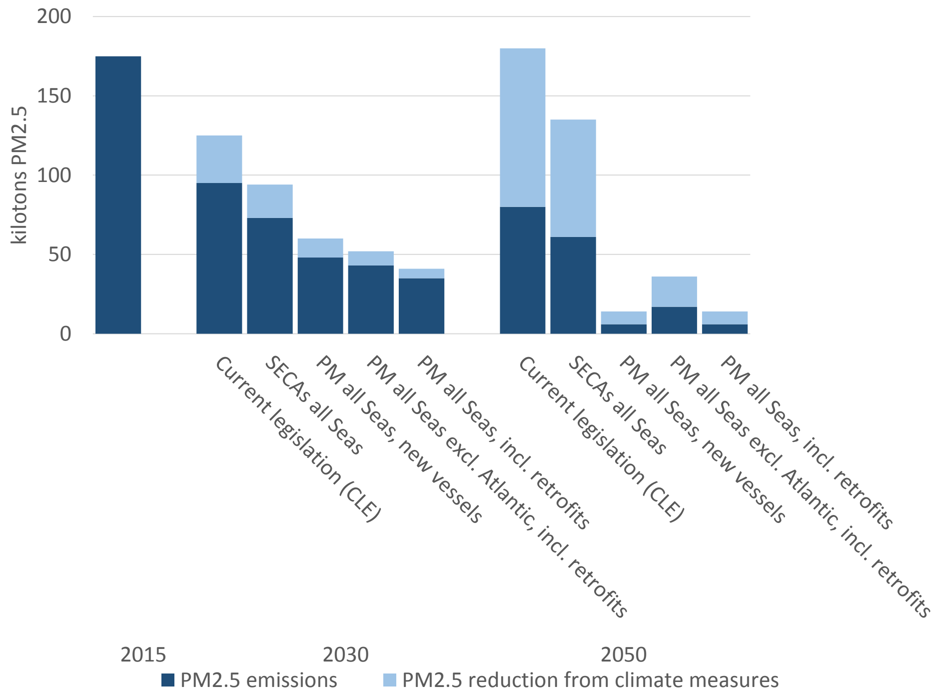


Figure 10: PM2.5 emissions from international shipping in the European Seas, measures applied in all Sea regions. The total bars refer to the baseline case, while the light blue areas indicate the reduction from climate measures.

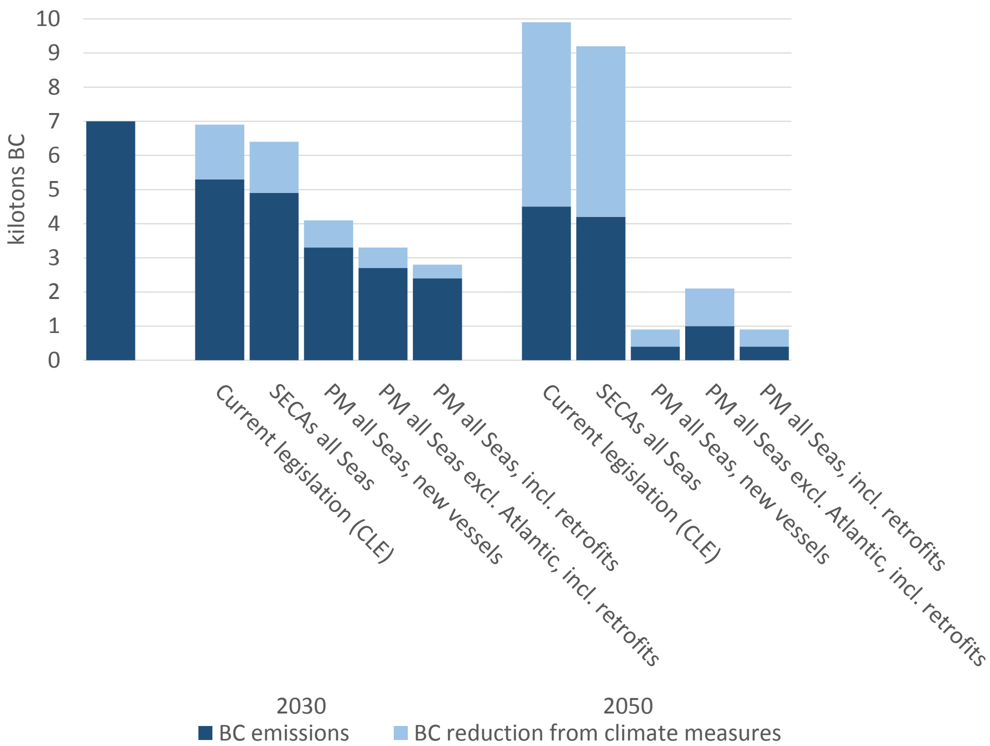


Figure 11: BC emissions from international shipping in the European Seas, measures applied in all Sea regions. The total bars refer to the baseline case, while the light blue areas indicate the reduction from climate measures.

4.3.4 NO_x emissions

For NO_x, current legislation will affect emissions at a slower pace, due to the fact that the IMO NO_x standards apply to new vessels only. Thus, the benefits of Tier III standards in the NECAs in the Baltic and the North Sea and of the Tier II standards in other Sea regions will be partly offset by expected increased fuel consumption in the baseline scenario. Thus, baseline NO_x emissions in the European Seas increase by 26 percent until 2030, and up to 60 percent by 2050. In contrast, the climate measures scenario stabilizes NO_x emissions in the European Seas in the coming decades, and reduces them by one third until 2050.

Larger emission reductions could be achieved through enhanced application of Tier III standards. If applied to all new vessels from 2025 onwards, NO_x emissions would not grow by more than five percent in 2030 in the baseline, and could decline by 16 percent if combined with greenhouse gas measures. Retrofitting vessels to Tier III standards would cut NO_x already in 2030 by 16-31 percent, depending on climate measures. Imposing these regulations from 2021 onwards would reduce NO_x emission by 22-36 percent in 2030.

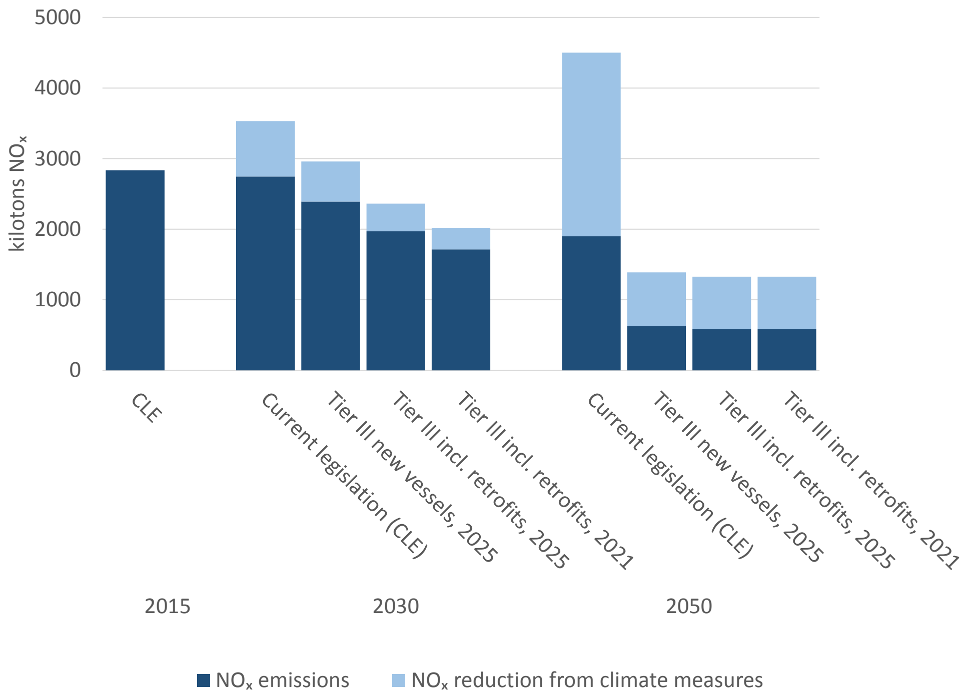


Figure 12: NO_x emissions from international shipping in the European Seas, measures applied in all Sea regions

4.4 Emissions in the Mediterranean Sea

While this assessment has been carried out for all European Sea regions (detailed results are presented in Annex 5), there is special interest in the potential impacts of emission controls in the Mediterranean Sea. For this purpose, the emission control variants introduced in Section 4.2 have been explored in details for four potential ECAs in the Mediterranean:

- Territorial waters (12 nm from coast) of EU countries
- Exclusive economic zones (12 - 200 nm from coast) of EU countries
- Territorial waters of all countries
- Exclusive economic zones of all countries (i.e., the whole Mediterranean).

A SECA in the 12 nm zones of EU Member States would reduce SO_2 emissions by about 15 percent compared to the baseline situation, and by 50 percent if extended to the 200nm zones of EU Member States. Applied to all coastal States in the Mediterranean, a 12 nm SECA would lead to about 25 percent lower emissions, and the 200 nm zone to 80 percent lower SO_2 (Figure 13).

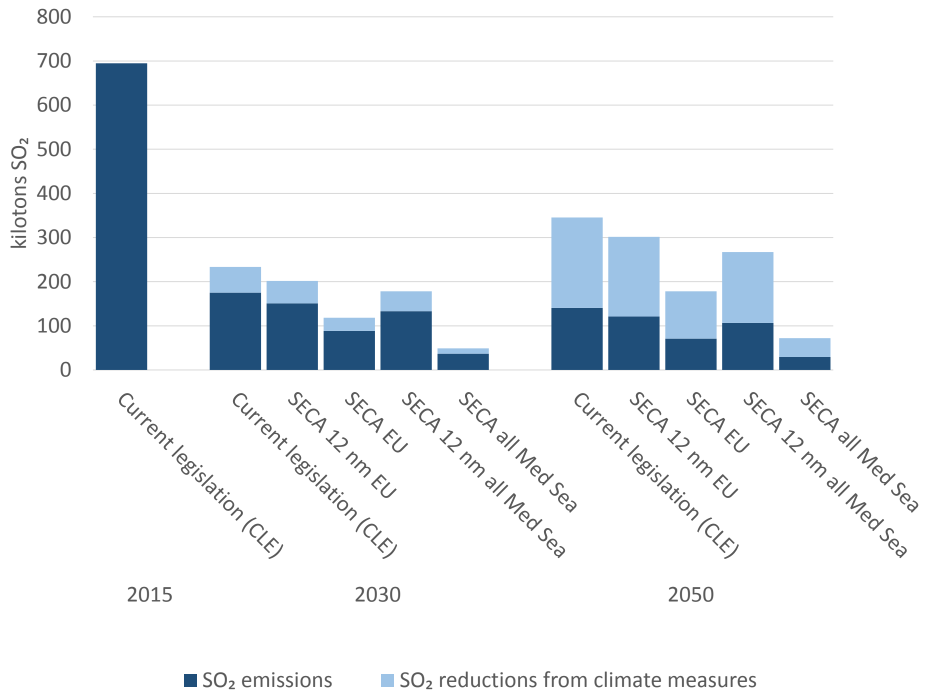


Figure 13: SO_2 emissions from international shipping in the European Seas, measures applied in the Mediterranean Sea

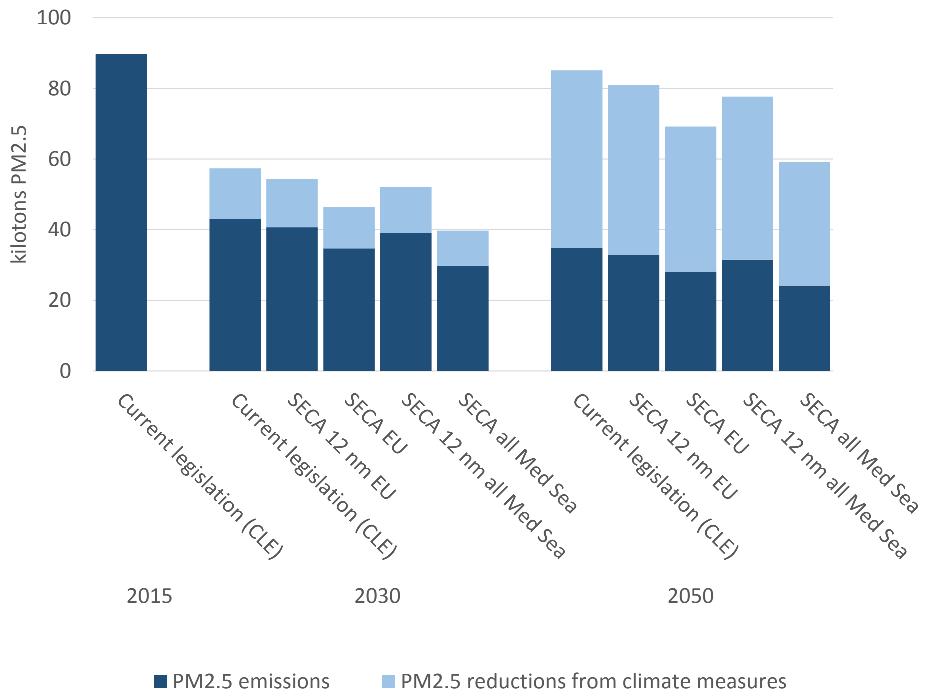


Figure 14: PM2.5 emissions from international shipping in the European Seas, measures applied in the Mediterranean Sea

The lower sulphur content will also reduce PM2.5 emissions, by 5 percent and 20 percent for the 12 nm and 200 nm zones of EU countries, respectively, and by 10 percent and 30 percent if applied in all coastal countries (Figure 14).

Declaration of the whole Mediterranean Sea as a NECA in 2025 would reduce NO_x emissions by 17 percent in 2030, of which 10 percentage points are achieved in EU waters. A NECA declaration in 2021 would increase the emission reduction to 28 percent in 2030 (17 percentage points in EU waters). By 2050, NO_x reductions increase to about 46 percent for a NECA in EU waters, and to 73 percent for the whole Mediterranean Sea (Figure 15).

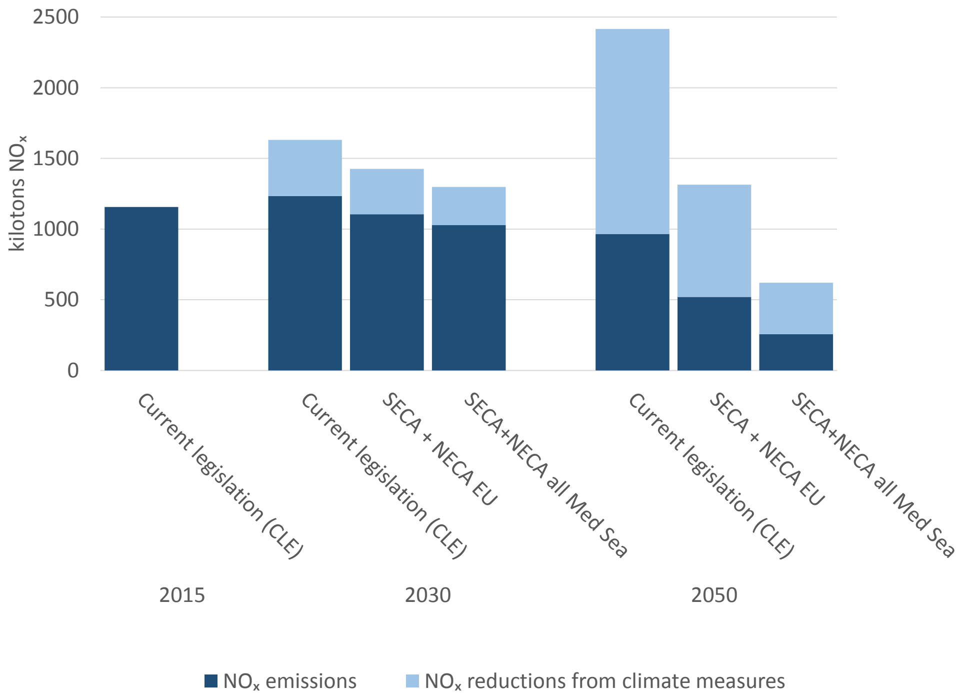


Figure 15: NO_x emissions from international shipping in the European Seas, measures applied in the Mediterranean Sea

5 Emission control costs

As an input for the assessment of costs and benefits of additional emission controls for international shipping, this study assesses, for each of the scenarios presented above, the costs for implementing the emission reduction measures. These estimates have been derived with IIASA's GAINS model (Amann et al. 2011) based on data about technologies and costs from literature sources. Methodology and data used for the cost calculation are presented in Annex 6.

The evaluation of emission control costs in the future will critically depend on a number of factors that are hard to predict. These include the stringency of future climate policy measures, which will determine the future volumes of fuel consumption and thus the need for emission controls. In addition, SO_2 control costs depend heavily on the future price premium for low sulphur marine fuels on the world market, as well as on the penetration rates of sulphur scrubbing. The developments of both factors are uncertain, and there are likely strong connections between the price premiums and the penetration of scrubbing. With the fuel price premiums that have been presented in (MECL 2017; IHS Markit 2018), sulphur scrubbing appears as a competitive option for meeting the SO_2 emission standards (see Annex 6).

5.1 Measures in all European Seas

Assuming the penetration schedule as listed in Annex 6, costs for implementing the current legislation for SO_2 are estimated between 4.0 and 3.1 billion €/yr in 2030, for the baseline and 'with climate measures' cases, respectively. By 2050, they would decline to 3.7 billion €/yr in the baseline, and to 1.8 billion €/yr with climate measures. Without scrubbers, baseline costs would increase to 4.7 billion €/yr in 2030 and to 7.0 billion €/yr in 2050. Lower fuel consumption from climate measures reduces emission control costs to 3.7 billion €/yr in 2030 and to 3.2 billion €/yr in 2050. Details are presented in Annex 6.

In a sensitivity analysis with the assumptions on the fuel price premiums taken from the recent REMPEC study (by EERA/FMI 2018), costs would increase to 7.0 billion €/yr ('with climate measures') and to 9.1 billion €/yr (baseline) in 2030, and to 2.8 – 6.0 billion €/yr in 2050. About 40 percent of these costs are linked to the SECAs in the Baltic and the North Sea.

An extension of the SECA regulations to all European Seas would entail additional costs of 1.2 billion €/year (baseline) and 0.9 billion €/year ('with climate measures').

For NO_x, emission control costs for current legislation range between 0.18 and 0.24 billion €/year in 2030 and 0.35-0.69 billion €/year in 2050, for the baseline and the 'with climate measures' cases, respectively. Additional costs for Tier III for all new vessels from 2025 onwards amount to 0.1-0.17 billion €/year in 2030, and 0.44-1.06 billion €/year in 2050. With retrofits of existing vessels to Tier III, additional costs (on top of current legislation) increase to 0.46-0.69 billion €/year in 2030, and to 0.47-1.11 billion €/year in 2050 (Annex 6).

Introduction of particle filters (including retrofits) would require 0.21-0.39 billion €/year in 2030 and 0.21-0.50 billion €/year.

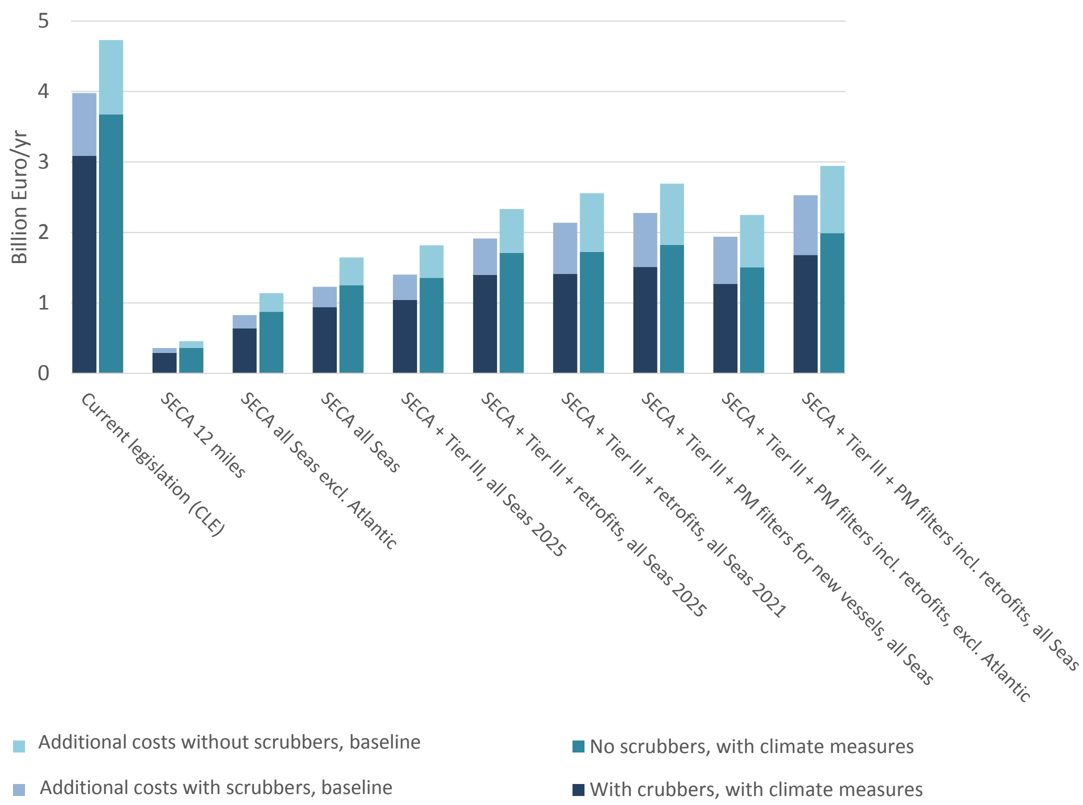


Figure 16: Current legislation emission control costs in 2030 and incremental costs for additional ECA scenarios.

5.2 Measures in the Mediterranean Sea

For 2030, costs for SECAs in the 12 mile zones of the EU Member States are estimated between 146 and 176 million €/yr, depending on the climate policy measures and assuming penetration of scrubbing. Without scrubbers, estimates increase to 179-219 million €/yr. SECAs in all 12 mile zones in the Mediterranean would increase costs by about 50 percent, while a SECA covering the entire Mediterranean would triple costs.

For 2050, the costs for SECAs for the 12 mile zones of the EU Member States decrease to 76-110 million €/yr (with scrubbing), depending on the climate policy measures. Without scrubbers, estimates range between 150 and 271 million €/yr.

Costs of applying Tier III NO_x standards in the EU economic zones range between 60 and 90 million €/year in 2030, and between 90 and 140 million €/year if applied to the entire Mediterranean (see Annex 5). For 2050, costs are estimated at 210-464 million €/yr for the EU economic zones, and at 316-738 million €/yr for the entire Mediterranean.

6 Ambient air quality

The policy measures to reduce emissions from international shipping on European Seas will have impacts on air quality and subsequently on human health. To this end, IIASA's GAINS model, complemented by more detailed calculations with the latest version of the EMEP atmospheric chemistry and transport model by the Norwegian Meteorological Institute (Simpson et al. 2012) has been used to estimate the decrease in ambient concentrations of PM2.5 across Europe and along the Mediterranean coast, as well as the impacts on population exposure in the various countries. Human exposure to PM2.5 has been chosen as the most relevant health impact indicator, due to the strong epidemiological evidence on its association with premature mortality. Note that lower primary emissions of PM2.5 will have direct impact on ambient PM2.5 levels. In contrast, the impacts of lower SO_2 and NO_x emissions on ambient PM2.5 occur through chemical reactions with NH_3 that form secondary PM2.5 aerosols, i.e., ammonium sulphate and ammonium nitrate. The EMEP atmospheric chemistry and transport model simulates these reactions, which depend *inter alia* on the availability of NH_3 (ammonia) in the atmosphere.

6.1 Ambient concentrations of PM2.5

In general, the emission reduction scenarios show largest effects along the coast of Mediterranean countries, and in particular along the North African coast. Here the concentrations of PM2.5 decrease by up to 1.2 µg/m^3 in 2030 (Figure 17) and up to 1.5 µg/m^3 in 2050 (Figure 18). Biggest improvements emerge for extended SECAs; NECAs deliver lower reductions, especially in the short run and when the introduction of Tier III standards is limited to new vessels only.

In the Mediterranean, tighter sulphur standards deliver the largest air quality improvements along the coast line (upper panel in Figure 19 and Figure 19). Also here, the benefits of Tier III standards are limited, especially in 2030 when only a small share of the fleet will be affected (lower panels in Figure 19 and Figure 19).

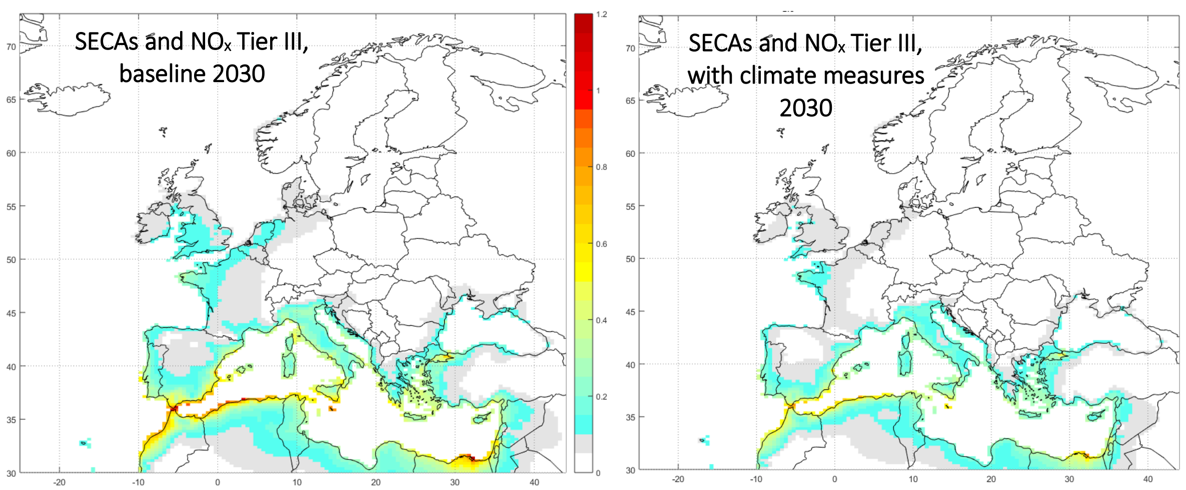


Figure 17: Decrease of ambient PM2.5 concentrations (µg/m^3) in 2030 from implementation of SECAs and Tier III standards for NO_x (including retrofits) in all European Sea regions, for the baseline case (left panel) and the scenario with climate measures (right panel)

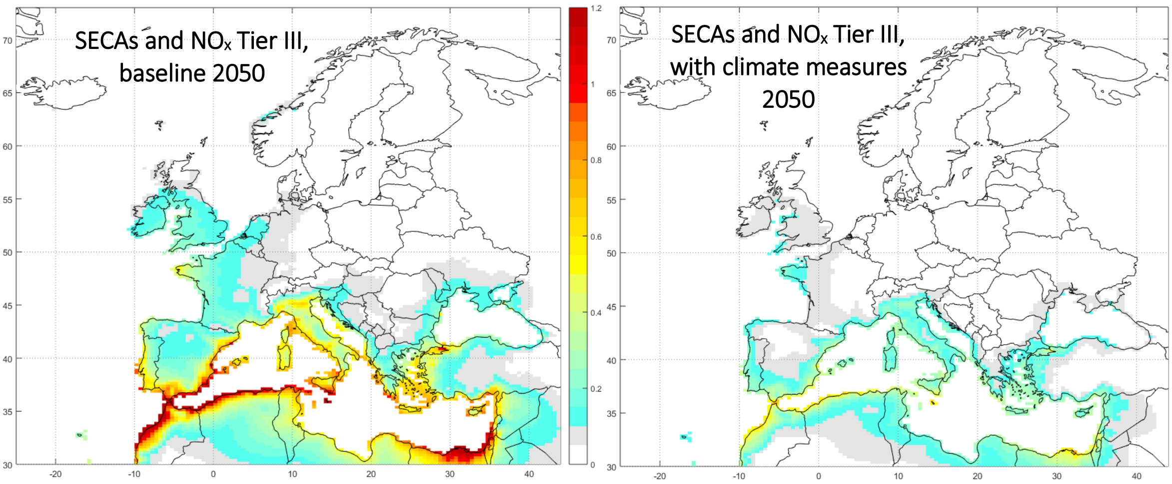


Figure 18: Decrease of ambient PM2.5 concentrations (μg/m^3) in 2050 from implementation of SECAs and Tier III standards for NO_x (including retrofits) in all European Sea regions, for the baseline case (left panel) and the scenario with climate measures (right panel)

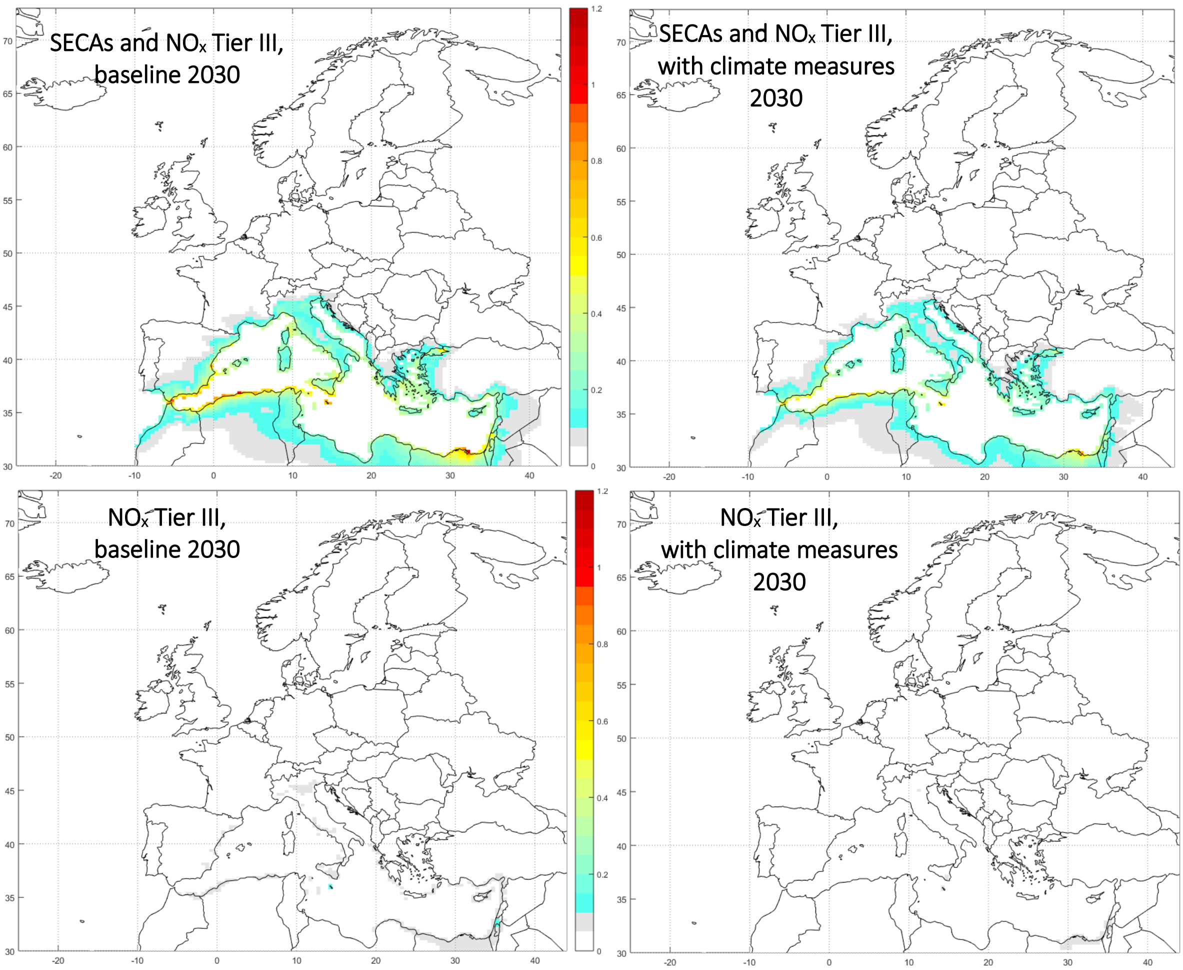


Figure 19: Decrease of ambient PM2.5 concentrations (μg/m^3) in 2030 from implementation of SECAs (upper panels) and Tier III standards for NO_x including retrofits (lower panels) in the Mediterranean Sea, for the baseline case (left panel) and the scenario with climate measures (right panel)

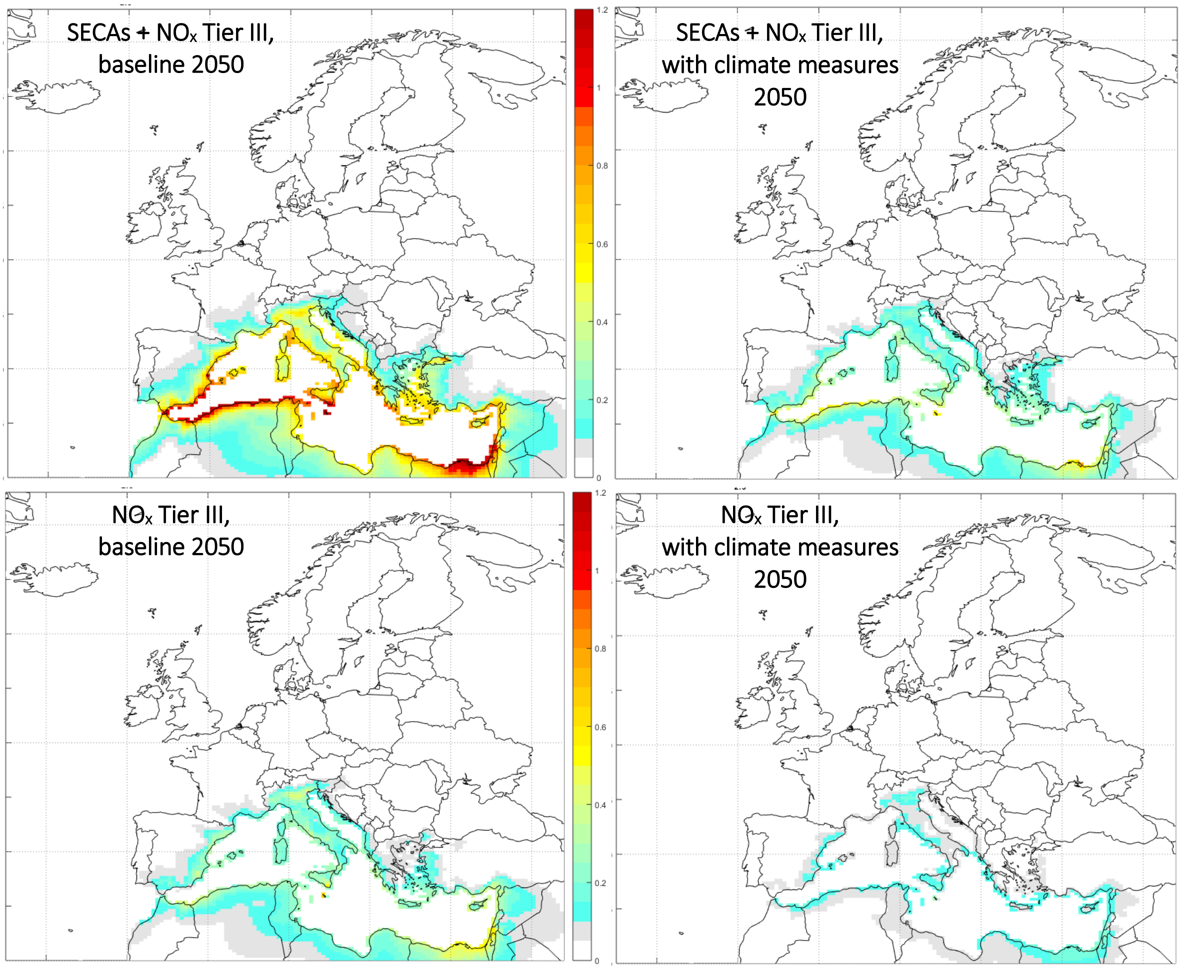


Figure 20: Decrease of ambient PM2.5 concentrations (μg/m^3) in 2050 from implementation of SECAs (upper panels) and Tier III standards for NO_x including retrofits (lower panels) in the Mediterranean Sea, for the baseline case (left panel) and the scenario with climate measures (right panel)

Air quality impacts from emission controls for international shipping are largest along the coast. Almost half of the EU's population lives less than 50 km from the Sea, and within the model domain approximately 23 percent within a 30 km distance to the coast (27 percent in the EU-28, 16 percent in other European countries, and 24 percent in Africa and Middle East). Especially large impacts of shipping emissions, and subsequently of emission controls, occur in port cities, for which the contributions from shipping to ambient PM2.5 levels estimated in this study (typically between 5 and 15 percent in 2015; Figure 21) align well with other assessments (Viana et al. 2014).

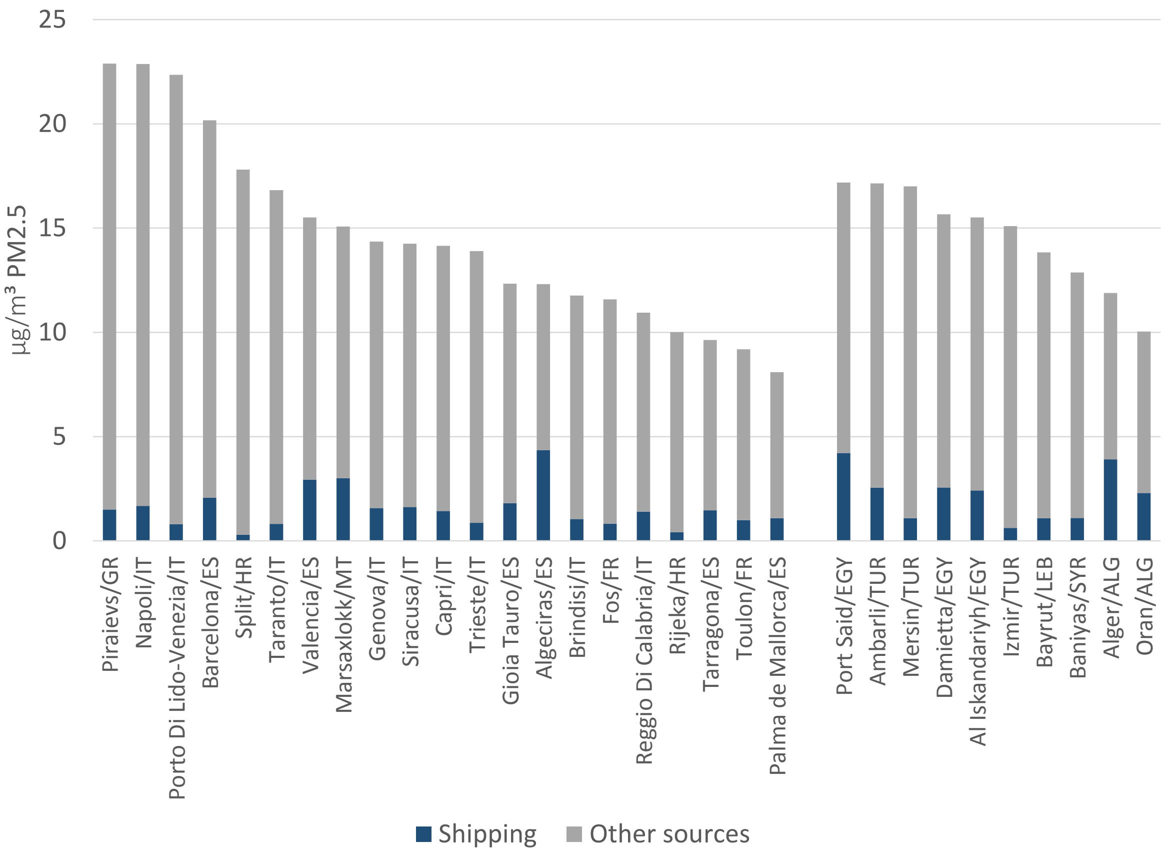


Figure 21: Contribution of shipping emissions to ambient PM2.5 concentrations in the 28*28 km grid cells with Mediterranean port cities in 2015 (Source: GAINS calculations)

A SECA in EU waters of the Mediterranean Sea could reduce PM2.5 concentrations on average by 0.5 µg/m^3 compared to the baseline levels in 2050, and by up to 1 µg/m^3 in Algeciras/ES, Valencia/ES and Marsaxlokk/MT. Tier III standards for NO_x could deliver an additional 0.2 to 0.3 µg/m^3 in port cities by 2050. SECAs and NECAs covering the whole Mediterranean Sea could reduce ambient PM2.5 concentrations in non-EU ports typically by 1 µg/m^3 in 2050 (Figure 23).

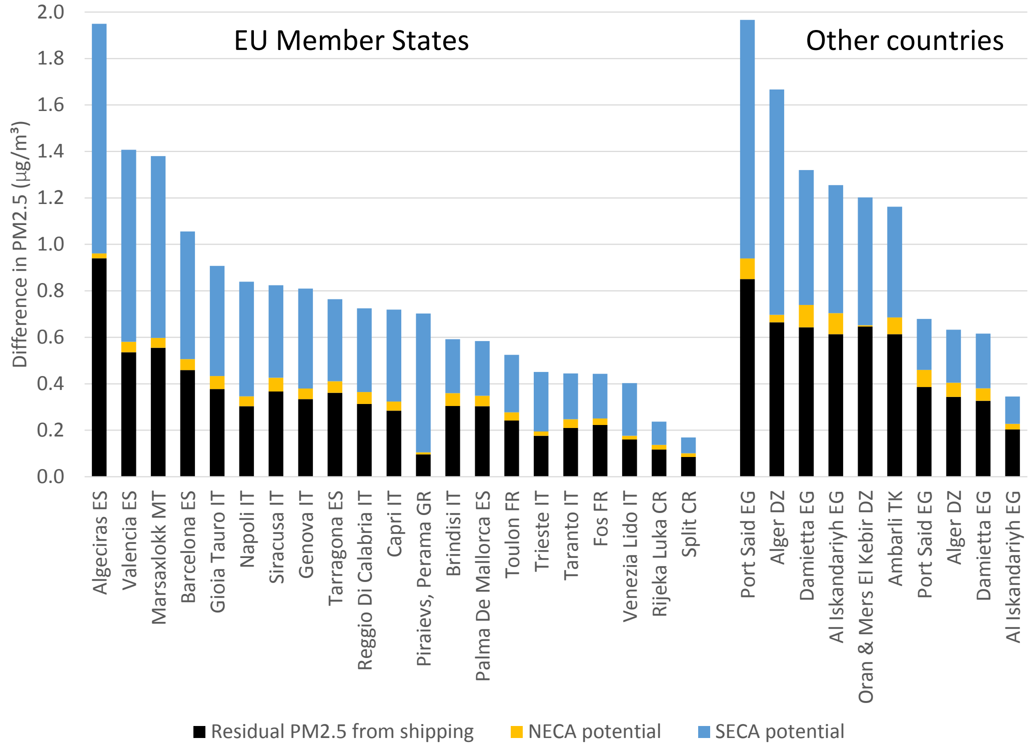


Figure 22: Estimated reductions of ambient PM2.5 concentrations in port cities from SECAs and NECAs (averaged across the 28*28km grid cell of the city), baseline 2030

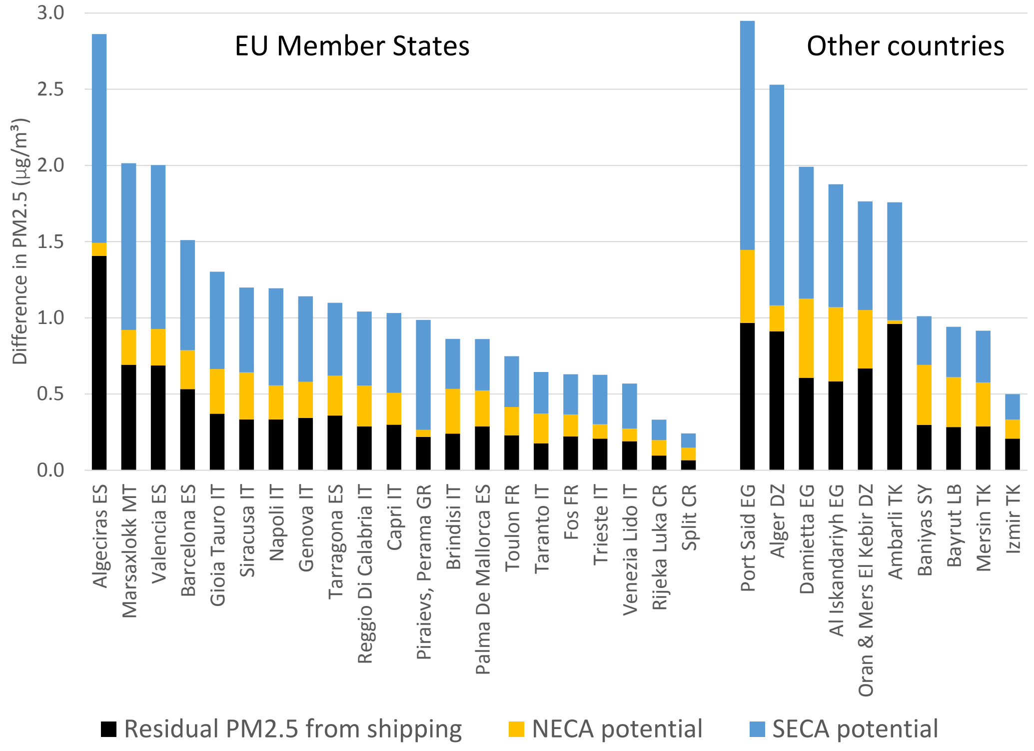


Figure 23: Estimated reductions of ambient PM2.5 concentrations in port cities from SECAs and NECAs (averaged across the 28*28km grid cell that contains the port city), baseline 2050

7 Benefits of the emission controls

7.1 Premature mortality

The reduced population exposure to PM2.5 that would occur as a consequence of lower shipping emissions will alleviate health impacts from air pollution and avoid, inter alia, thousands of cases of premature deaths annually.

In 2030, the most ambitious emission controls, i.e., SECAs, NECAs and PM filters together, could avoid up to 8000 cases of premature deaths, about 40 percent of them in North Africa and the Middle East (Figure 24). Enhanced penetration of emission controls combined with population growth will double this number in 2050 (Figure 25).

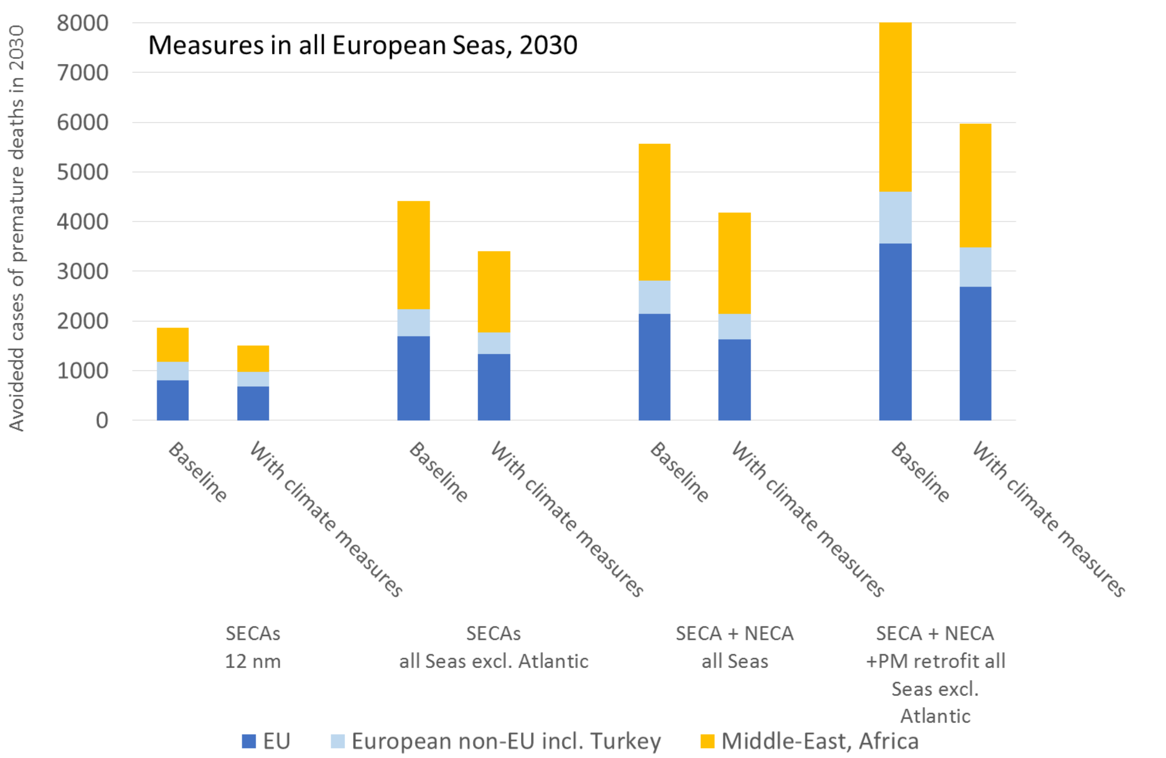


Figure 24: Avoided cases of premature deaths from the control of shipping emissions in all European Seas in 2030

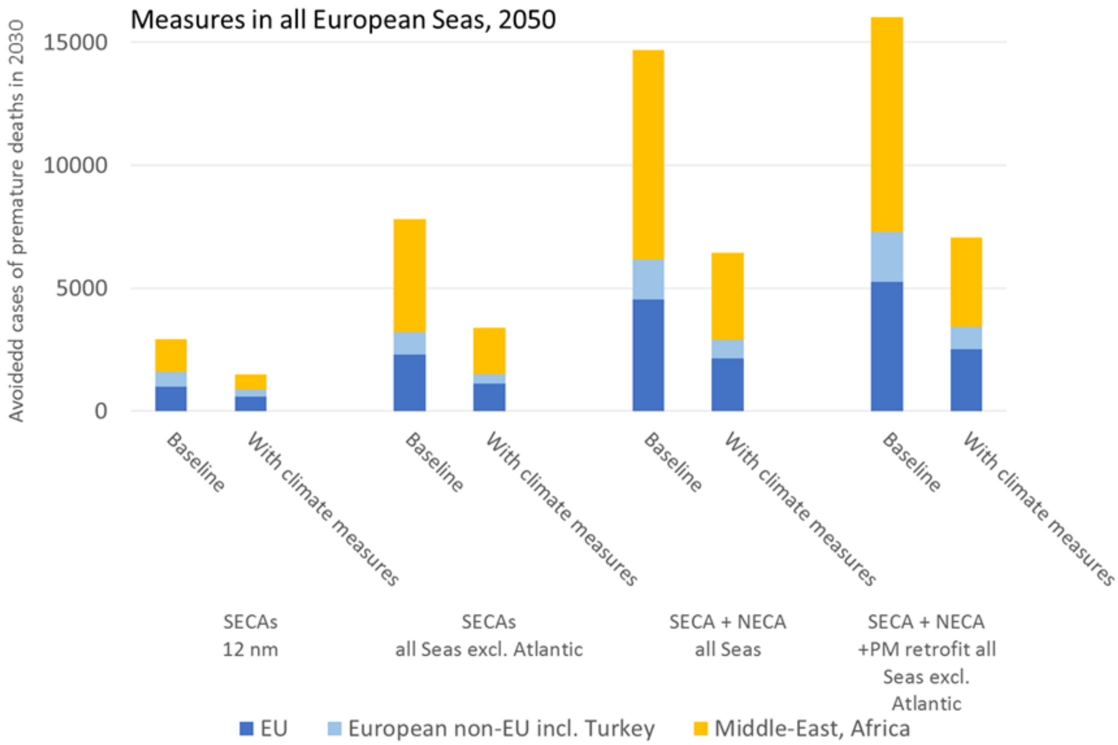


Figure 25: Avoided cases of premature deaths from the control of shipping emissions in all European Seas in 2050

SECAs and NECAs in the Mediterranean Sea could avoid between 3,100 and 4,100 cases of premature deaths in 2030, of which about one third occur in the EU Member States and more than half in North Africa and the Middle East (Figure 26). By 2050, these measures could save more than 10,000 lives in the region annually, especially in North Africa where significant population growth is expected (Figure 27).

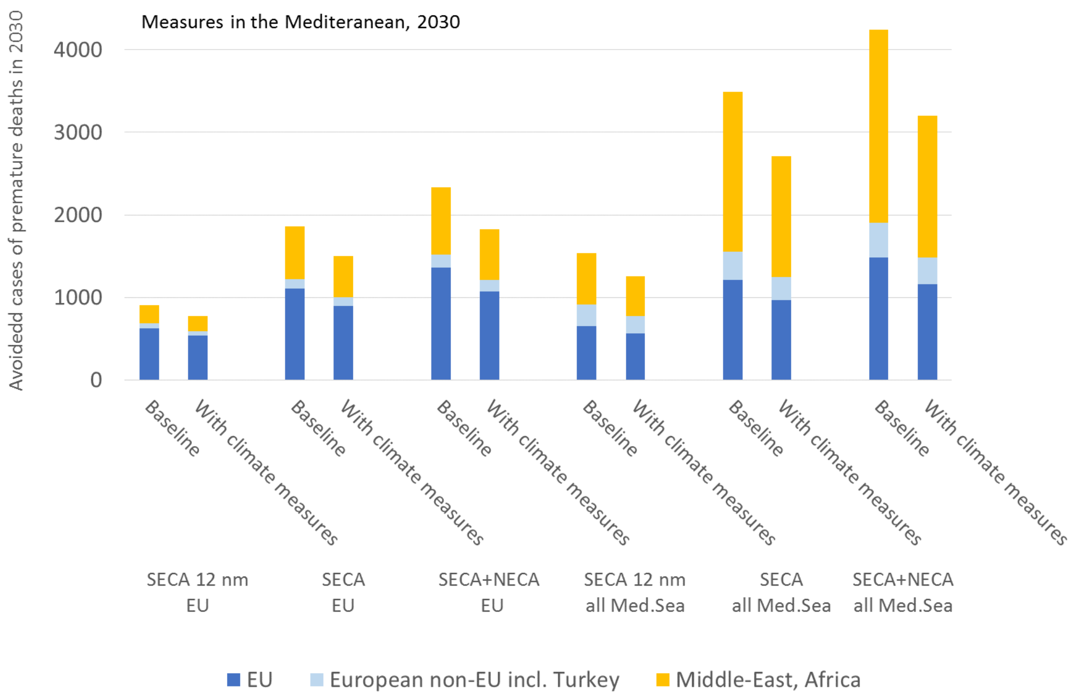


Figure 26: Avoided cases of premature deaths from the control of shipping emissions in the Mediterranean Sea in 2030

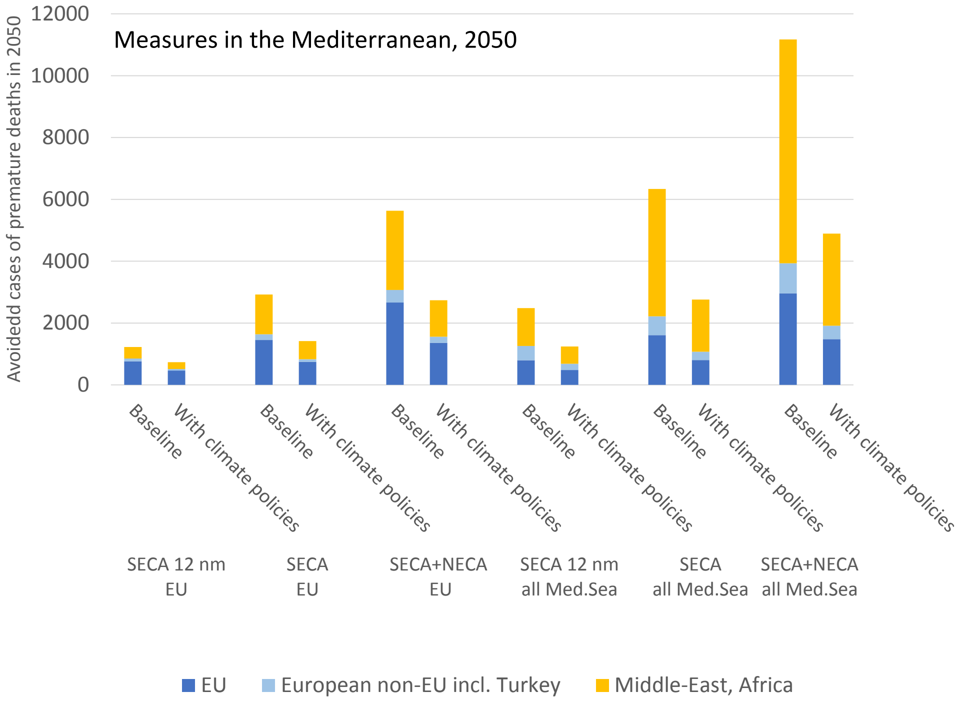


Figure 27: Avoided cases of premature deaths from the control of shipping emissions in the Mediterranean Sea in in 2050

7.2 Monetized health benefits

Monetized health benefits have been estimated along the impact pathway approach as used previously for analysis of proposals made in the context of the EU's Thematic Strategy on Air Pollution and Clean Air Programme ((Holland 2014a, b) using the ALPHA-Riskpoll (ARP) model (Holland et al. 2013). For the present analysis the model has been extended to include countries in North Africa and the Middle East. A detailed description of the methodology is provided in Annex 7. Key inputs to the analysis, in addition to information on population-weighted pollution exposure data PM2.5 from the GAINS model were:

- Population data: UN Medium Projections (UN 2017);
- Health response functions: WHO-Europe's HRAPIE (Health Risks of Air Pollution in Europe) study (WHO Regional Office for Europe 2013; Holland 2014b);
- Valuation data: Estimates adopted for the EU's Clean Air Package of 2013 (Holland 2014a). Valuation data are given in Euro, at 2005 prices to match the cost data used in GAINS.

Analysis preformed with the ALPHA-Riskpol model reveals that the most important monetary benefit from controlling emissions of air pollutants is reduction of premature mortality.

7.2.1 Measures in all European Seas

For emission controls in all European Seas, largest benefits occur for simultaneous controls of SO_2, NO_x and PM2.5 emissions. Benefits estimate vary for different methodological approaches, e.g., depending whether the value of a life year (VOLY) or the value of statistical life (VSL) is applied for the monetization of premature mortality, as well as for the different assumptions on climate measures, which have large impact on emissions, exposure and mortality. In 2030, benefits estimate reach up to 20 billion €/year, and double until 2050 (Figure 28).

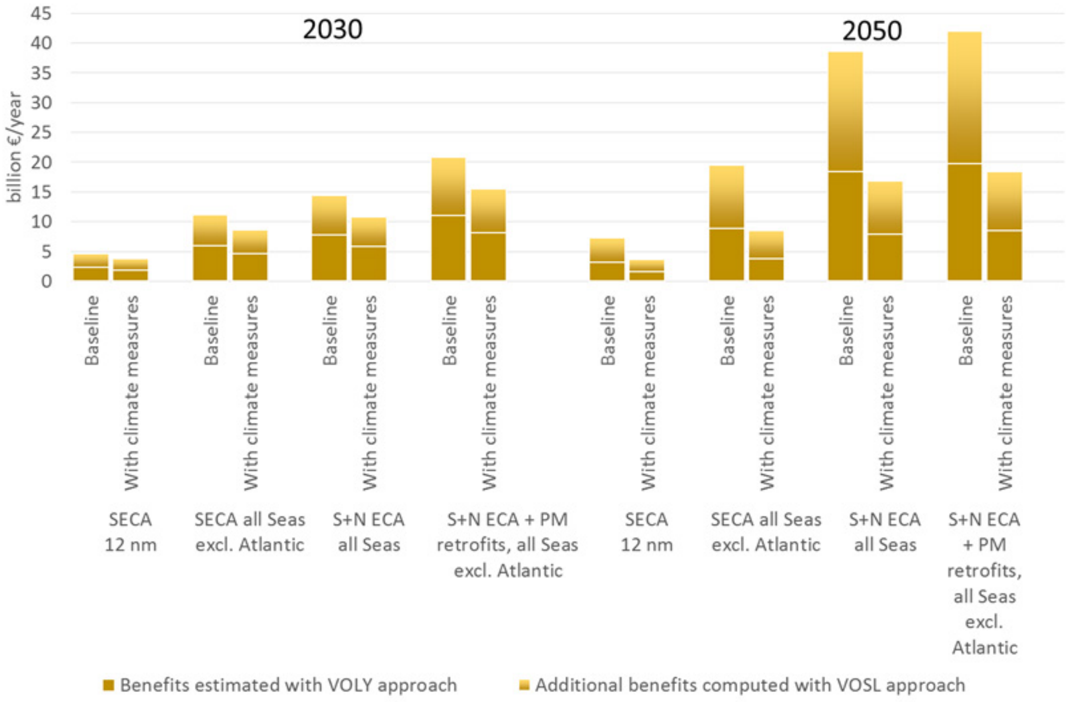


Figure 28: Benefits estimated for the emission control scenarios for all European Seas

7.2.2 Measures in the Mediterranean Sea

For the emission controls in the Mediterranean, the estimates of monetized benefits reach up to 10 billion €/year in 2030 and increase to almost 30 billion €/year in 2050 (Figure 29). Details are provided in Annex 7.

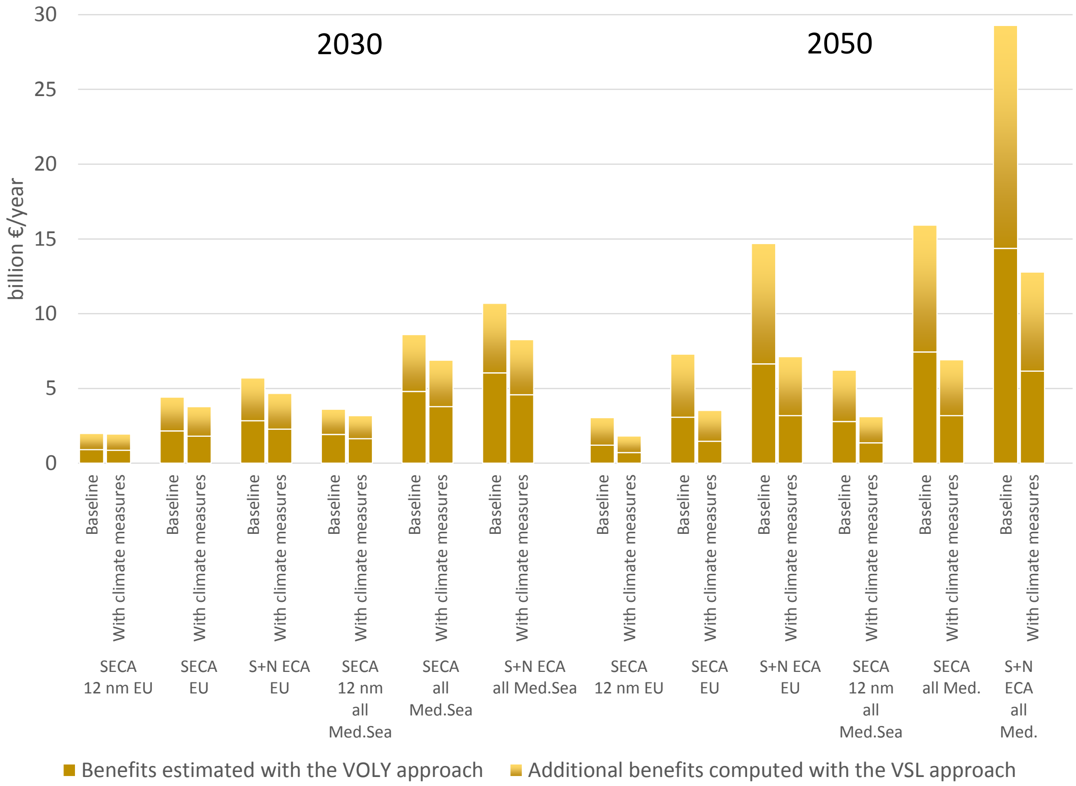


Figure 29: Benefits estimated for the emission control scenarios in the Mediterranean Sea

8 Comparison of costs and benefits

A comparison of costs (see Section 5) and monetized benefits (Section 7) clearly reveals that for all examined emission control scenarios the benefits outweigh the emission control costs by a wide margin (Figure 30). For measures across all European Seas, on average the monetized benefits exceed costs by a factor of 6 in 2030 (Figure 31) and a factor of 12 in 2050 (Figure 32).

8.1.1 Measures in all European Seas

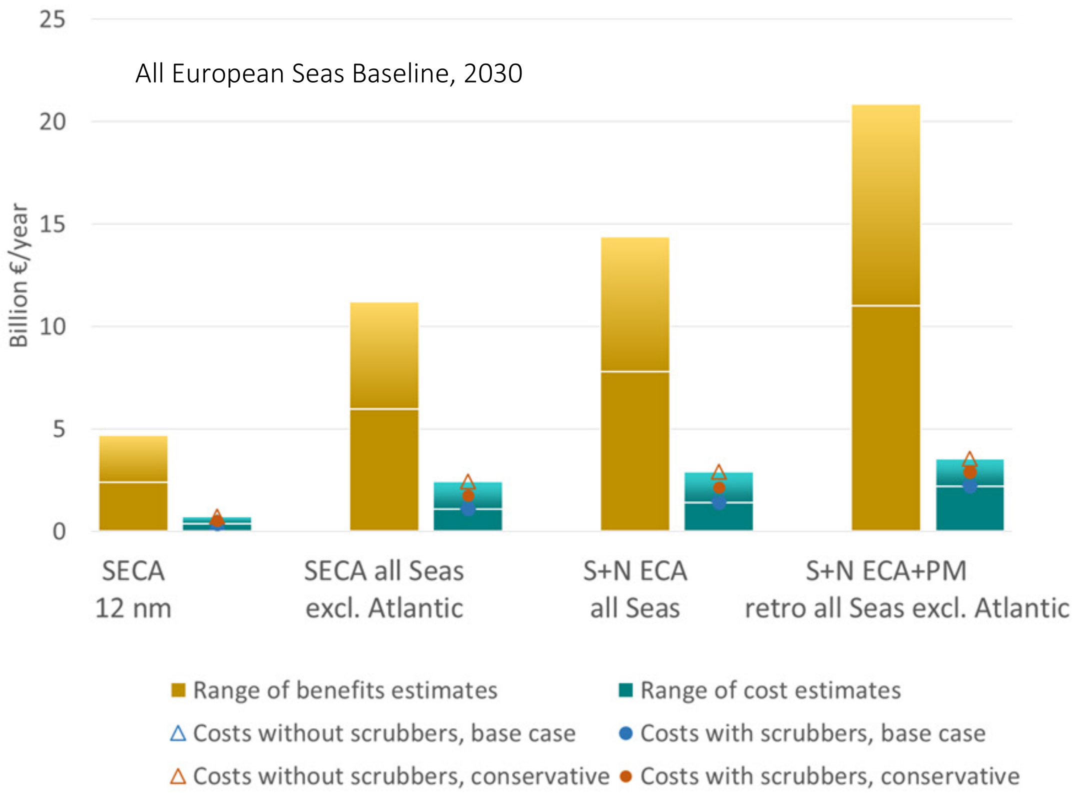


Figure 30: Monetized benefits and costs for the emission control scenarios for all European Seas in 2030. Base case – base estimate of low sulphur fuel price premium; conservative – conservatively high cost premium for low sulphur fuel

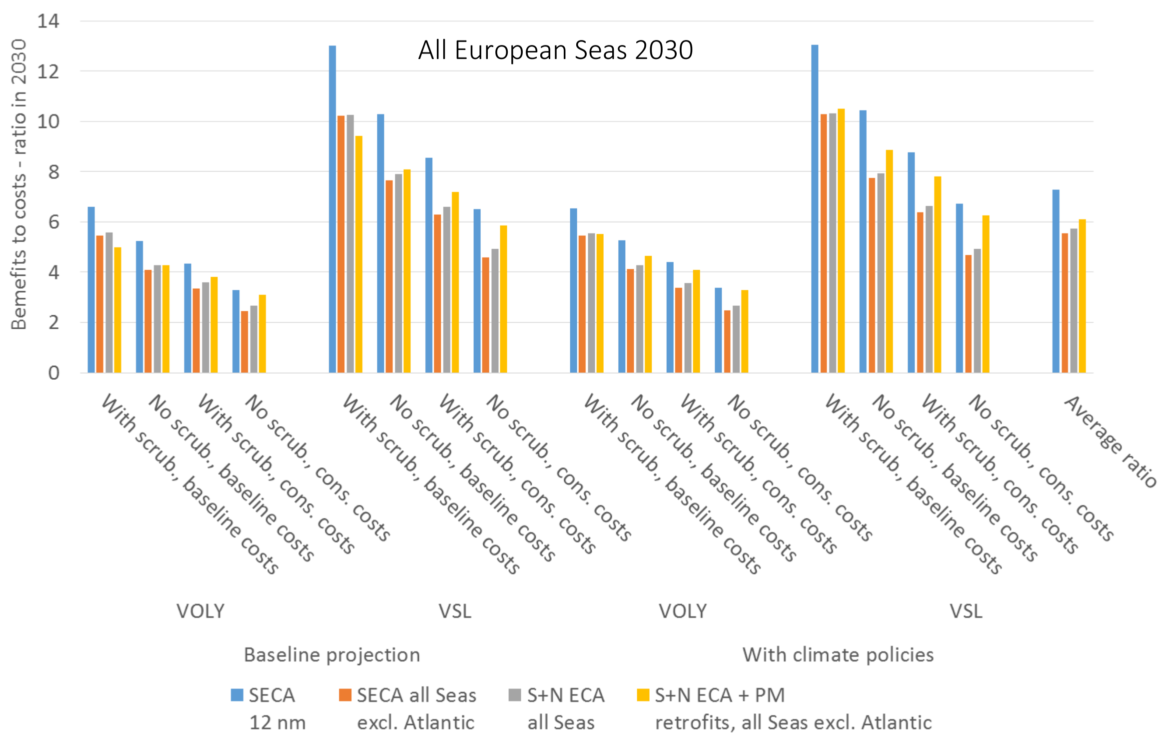


Figure 31: Benefits-to-costs ratios for the emission control scenarios for all European Seas, 2030 (VSL –Value of Statistical Life; VOLY –Value of Life Year. Baseline costs - base estimate of low sulphur fuel price premium; cons. costs – conservatively high cost premium for low sulphur fuel

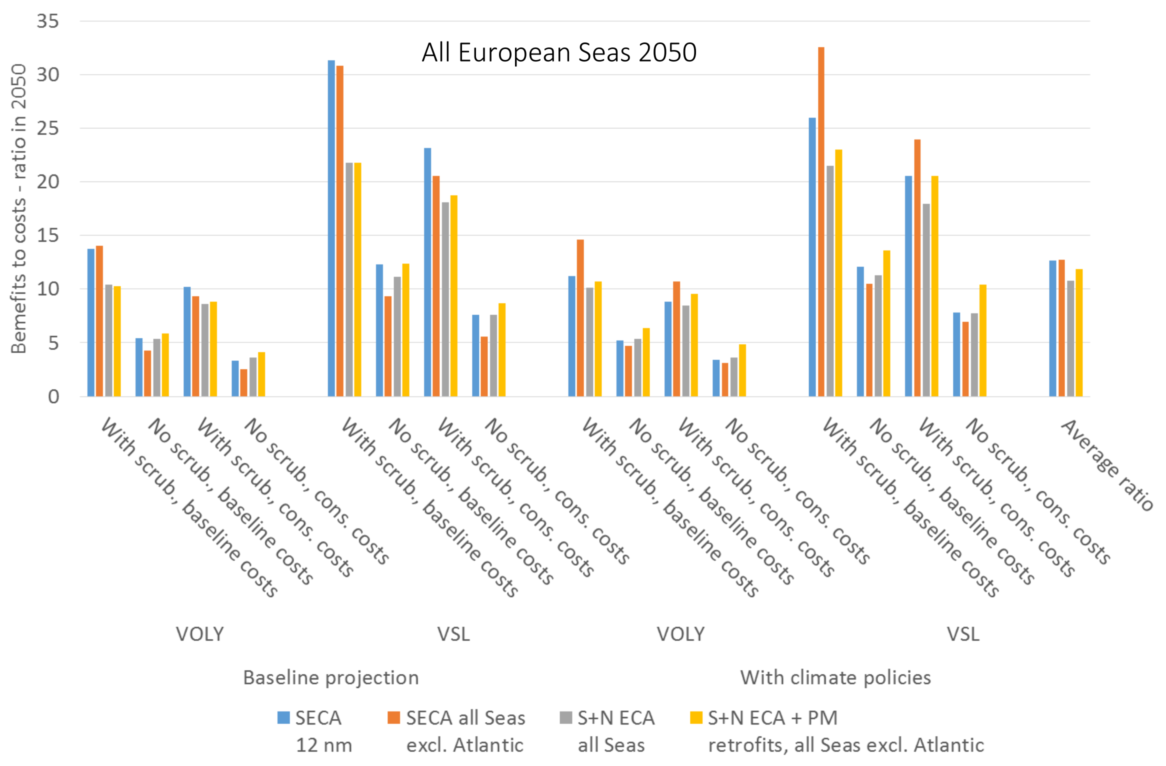


Figure 32: Benefits-to-costs ratios for the emission control scenarios for all European Seas, 2050 (VSL – Value of Statistical Life; VOLY –Value of Life Year. Baseline costs - base estimate of low sulphur fuel price premium; cons. costs – conservatively high cost premium for low sulphur fuel Measures in the Mediterranean Sea

For the emission controls for the Mediterranean Seas, monetized benefits exceed costs on average by a factor of 6.5 in 2030 (Figure 33, Figure 34) and a factor of 12 in 2050 (Figure 35, Figure 36).

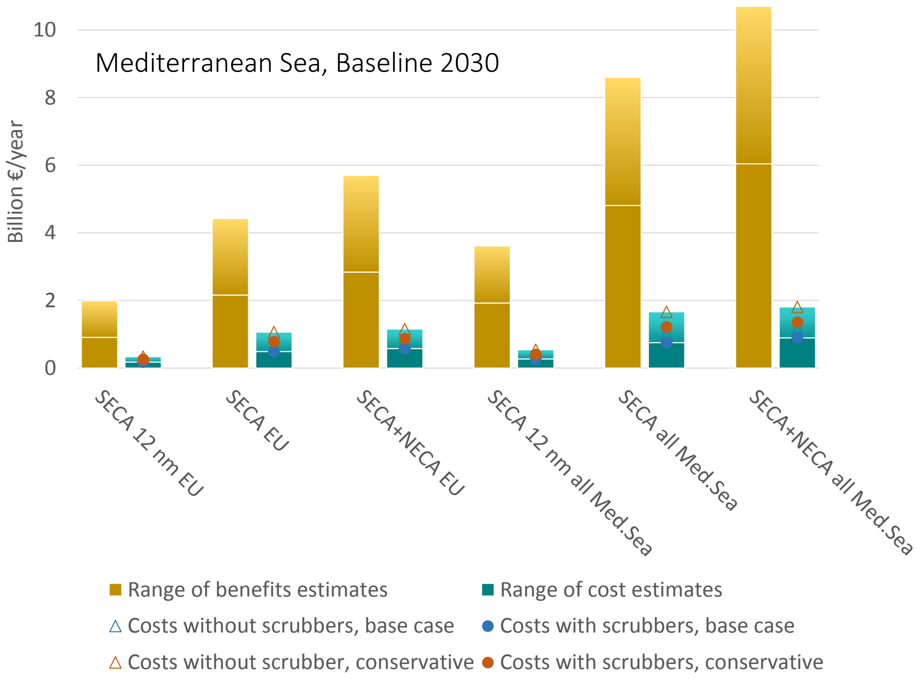


Figure 33: Monetized benefits and costs for the emission control scenarios for the Mediterranean Sea, 2030. Base case – base estimate of low sulphur fuel price premium; conservative – conservatively high cost premium for low sulphur fuel

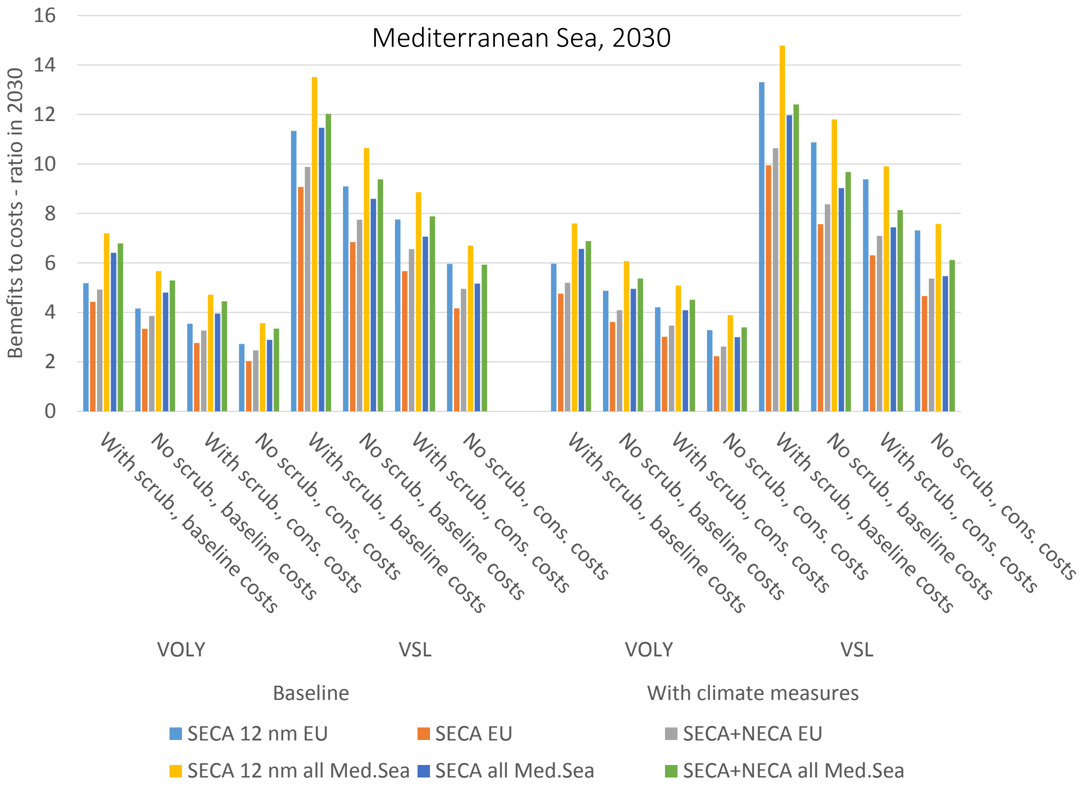


Figure 34: Benefits to costs ratios for the emission control scenarios in the Mediterranean Sea, 2030 (VSL – Value of Statistical Life; VOLY –Value of Life Year; cons. costs – conservatively high cost premium for low sulphur fuel

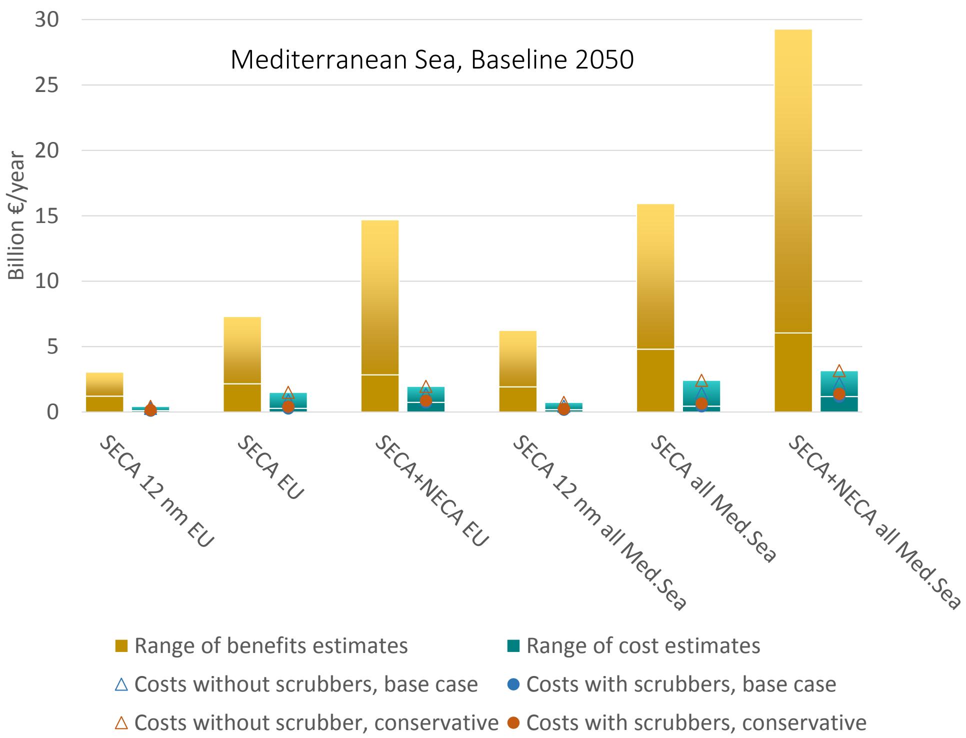


Figure 35: Monetized benefits and costs for the emission control scenarios for the Mediterranean Sea, 2050. Base case – base estimate of low sulphur fuel price premium; conservative – conservatively high cost premium for low sulphur fuel

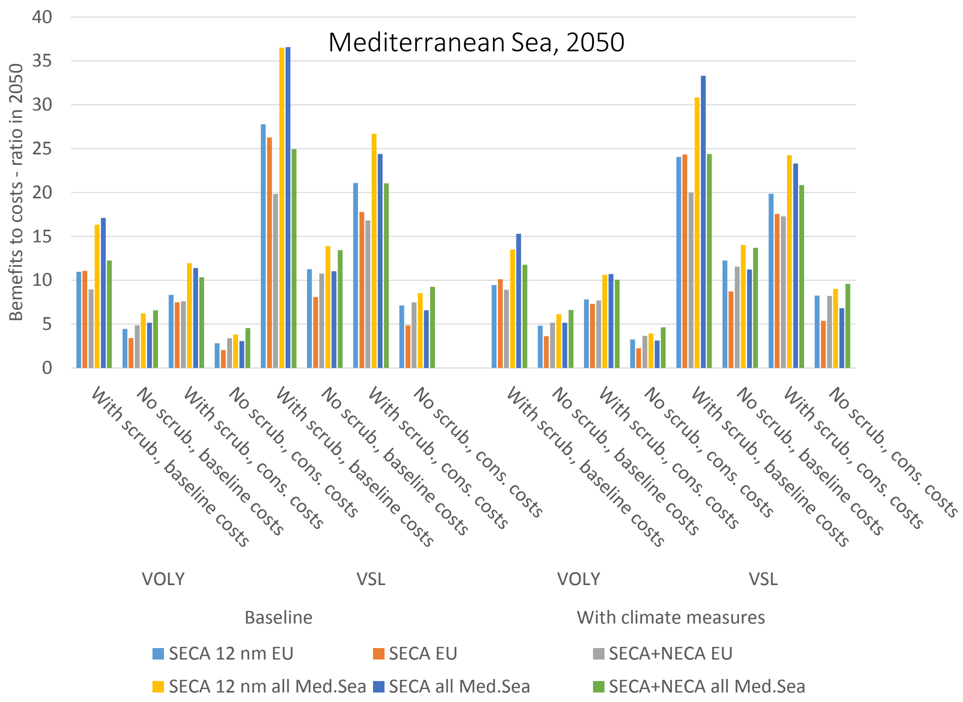


Figure 36: Benefits to costs ratios for the emission control scenarios in the Mediterranean Sea, 2050 (VSL – Value of Statistical Life; VOLY –Value of Life Year; cons. costs – conservatively high cost premium for low sulphur fuel

9 Conclusions

This report revisits the potentials for further emission reductions from international shipping in the European Seas and compares associated costs with resulting benefits. Maintaining consistency with other recent studies, this report:

- updates the projections of the likely development of maritime transport activities,
- provides new assessments of costs of compliance with current legislation,
- improves the understanding of the role of emissions from vessels in ports, and the options for reducing these emissions,
- develops new scenarios of future emissions that would result from different policy interventions, including additional ECAs in the Mediterranean Sea and other European Sea regions,
- assesses their impacts on ambient air quality and resulting population exposure, and
- estimates the associated benefits to human health, and quantifies these benefits in monetary terms.

As a central tool, this report employs the GAINS (Greenhouse gas – Air Pollution Interactions and Synergies) model (Amann et al. 2011), complemented by more detailed computations with MET Norway's EMEP atmospheric chemistry-transport model (Simpson et al. 2012). Subsequently, EMRC's ALPHA-RiskPoll model (Holland et al. 2013) provided full benefit analyses.

Maritime shipping is found as an important contributor to poor air quality in Europe, and has particularly large impacts in port cities and coastal areas. While current IMO and EU regulations will cut sulphur emissions up to 2030, current fuel consumption trends imply that emissions from international shipping will grow further after 2030 in the absence of additional regulations. Overall, current legislation is expected to cut SO_2 emissions by 50-80 percent in the coming decades. In contrast, NO_x emissions are expected to further increase and shortly after 2030 they will reach levels that exceed total land-based emissions in the EU-28.

Enhanced emission controls could cut emissions from international shipping in the European Seas by 80-90 percent compared to 2015. An extension of the sulphur emission controls to all Sea regions could reduce SO_2 emissions by more than 90 percent, accompanied by a 20 – 70 percent reduction of PM2.5 emissions. Tier III standards could lower NO_x emissions in the European Seas by 50 – 80 percent in 2050.

Climate policy measures, through their reduction of fuel consumption, have significant co-benefits on air pollutant emissions from shipping. Compared to a 130% increase in CO_2 emissions from international shipping in the European Seas that would emerge in 2050 from current fuel consumption trends, a scenario that assumes climate measures that lead to the stabilization of CO_2 emissions from shipping by 2050 (but does not achieve the 50 percent emission cut established by the IMO) would allow an additional 50 percent reduction in SO_2, NO_x and PM2.5 emissions compared to what could be achieved with the full set of emission controls in the baseline scenario.

Further emission controls for international shipping could deliver important improvements for air quality throughout Europe, particularly in coastal areas. Such measures could improve air quality for a large share of European population, given that about half of the EU population lives within 50 km distance from the Sea. Largest improvements would occur along the coast of Mediterranean countries, and in particular along the North African coast. Here the ambient concentrations of PM2.5 could decrease by up to 1.2 µg/m^3 in 2030 and up to 1.5 µg/m^3 in 2050.

The air quality improvements of further emission controls could save up to 15,000 cases of premature deaths annually, about one third of them in the EU Member States, and 50 percent in North Africa and the Middle East. Until 2030, sulphur in fuel controls that can be quickly introduced offer the largest potentials for fast improvements, and 40 percent of the full potential of the SECAs could be obtained with measures in the 12 nm zones. Application of Tier III standards for NO_x will need longer time until their full benefits are unfolded, but by 2050 the NO_x reductions will double the benefits of SECAs.

It is found that the benefits of further emission controls for international shipping outweigh the costs by a wide margin. For measures across all European Seas, on average the monetized benefits exceed costs by a factor of 6 in 2030 and by a factor of 12 in 2050.

Specifically for the Mediterranean Sea, designating this Sea as an Emission Control Area could by 2030 cut emissions of SO_2 and NO_x from international shipping by 80 and 20 percent, respectively, compared to current legislation. These additional emission reductions could avoid 4,100 cases of premature deaths in 2030 and more than 10,000 annual premature deaths in 2050.

For measures on the Mediterranean Sea, on average the monetized benefits exceed costs by a factor of 6.5 in 2030 and by a factor of 12 in 2050. Even with the most conservative assumptions for health valuation, monetized benefits are on average 4.4 times higher than the costs in 2030 and 7.5 times higher in 2050.

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