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Foreword

Emissions of nitrogen oxides (NOx) cause damage to health and ecosystems, and ships account for a large and growing share of these emissions in Europe.

Over the last few decades, the EU and its member states have gradually strengthened NOx emission abatement for a wide range of land-based activities including road vehicle transport. As a result, annual NOx emissions in the EU28 have come down by more than half since 1990, and now amount to about 7.8 million tonnes.

At the same time, NOx emissions from international shipping in the sea areas surrounding Europe have remained largely unregulated and kept on growing. As a result, shipping emissions around Europe now amount to approximately 3 million tonnes per year.

If no additional abatement measures are taken, NOx emissions from shipping around Europe are projected to keep on growing and may soon equal or even surpass the total from all land-based sources in the EU's 28 member states combined. As a consequence, the health impacts from ozone and PM exposure in Europe are likely to remain high.

NOx emissions from international shipping are regulated by the International Maritime Organization (IMO), but the currently applicable global Tier II limit values are very weak, and as they apply to new ships only it will take around 30 years until all ships comply.

There is however a stricter Tier III standard that requires emission reductions of about 80 per cent compared to an unabated Tier I engine, but this applies only to newly built ships in designated NOx Emission Control Areas (NECAs), which currently exist only in North America. However, in 2016 the countries surrounding the Baltic Sea and the North Sea jointly submitted a proposal to the IMO that these two sea areas should be designated as NECAs with application of the stricter Tier III standards as from 2021.

This report is a follow-up to the report "NOx controls for shipping in EU seas" by IVL Swedish Environmental Research Institute and CE Delft, published in June 2016, which presented NOx emission projections up to 2040 for the Baltic Sea and the North Sea with and without a NECA. It also analysed a number of alternative or complementary policy options, including economic instruments.

Clearly all sea areas surrounding Europe should become full emission control areas, with stricter standards both for NOx and sulphur emissions. In order to not only limit the growth in ships' NOx emissions, but actually to reduce them, there is a need to cut emissions from existing vessels and to speed up the introduction of efficient NOx abatement. The analyses by IVL Swedish Environmental Research Institute and CE Delft have shown that a NOx levy and fund system would be a cost-effective complement to NECAs and it would ensure much needed faster and further emission reductions.

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AirClim

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Summary and main conclusions

The purpose of this study is to perform a cost-benefit analysis for two selected policy instruments designed to reduce nitrogen oxide (NOx) emissions from shipping in the Baltic Sea and the North Sea. One instrument is a NOx emission control area (NECA) in the Baltic Sea and the North Sea; the other is a combination of NECA and a NOx levy with revenues returned to shipping companies as a subsidy for NOx abatement uptake. Both instruments are assumed to be in force in 2021.

In the analysis, we examine three main scenarios:

- Baseline (no additional policy instruments)
- NECA
- NECA + levy & fund

In the NECA scenario we assume that no extra use of liquefied natural gas (LNG) is introduced and that the Tier III requirements for vessels running on marine gasoil (MGO) are fulfilled by installing selective catalytic reduction (SCR). In the NECA + levy & fund scenario it is further assumed that Tier 0 vessels will not install SCR but pay the levy instead, and that 75 per cent of Tier I and Tier II vessels will take up retrofit SCR, given that it is more profitable than paying the levy.

Total abatement costs have been assessed from the social perspective, assuming a low interest rate and long investment lifetime when calculating annual investment cost. Health benefits have been estimated with the GAINS and the ALPHA-Riskpoll models. The method for estimating health benefits is the same as applied in cost-benefit analyses that support the European Commission's work on air pollution abatement strategies and the work of the Convention on Long-Range Transboundary Air Pollution.

The introduction of a NECA in the Baltic Sea and the North Sea in 2021 is calculated to result in total accumulated NOx emission reductions of about 4,500 ktonnes during 2020–2040, on top of the baseline. Emission reduction costs are estimated at $€_{2010}$1.38/kg NOx. The accumulated net health benefits (Value of Life Year lost – VOLY, median) from NECA implementation would amount to $€_{2010}$6,600 million, with a benefit-cost ratio of 2.1. Annual reduction in NOx deposition on land would gradually increase and reach 60 ktonnes N in 2040.

Combining a NECA with the introduction of the NOx levy & fund effective from 2021 is calculated to result in accumulated emission reductions over the period 2020–2040 of about 9,900 ktonnes NOx at a cost of $€_{2010}$1.68 per kg NOx. The accumulated net health benefits (median VOLY) in this scenario are $€_{2010}$11,800 million, with an average benefit-cost ratio of 1.7. Reduction in NOx deposition on land amounts to between 65 and 80 ktonnes N per year.

The total calculated abatement costs and health benefits accumulated over the period 2020–2040 in the cases of a NECA alone and a NECA combined with the NOx levy and fund are presented in Figure S1 below.

In the sensitivity analysis we consider the case of a less optimistic annual energy efficiency increase (0.84 percent per year) than assumed in the main analysis (1.3–2.3 percent per year). The results indicate that the total accumulated health benefits from implementation of the considered policy instruments are approximately 30 per cent higher than in the main analysis.

The calculations show that in the short-term perspective (2020–2030) the introduction of a levy and fund on top of a NECA would result in accumulated additional net health benefits of about €$_{2010}$3,400 million (median VOLY) attributable primarily to health improvements among the population in coastal countries. A levy and fund appears to be an effective complement to a NECA with the potential to bring noticeable health and environmental benefits shortly after its enforcement.

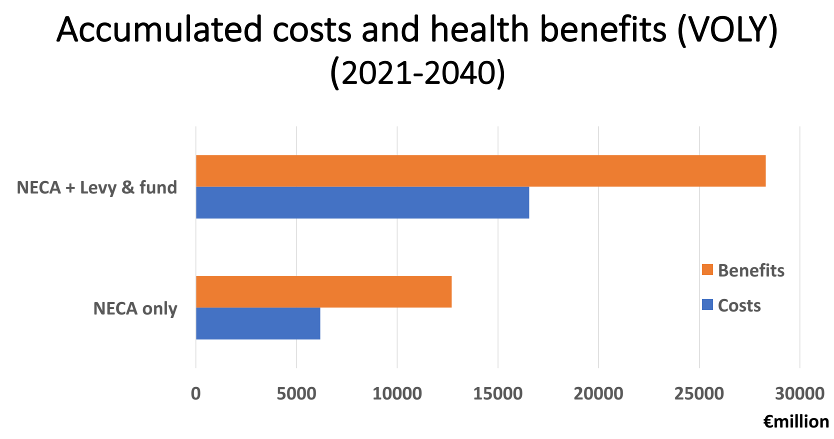

Figure S1. Total calculated abatement costs and health benefits (VOLY) accumulated over the period 2020–2040 (€million).

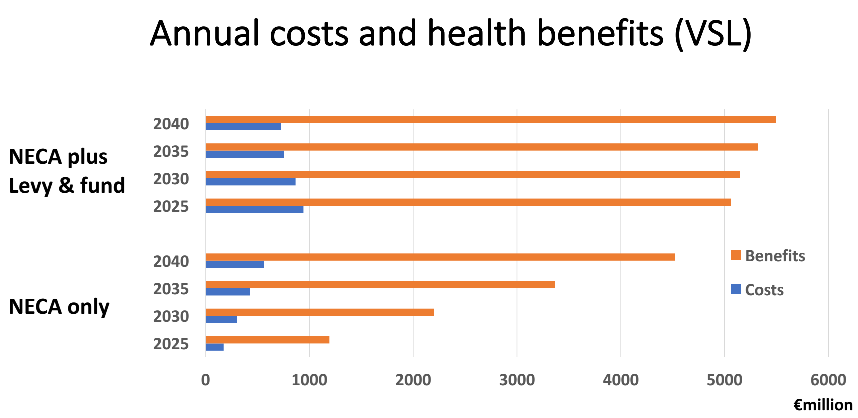

Figure S2. Comparison of annual costs and monetised health benefits for the NECA and the combined NECA + levy & fund scenarios (€million).

Table S1. Calculated costs and benefits for the NECA scenario and the NECA + levy & fund scenario using median VOLY and mean VSL (€million).

Year	NECA					NECA + levy & fund				
	Benefits		Costs	Net benefits		Benefits		Costs	Net benefits	
	VOLY	VSL		VOLY	VSL	VOLY	VSL		VOLY	VSL
2021	80	240	30	40	210	1,220	3,950	820	400	3,130
2025	350	1,190	170	180	1,020	1,490	5,050	940	550	4,110
2030	620	2,200	300	320	1,900	1,450	5,150	870	590	4,280
2035	880	3,360	430	450	2,930	1,420	5,320	760	670	4,560
2040	1,150	4,520	560	580	3,960	1,390	5,490	720	670	4,770
2020–2040 accumulated	12,700	-	6,200	6,600	-	28,300	-	16,500	11,800	-

Introduction

Emissions of air pollutants from shipping (NOx, SOx, and $PM_{2.5}$) make a significant contribution to total emissions in Europe and worldwide. According to an analysis by Brandt et al. (2013), shipping emissions cause about 50 thousand premature deaths per year in Europe. Significant proportions of the sulphur and nitrogen depositions that cause acidification and eutrophication emanate from ship emissions. NOx emissions contribute to the formation of secondary particles and ozone, resulting in higher levels of respiratory and cardiovascular diseases among the population, especially in coastal states.

NOx emissions from anthropogenic sources reported by the 28 member countries of the European Union to the Convention on Long-Range Transboundary Air Pollution (CLRTAP) amounted to 7,820 ktonnes in 2014 (CEIP, 2017), while emissions from international shipping in European seas for the same year are estimated at 3,186 ktonnes (EMEP, 2016). As more stringent NOx emission controls are gradually enforced for stationary and mobile sources on land, the share of NOx emission reduction potential attributable to international shipping is expected to increase in the future.

NOx emissions from international shipping are regulated by the MARPOL Convention (International Maritime Organization, 2013). The emission reduction system is divided into three tiers, with each subsequent tier requiring newly built vessels to reduce emissions further than the previous tier. Tier I vessels comprise those constructed between 2000 and 2011, while Tier II are vessels constructed after 2011. Tier III requirements apply only in the specially designated areas – NOx Emission Control Areas (NECAs), and only to vessels built after the implementation year for each particulate NECA (Annex VI, International Maritime Organization, 2013). Currently, NECAs exist only along the North American coast – the North American NECA and the United States

Caribbean Sea NECA. In October 2016, the International Maritime Organization (IMO) approved designation of the North Sea and the Baltic Sea as a NECA, with 1 January 2021 as the effective date for Tier III requirements. The final decision is expected to be taken in July 2017 (HELCOM 2016, International Maritime Organization 2017).

The costs of introducing a NECA in the Baltic Sea and/or North Sea have been estimated in a series of recent studies (Åström et al. 2014, Campling et al. 2013, Danish EPA 2013, HELCOM 2012). Because a NECA only requires new vessels to fulfil Tier III requirements, emission reductions will be gradual and linked to the fleet renewal rates. The full Tier III emission reduction potential will therefore only be implemented 25–30 years after the NECA enforcement date. There is also a range of policy instruments with potential to supplement NECAs and cover emissions from 'existing vessels' – those built before 2021. Several of these policy instruments are analysed in Winnes et al. (2016). In particular, emissions and costs have been estimated for the introduction of a NOx levy and fund – a levy that returns revenue to shipping companies, earmarked as a subsidy for the uptake of NOx abatement measures.

The purpose of this study is to update the analysis carried out in Åström et al. (2014) and Winnes et al. (2016), and to extend it by estimating country-specific health benefits for two particular cases:

1. Introduction of a NECA in the Baltic Sea and the North Sea in 2021
2. NECA combined with introduction of NOx levy and fund in 2021

The study will also assess nitrogen deposition and population-weighted secondary $PM_{2.5}$ concentrations, and provide a cost-benefit analysis for the two considered policy instrument combinations.

Method, assumptions, limitations

In this study, we consider the time period from 2020 to 2040. Emissions, costs, health effects and monetary benefits are analysed for the following three main scenarios:

- Baseline
- NECA
- NECA + levy & fund

The baseline emissions, together with the underlying fleet parameters and assumptions, are described in detail in Winnes et al. (2016). The fleet is assumed to be running on marine gasoil (MGO) and liquefied natural gas (LNG). The use of heavy fuel oil with a high sulphur content has dropped in response to the new sulphur emissions regulations valid from 1 January 2015 (Annex VI of the MARPOL Convention, International Maritime Organization, 2013). We assume an increase in transport efficiency of 1.3–2.3 per cent and a traffic increase of 1.5–3.5 per cent (depending on the ship category) each year during 2020–2040. In the sensitivity run, we analyse all three cases under the assumption that energy efficiency improvements during 2020–2040 will not be as optimistic as assumed in the baseline.

The main assumptions in the NECA and the NECA + levy & fund scenarios are the same as in Winnes et al. (2016). We assume that both policy instruments are effective from 2021 onwards in the Baltic Sea and the North Sea (including the English Channel). In the NECA scenario, we assume that no extra LNG consumption will be induced and that compliance with Tier III requirements for new vessels will be assured by installing catalytic converters (SCR), not by using exhaust gas recirculation (EGR) technology, which has not been as widely tested on ships. We estimate that the costs for reducing NOx are similar for SCR and EGR (at least for new-builds), so the use of EGR is not expected to change the results. Applying a levy & fund in addition to the NECA will further stimulate the retrofitting of existing vessels with SCR (since neither LNG nor EGR are considered as suitable options for retrofitting in existing ships).

In reality, some of the vessels built in 2021 or later are in fact Tier II vessels, since the construction process is often delayed and the implementation date refers to the date when the keel of the ship is laid. We assume that emission input from these vessels is negligible.

All monetary assessments in the study are expressed in euro at 2010 prices – $€_{2010}$.

The analysis is conducted from a techno-economic perspective. We do not take into account effects such as potential modal shift from sea to road or other possible implications of increased abatement costs. Macroeconomic and social effects such as economic growth or employment are not included in the scope of the study. Neither do we account for administrative costs associated with the introduction of subsidies and their infrastructure; only technology costs are considered. Unit costs are assumed to be constant over the period 2020–2040.

All comparisons in this study are made between the baseline and the two scenarios with implementation of policy instruments, for the period 2020–2040.

NOx emissions

Emission trends

Reliable estimates of emissions from international shipping have been a challenge for a long time. When calculating emissions, concentrations and deposition in the EMEP model, data is usually obtained from the Centre on Emission Inventories and Projections (CEIP) and is based on ENTEC, IIASA or TNO estimates (EMEP, 2016). According to this data, NOx emissions from ships in the Baltic Sea and the North Sea increased by 210 ktonnes (28 per cent) between 1990 and 2000 (see Table 1). The share of emissions in the Baltic Sea in relation to the total emissions in the Baltic Sea and the North Sea is assumed to be constant over time, at 32 per cent. The trend of increasing emissions continued during 2000–2005.

Table 1. NOx emissions in the Baltic Sea and the North Sea during 1990–2000, ktonnes. From EMEP (2007).

Year	Baltic Sea	North Sea	Total
1990	236	508	744
1995	268	575	843
2000	303	652	955

For 2006 and subsequent years, information on real ship movements obtained via the Automatic Identification System (AIS) is available as a data source. The AIS NOx emission data for the Baltic Sea plotted in Figure 1 below indicates up to 30 per cent higher emissions than CEIP estimates. For the North Sea, available NOx emissions based on AIS data are also higher. It is worth noting that emissions from international shipping used for EMEP modelling are the same for the years 2011, 2012, 2013 and 2014. Other possible reasons for the discrepancies are discussed in Jalkanen et al. (2016).

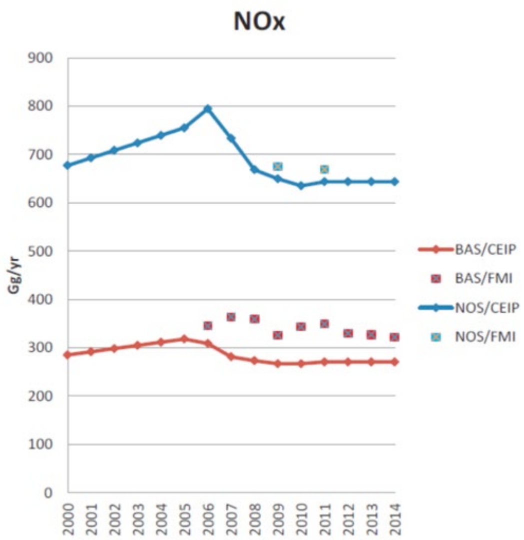

Figure 1. NOx emissions in the Baltic Sea and the North Sea during 2000–2014. From EMEP (2016).

In the analysis of policy instruments for reducing shipping emissions conducted by Campling et al. (2013) for the European Commission, the EXTREMIS/EUROSTAT dataset was used to estimate baseline emissions. Campling et al. (2013) estimates base year (2005) NOx emissions at 220 ktonnes in the Baltic Sea and 518 ktonnes in the North Sea – about 740 ktonnes in total, which is considerably less than the figure of 1,080 ktonnes NOx given in EMEP, 2016.

The trend of increasing NOx emissions from shipping in the Baltic Sea and the North Sea seems to have changed after 2005. Current emissions are still higher than in 1990 but they are no longer rising as sharply as during 1990–2005. The span in the existing estimates of NOx emissions from international shipping in the Baltic Sea and the North Sea indicates large uncertainties that should be taken into account when choosing base year emission estimates in order to develop projections.

Emission projections and scenarios

A summary of the recent studies estimating NOx emissions in 2000–2012 and providing projections is presented in Winnes et al. (2016). In this analysis, as in Winnes et al. (2016), we use NOx emission projections for 2020–2040 based on the study of Kalli et al. (2013). The study includes emissions from commercial ships only, i.e. the bulk of international and domestic shipping. Estimates by Kalli et al. (2013) are obtained from the STEAM model using AIS data as input. The underlying assumptions in our emission projections (including energy efficiency increase, rates of LNG introduction, vessel renewal rates and more) are described in detail in Winnes et al. (2016).

In order to estimate emissions during 2021–2025 and apply abatement costs, in this study we present emissions separately for each of the following categories (see Annex 1):

- Tier 0 vessels
- Tier I vessels
- Vessels built before 2021 (Tier II)
- Vessels built 2021 or later (Tier III)
- LNG-fuelled vessels
- Boilers (all vessels)

The total NOx emissions in the three considered scenarios are presented in Figure 2 below. In the NECA scenario, the emission decline is linear from 2020 to 2040, whereas for the NECA + levy & fund scenario there are three distinct periods with different decline trends: a rapid drop between 2020 and 2021, continued decline from 2021 to 2025, and a much shallower decline between 2025 and 2040.

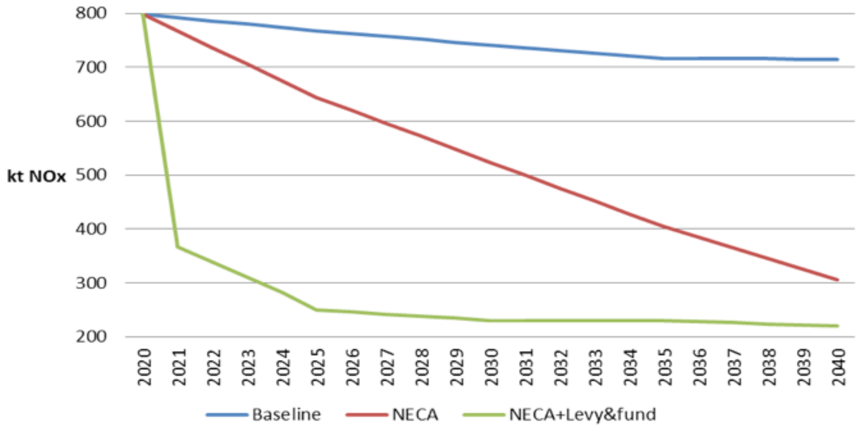

Figure 2. Projections of NOx emissions according to the three main scenarios: Baseline, NECA, and NECA + levy & fund.

The trend change in the NECA + levy & fund scenario is explained by the fact that not all vessels will take up SCR in response to the policy instruments. It is assumed in Winnes et al. (2016) that Tier 0 vessels are too old to install SCR and will pay the levy instead. Tier 0 vessels will be present in the fleet until about 2025; their gradual phase-out and input into NOx emissions is seen clearly in Figure 3. Emissions from Tier I and Tier II vessels decline by 62 per cent between 2020 and 2021, assuming that 75 per cent of the existing vessels will install retrofit SCR after the NOx levy introduction (Winnes et al., 2016). Figure 3 also shows a small amount of NOx emissions emitted by Tier III vessels built between 2021 and 2025. Emissions from boilers and from LNG-fuelled vessels are considerably lower than from MGO-fuelled vessels.

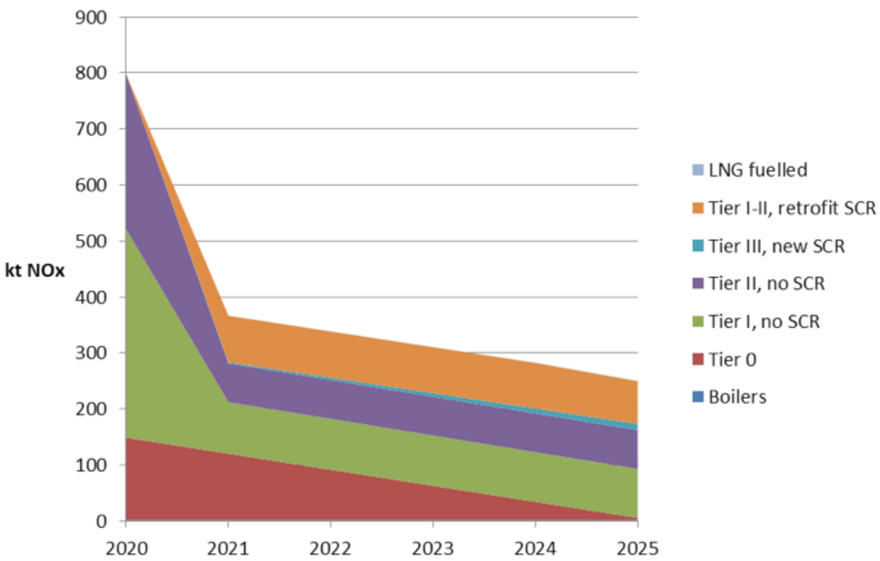

Figure 3. NOx emissions decline between 2020 and 2025 in the NECA + levy & fund scenario.

Accumulated NOx emission reductions (compared to the baseline) over the period 2020–2040 are summarised in Annex 2. By the year 2040, the accumulated emission reductions in the NECA + levy & fund scenario amount to

9,900 ktonnes – twice as high as the emission reductions in the NECA scenario (4,500 ktonnes). Due to the different characters of the policy instruments, the accumulated reduction trends look different. In the NECA scenario, annual emission reductions compared to baseline increase gradually, following fleet renewal and the introduction of vessels obliged to comply with the Tier III requirements. In the NECA + levy & fund scenario, annual emission reductions increase slightly between 2021 and 2025 (mainly due to phase-out of Tier I vessels) and remain relatively constant at about 500 ktonnes NOx reduced per year thereafter. The trend for accumulated emission reductions in the NECA + levy & fund scenario is thus much more linear than the trend in the NECA scenario.

Abatement costs

Since it is assumed that all emission reductions compared to the baseline will be ensured by either installing SCR in newly built ships or by retrofitting the existing vessels with SCR, we only focus on the costs of this particular technology in the analysis.

The total costs comprise investment costs, including installation costs where available, and operation and maintenance (O&M) costs. Investment costs are annualised with Equation 1 (Bosch et al. 2009):

Equation 1

$$I_{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1}$$

Where

I_{an} = Annual investment costs (€$_{2010}$)

I = Total investment costs (€$_{2010}$)

q = Investment interest rate (shares)

lt = Investment lifetime (years)

SCR costs and cost calculation parameters are specified in Annex 3. Costs in €$_{2010}$ per kg NOx are calculated using costs in €$_{2010}$ per kWh of engine work output and emission factors presented in Table 2 below.

Table 2. NOx emission factors per engine type. From Winnes et al. (2016).

Engine type	Fuel	NOx emission factor, g/kWh			
		Tier 0	Tier I	Tier II	Tier III
Slow-speed diesel engine	MGO	17	17	14.4	3.4
Medium-speed diesel engine	MGO	13.2	13	10.5	2.6
High-speed diesel engine	MGO	12	11	9	2.3
Duel fuel LNG engine	LNG	2.6	2.6	2.6	2.6

SCR abatement costs specified in Annex 3 are calculated using a range of parameters which can be divided into economic and technology parameters. Economic parameters include investment per kW of engine power, catalyst replacement costs, urea costs, and labour costs. Data found in the literature are averaged and used to estimate these parameters in cost calculations; more details can be found in Winnes et al. (2016). Technology parameters include ship categories, engine types, installed power per vessel, engine work output with abatement equipment in use, and NOx emission reductions achieved by Tier III in comparison to Tiers I/II. For technology parameters, we calculated weighted average values representative for the fleet navigating in the Baltic and North Seas. The fleet structure for 2030 is summarised in Annex 4. We assume that shares of different ship categories and engine types are the same for the whole period 2020–2040.

With respect to this fleet parametrisation, the following weighted average values are derived:

- Installed engine power, per vessel – 13.4 MW
- Engine work output with abatement equipment in use, per vessel per year – 5,000 MWh
- NOx emission reduction, conversion from Tier II to Tier III – 9.4 kg/MWh
- NOx emission reduction, conversion from Tier I to Tier III – 11.9 kg/MWh

Annex 3 summarises both the social and the private investor cost perspectives. The social perspective implies that the decision is made by a public planner and results in maximum benefits for all members of society. In contrast, a private investor's decisions are mainly driven by economic benefits and risks viewed in a much shorter time perspective. The cost estimate methodologies for these two perspectives differ by applying different interest rates and investment lifetime to calculate the annual cost of investment. For the social cost perspective, the accepted values of 4 per cent interest rate and an investment lifetime equal to the equipment lifetime are used for annualisation (Bosch et al. 2009, Amann et al. 2011). Private investors such as shipping companies usually consider a much shorter time period when annualising investment costs. Costs are the main factor for companies when they choose, for example, a specific abatement technology and whether to use abatement or pay a levy instead. There is, however, no common agreement on which values should be used for the private investors' perspective in socio-economic analyses: the choice is quite subjective and is affected by factors such as the current economic situation in a country, uncertainties in fuel prices and branch-specific circumstances. In Åström et al. (2014), the values of 10 per cent interest rate and 2 years investment lifetime were used to calculate costs from the company perspective – a quite cautious approach based on a very short investment lifetime. In Winnes et al. (2016), 7 per cent and 5 years were used – these numbers are based on discussions with Swedish shipping company representatives. In a study by Höglund-Isaksson (2012), which also presented emission abatement costs from two different perspectives (in another sector), 10 per cent interest rate and 10 years investment lifetime are chosen for analysis. In Annex 3, we show several alternatives for private costs, including the option used in Winnes et al. (2016). To estimate the total costs in this analysis, we use the social cost perspective.

To calculate the total costs on top of the baseline for the NECA and NECA + levy & fund scenarios, we apply costs per kg NOx to emission reductions achieved by different abatement options – SCR on new vessels and retrofit SCR on Tier I and Tier II vessels. We assume that all revenues are returned to shipping companies, so we do not consider levy/revenues as a separate cost parameter in this study. In principle, we look at this particular policy instrument combination as stimulating SCR uptake by existing Tier II and Tier I vessels but without adding any additional costs beside the cost related to the abatement installation and operation.

The resulting annual total costs are summarised in Annex 5. In the NECA scenario, annual costs gradually increase from $€_{2010}$30 million in 2021 to 560 million in 2040 due to a constantly increasing share of vessels equipped with SCR as a result of fleet renewal. In the NECA + levy & fund scenario, the annual costs increase from $€_{2010}$820 million to 870 million between 2021 and 2025 and then decrease to $€_{2010}$ 720 million in 2040. The decrease after 2025 is caused by the phase-out of Tier II and Tier I vessels and prevailing input of growing costs for SCR on new vessels in the total abatement costs. These different annual cost trends also explain the accumulated cost trends for 2020–2040 presented in Annex 2. Over the period 2020–2040, the total accumulated costs in the NECA and the NECA + levy & fund scenarios are $€_{2010}$6,200 million and 16,500 million, respectively.

With the method described above, investment costs per MWh of engine work output are calculated using the parameter 'engine work output with abatement equipment in use', which depends partly on the total installed power and partly on the number of hours at sea spent within the area where the considered policy instrument is in force. The more a vessel navigates using the abatement equipment, the lower the investment costs become per abated unit of NOx. The other cost component – O&M costs – does not depend on the power use if expressed in € per MWh of engine work output. This affects the relationship between the total annual abatement costs and hours at sea: O&M costs increase with more operative hours at sea while investment costs are constant. When calculating costs in € per MWh of engine work output, only the O&M cost component can be estimated independent of traffic pattern; investment costs as well as total abatement costs should be considered for a certain area where vessels spend a certain number of hours.

Time at sea in the area comprising the Baltic Sea and the North Sea (a potential NECA area) is a quite uncertain parameter in the calculations. Estimates of the time in the area for the different ship size categories used in the study have been made. It is assumed that for all ship types, the smallest categories spend more time in the area than the larger vessels. The time spent in the area by smaller vessels has been estimated to be 100 per cent (RoRo/ferries), 25 per cent (container vessels), or 50 per cent (all other ship types). These were judged reasonable numbers. The amount of fuel used by these small ships could be calculated based on the number of small ships, the time estimate and a generic value for installed engine power in the ships. Similar calculations for the larger vessels further verified that these assumptions allowed for reasonable assessments of the larger ship sizes. The final values were checked against the total amount of fuel used by different ship size categories. An overview of the estimated time spent by different ship types and size categories in the area is given in Annex 4.

Scenario-specific hours at sea were taken into account in Åström et al. (2014), where hours in NECA per ship category and size were applied together with fuel and power use for each category to estimate the total costs – but not in Winnes et al. (2016), where the cost intervals are based on the available ranges for each parameter rather than on fleet structure information. In the simplified method used in Winnes et al. (2016), it was implied that abatement would be used all the time, not just while navigating NECA area. This was done to enable cost comparisons for different technologies, since they are not all switched off outside a NECA. But due to the reasons described above this method is not preferable for estimating total costs of abatement within the Baltic Sea and the North Sea. Here, we include hours in NECA in the calculations instead of the total annual hours, which is the reason for significantly higher costs in both the private and in the social perspectives, compared to the numbers presented in Winnes et al. (2016).

GAINS model scenario setup

To analyse NOx deposition and health effects due to exposure to secondary particles, we use the GAINS model (Amann et al. 2012). Emission dispersion calculations in the model are based on simplified linear source-receptor matrices obtained from particular source-receptor simulations of the EMEP model (Simpson et al. 2012). Equation 2 describes the relationship between annual mean concentration of $PM_{2.5}$ at the receptor point, and emissions of precursors:

Equation 2

$$
\begin{aligned}
PM2.5_j &= \sum_{i\in I}\pi_{ij}^{A} * p_i + \sum_{i\in I}\sigma_{ij}^{A} * s_i + \\
&+ 0.5 * (\sum_{i\in I}\alpha_{ij}^{S} * a_i + \sum_{i\in I}\nu_{ij}^{S} * n_i) + \\
&+ 0.5 * \min(\max(0, \sum_{i\in I} c1 * \alpha_{ij}^{W} * a_i - \sum_{i\in I} c1 * \frac{14}{32} * \sigma_{ij}^{W} * s_i + k1_j), \sum_{i\in I} c2 * \nu_{ij}^{W} * n_i + k2_j)
\end{aligned}
$$

Where:

$PM_{2.5j}$	=	Annual mean concentration of $PM_{2.5}$ at receptor point j
p_i, s_i, n_i, a_i	=	Emissions of primary $PM_{2.5}$, SO_2, NOx and HN_3 in country i
$\alpha^{S,W}_{ij}$, $\nu^{S,W,A}_{ij}$, $\sigma^{W,A}_{ij}$, π^{A}_{ij}	=	Matrices with coefficients for reduced and oxidised nitrogen, sulphur and primary $PM_{2.5}$, for winter, summer and annual average

For modelling emissions on land, we use the latest public baseline scenario developed by IIASA in 2015 – ECLIPSE_V5a_CLE_base. This scenario is based on the baseline produced as supporting information for the European Commission's work on reviewing the Thematic Strategy on Air Pollution, as described in Amann et al. (2015). It is further updated with more recent information on population distribution, open biomass burning, oil and gas production, brick making, non-ferrous metals, and includes previously unaccounted or not separately distinguished sources such as wick lamps, diesel generators and high-emitting vehicles (Stohl et al. 2015).

Since GAINS operates with 5-year intervals, it is not possible to model effects for the years 2021–2024 directly. It is reasonable to assume that trends in health and environmental effects will follow emission trends in the considered scenarios. For the years 2025–2040, the trends for 'in-between' years are rather linear, so in order to estimate effects for those years we use interpolation. For the years 2021–2024, interpolation cannot be used because it would not reflect the rapid drop in NOx emissions expected in 2021 in the NECA + levy & fund scenario. In order to take into consideration the non-linear trend between 2020 and 2025, we use a scenario setup with shipping emissions for 2021 and land emissions and human population for 2020. We thus assume that there are no major changes in land emissions between 2020 and 2021. The effect trends between 2021 and 2025 are assumed to be linear; for these years we interpolate values.

The GAINS methodology for shipping emissions is described in Campling et al. (2013). Emissions from shipping in the European seas are divided into zones in the GAINS input dataset:

- Within the internal waters and the territorial seas (12 nautical miles from the internal waters' boundary) – for all the European seas together
- Within the exclusive economic zones (200 nautical miles from the internal waters' boundary)
- Outside the exclusive economic zones – not relevant for the Baltic Sea and the North Sea

To compile the GAINS input dataset for international shipping we use emissions as specified in Campling et al. (2013) for all sea regions except for the Baltic Sea and the North Sea. For these regions we replace the IIASA data with the calculated emission values for NOx specified in Annex 1. We allocate all emissions from the Baltic Sea and the North Sea to the exclusive economic zones and reduce the total emissions in the 12-mile zone accordingly. This adaptation is necessary since the entire European 12-mile zone is modelled as one emitting region in the GAINS model. With this model, a scenario for the Baltic Sea and the North Sea would thus imply emission reductions along the coastline of the Mediterranean Sea, for example. To avoid this we imply that emission reductions due to implementation of new policy instruments mainly take place outside the territorial seas. The calculated health impacts – and consequently the calculated monetary benefits – are therefore underestimations.

In the GAINS model, emissions from domestic shipping are accounted separately. To avoid double-counting (since our emission values include both domestic and international shipping), we subtract domestic emissions in the Baltic Sea and the North Sea from the GAINS country-specific input datasets in the same way as described in Åström et al. (2014). To account for emissions of other pollutants from domestic shipping, we also replace the values from Campling et al. (2013) with our own estimates (as specified in Table 3) for SOx, NMVOC and $PM_{2.5}$ (other particle fractions are recalculated assuming the same relations to $PM_{2.5}$ as in Campling et al. (2013)). Emissions of these pollutants do not significantly change over the period 2020–2040, which is the result of energy efficiency improvements that outweigh traffic growth.

Table 3. Projected emissions from domestic and international shipping of $PM_{2.5}$, SOx and NMVOC, ktonnes.

Year	$PM_{2.5}$		SOx		NMVOC	
	Baltic Sea	North Sea	Baltic Sea	North Sea	Baltic Sea	North Sea
2020	1.8	4.1	7.7	17.2	4.5	10.1
2025	1.8	4.1	7.7	17.1	4.5	10.1
2030	1.8	4.1	7.7	17.1	4.5	10.1
2035	1.8	4.1	7.7	17.1	4.5	10.1
2040	1.8	4.1	7.7	17.1	4.6	10.2

Since we do not imply increased use of LNG or EGR technologies in the cases of NECA and NECA + levy & fund, emission values for SOx, NMVOC and $PM_{2.5}$ are the same for all three considered scenarios. For some ships, ammonia emissions associated with SCR use might be treated with a catalyst, also resulting in decreased NMVOC emissions. However, since ammonia abatement is neither required in the Tier III regulations nor profitable from a ship perspective, we assume that very few ships would use this type of treatment and consider its effect on NMVOC emissions as negligible.

NOx deposition

Deposition of oxidised nitrogen on land is estimated with the GAINS model. Deposition maps for the years 2021 and 2040 in Annex 6 show the spatial distribution of oxidised nitrogen deposition across Europe (expressed in mg N/m^2 per year) for the three analysed scenarios. The maps take into account all emission sources contributing to deposition, including anthropogenic emissions on land and at sea, as well as emissions from natural sources. Expected positive effects on deposition from the introduction of the considered policy instruments are mostly seen in the coastal countries. In both policy instrument scenarios, reductions in nitrogen deposition compared to the baseline are already noticeable by 2021, see Figure 4 below.

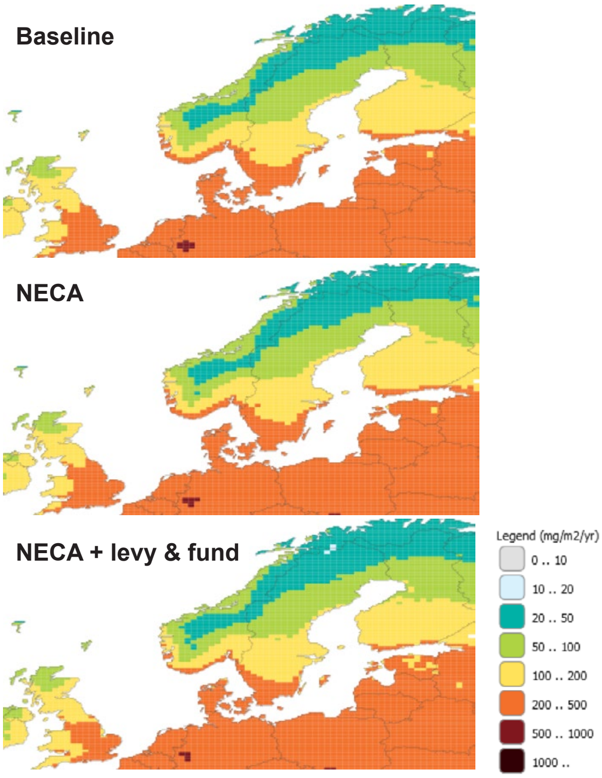

Figure 4. Deposition of oxidised nitrogen in the coastal areas in 2021.

To include estimates of deposition on the Baltic Sea and the North Sea, we use source-receptor tables presented in EMEP, 2016. Source-receptor tables for deposition of oxidised nitrogen are a product of EMEP model simulations analysing relations between emissions in chosen regions (sources) and deposition in other regions (receptors) attributable to the considered source regions. The tables are produced using specific meteorological conditions for each particular year.

In this study, we combine all regions into 'the Baltic Sea and the North Sea', 'other seas' and 'land'. We estimate deposition from shipping emissions in 2020–2040 by calculating 'deposition to emissions' ratios based on EMEP, 2016 and apply these ratios to emission estimates.

In 2014, deposited nitrogen (ktonnes N) in relation to nitrogen emitted in the Baltic Sea and North Sea (ktonnes N calculated from ktonnes NOx) amounts to:

- Deposited on the Baltic Sea and the North Sea – 0.28
- Deposited on other seas – 0.20
- Deposited on land – 0.49

These ratios indicate that most of the NOx emitted in the Baltic Sea and North Sea is deposited on land, at least for years with similar weather conditions as in 2014.

Deposition inputs from shipping in the Baltic Sea and the North Sea in the three considered scenarios are summarised in Annex 7. In the NECA scenario, the annual deposition in 2040 is reduced by 60 ktonnes of oxidised nitrogen deposited on land and by 34 ktonnes of oxidised nitrogen deposited on the Baltic Sea and the North Sea, compared to the baseline. In the NECA + levy & fund scenario, the numbers are 73 ktonnes and 42 ktonnes, respectively.

Health effects

To estimate reductions in adverse health effects caused by air pollution, we use both the GAINS model and the ALPHA-Riskpoll model (Holland et al. 2013, Holland 2014). In GAINS, calculated concentrations of secondary particles due to emissions from anthropogenic sources are further adjusted with respect to population density collocated with these concentrations. Population-weighted $PM_{2.5}$ concentrations for European countries are shown in Table 4 below – both the absolute numbers and the changes compared to the baseline for the two considered policy instruments. The concentrations per country are used as input in the ALPHA-Riskpoll model to assess adverse health effects attributable to this impact[1].

Table 4. European population-weighted concentrations from secondary $PM_{2.5}$, µg/m^3

	Absolute values			Reductions compared to baseline	
Year	**Baseline**	**NECA**	**NECA + L&F**	**NECA**	**NECA + L&F**
2021	8.98	8.97	8.95	0.002	0.030
2025	8.65	8.64	8.62	0.009	0.037
2030	8.47	8.45	8.43	0.015	0.036
2035	8.42	8.39	8.38	0.022	0.035
2040	8.50	8.47	8.46	0.029	0.035

1 The GAINS model also provides estimates of health effects (YOLL = years of life lost) attributable to the exposure to secondary $PM_{2.5.}$ However, the methodology for YOLL calculation in the GAINS model is very different from the methodology used in the ALPHA-Riskpoll model. ALPHA-Riskpoll operates with years of life lost during a considered year only, whereas the concept of YOLL in GAINS implies accumulated effects in population from this year onwards. This substantial methodological difference means that YOLL obtained in the two models are not directly comparable. In this study, we use the ALPHA-Riskpoll for health effect analysis.

The ALPHA-Riskpoll model enables analysis of a wide range of health effects from secondary $PM_{2.5}$ exposure, including mortality in adults and infants, respiratory and cardiac hospital admissions, and restricted activity days. Health effects per country are calculated by combining data on age distribution of population, population-weighted concentrations of secondary $PM_{2.5}$ and effect-specific dose-response relationships (Holland et al. 2013). The model uses the population age distribution projected for the years 2020, 2025, 2030 and 2040 – so health effects for the years 2022–2024, 2026–2029 and 2031–2039 are interpolated. For 2021, we use the concentrations of secondary $PM_{2.5}$ calculated for 2021 but assume the same population age distribution as for 2020.

The annual reductions in adverse health effects in European countries for the years 2025, 2030 and 2040 in the NECA and NECA + levy & fund scenarios, compared to baseline, are shown in Annex 8. Implementation of a NECA is expected to result in a gradual improvement in the health of the European population over the period 2020–2040. In the NECA scenario the results from the calculations show that some 1,700 premature deaths in adults and 4,100 additional cases of bronchitis in small children per year can be avoided in 2040, compared to the baseline scenario.

Combining a NECA with the introduction of a NOx levy & fund is found to significantly decrease the health impacts from air pollution. The calculated marginal impact of the added levy & fund on the annual number of reduced premature deaths is shown in Figure 5.

The calculated reductions in adverse health effects accumulated over the periods 2020–2030 and 2020–2040 are presented in Tables 5 and 6 below. The additional impact of the added levy & fund is found to be pronounced during the first ten years after the implementation and accounts for 70 per cent of the accumulated reduced effects over the period 2020–2040.

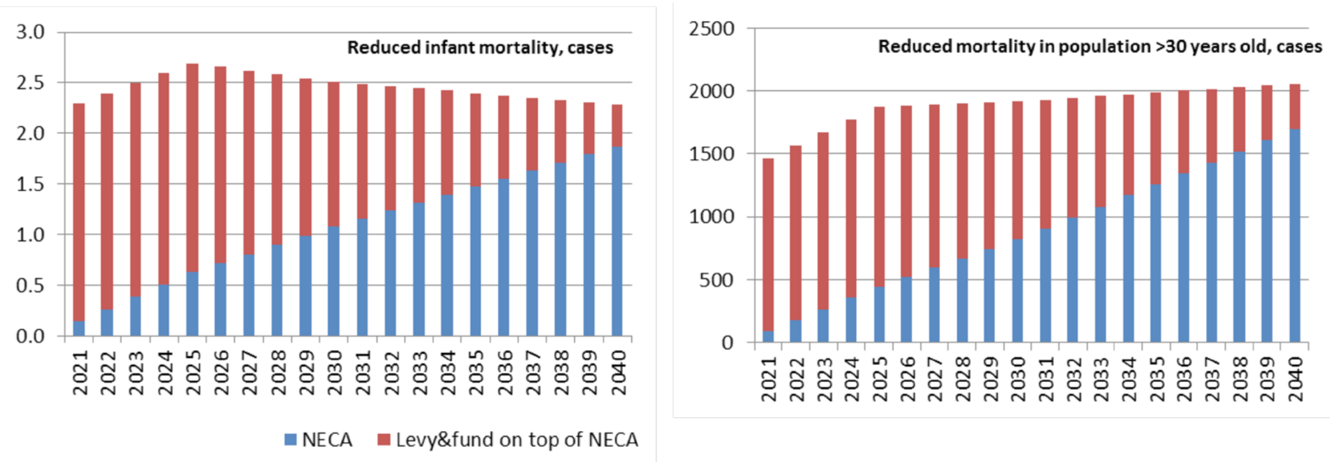

Figure 5. Reduced annual number of premature death cases in Europe.

Table 5. Calculated reductions of adverse health effects in Europe accumulated over the period 2020–2030.

Effect	Unit	NECA	NECA + L&F	L&F additional
Mortality, all ages	1000 life years lost	41	160	119
Chronic Bronchitis >27 years	Cases	3,693	14,215	10,522
Bronchitis in children, 6-12 years	Added cases	12,805	49,536	36,730
Respiratory Hospital Admissions, all ages	Cases	1,602	6,189	4,586
Cardiac Hospital Admissions, >18 years	Cases	1,171	4,525	3,354
Restricted Activity Days, all age	1000 days	5,184	19,908	14,724
Asthma symptom days, children 5-19 years	1000 days	141	543	403
Lost working days, 15-64 years	1000 days	1,217	4,767	3,550

Table 6. Calculated reductions of adverse health effects in Europe accumulated over the period 2020–2040.

Effect	Unit	NECA	NECA + L&F	L&F additional
Mortality, all ages	1000 life years lost	143	320	177
Chronic Bronchitis >27 years	Cases	13,353	29,178	15,826
Bronchitis in children, 6-12 years	Added cases	45,360	100,214	54,854
Respiratory Hospital Admissions, all ages	Cases	5,753	12,634	6,881
Cardiac Hospital Admissions, >18 years	Cases	4,197	9,226	5,029
Restricted Activity Days, all age	1000 days	18,852	41,055	22,203
Asthma symptom days, children 5-19 years	1000 days	499	1,101	602
Lost working days, 15-64 years	1000 days	4,190	9,423	5,232

Cost-benefit analysis

The method for economic valuation of health benefits applied in the ALPHA-Riskpoll model is described in Holland et al. 2005, Holland et al. 2013, and Holland 2014, among others. There are two main valuation metrics for health benefits:

- VOLY – Value of Life Year lost
- VSL – Value of Statistical Life

The VOLY method is based on life tables and gives results in terms of life expectancy. According to Holland et al. 2005, change in longevity aggregated across the population is the most relevant (and compliant with the WHO methodology) metric for valuation. The VSL method does not use life tables and instead operates with mortality rates and, unlike the VOLY method, allows estimation of 'attributable deaths'. This simplified method is widely used – for instance, it was applied for valuation of health benefits within the CAFE programme of the European Commission (Holland et al. 2005). It is also consistently used by US EPA and is the only metric for assessment of benefits considered in the US EPA Guidelines for Preparing Economic Analyses (US EPA 2010).

In this analysis, we use the same economic values of adverse health effects as used by the European Commission for its 2013 Clean Air Package (Holland, 2014).

The valuations of reduced adverse health effects are presented as median VOLY and mean VSL. All economic values are converted into $€_{2010}$. For all the European countries, both VOLY and VSL valuations of a certain health effect are the same, meaning that in this study all European lives are assigned the same economic value.

The results of the cost-benefit analysis for the NECA scenario and for the NECA + levy & fund scenario are summarised in Tables 7 and 8, respectively. They indicate that even as early as 2021, introduction of a NECA would result in health benefits estimated at 80–240 million $€_{2010}$ per year, and by 2040 this number increases to $€_{2010}$1,150–4,520 million. In the NECA + levy & fund scenario, much higher health benefits are expected in 2021, amounting to $€_{2010}$1,220–3,950 million. In 2040, the corresponding number would be $€_{2010}$1,390–5,490 million. Values for 2035 are interpolated since this year is not present in the ALPHA-Riskpoll model.

Over 90 per cent of the total benefits is expected to occur in coastal countries – France, UK, Germany, Netherlands, Poland, Belgium, Denmark, Sweden, Russia, Lithuania, Finland, Latvia, Norway, and Estonia. Detailed data on the calculated health benefits for these countries are presented in Annex 9. For several countries and years, one can see zero health benefits from the introduction of the considered policy instruments. This is due to the specific spatial population distribution and relatively high contribution from stationary sources on land to the $PM_{2.5}$ levels. This results in low relative influence on the levels from ship emissions and thus a lower effect of the calculated changes in emissions from the modelled policy instruments. The GAINS model cannot capture very small concentration changes – this effect is seen, in particular, for the European part of Russia, where the introduction of a NECA does not seem to bring any additional health benefits until 2025–2030.

The calculated accumulated health benefits for the period 2020–2040 (median VOLY) are presented in Annex 2. The shapes of the curves are very similar to those for accumulated emissions, since with the same population age distributions and the same response functions in different scenarios, benefits-to-emission relations are the same. Over the period 2020–2040, the accumulated health benefits in the NECA scenario are estimated at $€_{2010}$12,700 million, and in the NECA + levy & fund scenario at $€_{2010}$28,300 million.

Table 7. Cost-benefit analysis, results for the NECA scenario.

Result	Unit	2021	2025	2030	2035	2040	Acc.
Median VOLY							
Health benefits	Million $€_{2010}$	80	350	620	880	1,150	12,700
Net health benefits	Million $€_{2010}$	40	180	320	450	580	6,600
Benefit-cost ratio	-	2.2	2.1	2.1	2.1	2.0	2.1*
Mean VSL							
Health benefits	Million $€_{2010}$	240	1,190	2,200	3,360	4,520	-
Net health benefits	Million $€_{2010}$	210	1,020	1,900	2,930	3,960	-
Benefit-cost ratio	-	7.2	7.0	7.4	7.8	8.0	7.5*

*Average over the period 2020—2040

Table 8. Cost-benefit analysis, results for the NECA + levy & fund scenario.

Result	Unit	2021	2025	2030	2035	2040	Acc.
Median VOLY							
Health benefits	Million $€_{2010}$	1,220	1,490	1,450	1,420	1,390	28,300
Net health benefits	Million $€_{2010}$	400	550	590	670	670	11,800
Benefit-cost ratio	-	1.5	1.6	1.7	1.9	1.9	1.7*
Mean VSL							
Health benefits	Million $€_{2010}$	3,950	5,050	5,150	5,320	5,490	-
Net health benefits	Million $€_{2010}$	3,130	4,110	4,280	4,560	4,770	-
Benefit-cost ratio	-	4.8	5.4	5.9	7.0	7.6	6.2*

*Average over the period 2020—2040

Calculating accumulated values is reasonable for benefit valuation using VOLY, but not VSL. The reason is the risk of double-counting of impacts on mortality with the VSL approach, which is based on number of fatalities rather than shortened life expectancy. VSL is thus only suitable for consideration in relation to a specific year.

Estimates of costs and health benefits are both associated with relatively large uncertainties. In this study, we use weighted average values for costs and median VOLY / mean VSL values for benefits. To better illustrate uncertainties, the accumulated costs and benefits for both scenarios are also presented in interval form in Annex 10.

In both scenarios, the benefits of implementation of the policy instruments are higher than costs. The benefit-cost ratios (presented in Tables 7 and 8) indicate that both policy instruments seem cost-effective. In the NECA scenario, the benefit-cost ratio is estimated at 2.0 (median VOLY) to 8.0 (mean VSL), with average (over the period 2020—2040) values of 2.1 (median VOLY) and 7.5 (mean VSL). In the NECA + levy & fund scenario, the ratio is 1.5 (median VOLY) to 7.6 (mean VSL), with average values of 1.7 (median VOLY) and 6.2 (mean VSL). The average benefit-cost ratio is lower in the NECA + levy & fund scenario because the significant benefits from retrofitting a large number of relatively old vessels with SCR are associated with higher costs of retrofitting SCR, compared to installing SCR on a new-build.

Net health benefits are the difference between abatement costs and health benefits. Values in Tables 7 and 8 indicate that for both of the considered policy instruments total health benefits in Europe exceed emission abatement costs. The relative difference between net health benefits in the two scenarios tends to decrease between 2020 and 2040. Accumulated net health benefits (median VOLY) in the NECA scenario are $€_{2010}$6,600 million; for the NECA + levy & fund scenario the corresponding figure is $€_{2010}$11,800 million.

The additional annual net health benefits from levy & fund in the NECA + levy & fund scenario decrease from $€_{2010}$ 360–2,900 million in 2021 to $€_{2010}$ 90–810 million in 2040. The accumulated additional net benefits over the period 2020–2040 are estimated at $€_{2010}$ 5,200 million(median VOLY). The marginal benefit-cost ratio averaged over the same time period is 1.5 (median VOLY) with the annual variations of 1.5–1.7.

Sensitivity analysis

In the sensitivity analysis scenario (also referred to as 'SA' in the present study), we investigate the same three policy scenarios (baseline, NECA and NECA + levy & fund) under the assumption that the efficiency increase in fuel consumption is less optimistic than implied in the main analysis. All other parameters are the same as in the main analysis.

The annual efficiency increase in the sensitivity analysis is then assumed to be 0.84 per cent for all vessel types, compared to the main analysis assumption of 1.3–2.3 per cent. Energy efficiency recalculations are loosely based on what is expected to be obtained by IMO's Energy Efficiency Design Index regulations stipulating the energy efficiency improvements of vessels based on their size.

As a result of the lower increase in fuel efficiency, all emissions increase in all three considered scenarios, see Figure 6 and Table 9 below. The baseline NOx emission trend is ascending, and the remaining emissions in the NECA and NECA + levy & fund scenarios are higher than in the main analysis. At the same time, relative (compared to the baseline) NOx emission reductions due to the implementation of policy instruments are also higher. Costs and environmental/health benefits both increase in absolute numbers, compared to the main analysis, since larger amounts of emissions may be removed by using SCR.

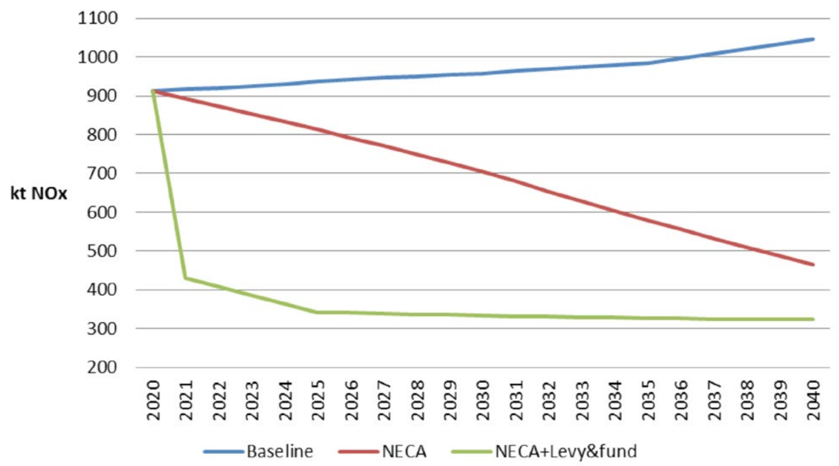

Figure 6. Projections of NOx emissions – sensitivity analysis.

Table 9. Projected emissions from domestic and international shipping of $PM_{2.5}$, SOx and NMVOC, ktonnes – sensitivity analysis.

Year	$PM_{2.5}$		SOx		NMVOC	
	Baltic Sea	North Sea	Baltic Sea	North Sea	Baltic Sea	North Sea
2020	2.1	4.7	8.9	19.9	5.2	11.7
2025	2.2	4.9	9.3	20.8	5.5	12.2
2030	2.4	5.2	9.9	22.1	5.9	13.0
2035	2.5	5.6	10.5	23.5	6.3	13.9
2040	2.7	5.9	11.2	25.0	6.7	14.9

The differences in the main results between the two scenarios sets are summarised in Annex 11 and also presented in Annex 8 (health effects), Annex 6 (spatial distribution of NOx deposition), and Annex 9 (health benefits by country).

Higher emissions, compared to the main analysis, result in higher deposition of oxidised nitrogen in coastal areas, clearly seen on the maps in Annex 6. Annual reduction in oxidised nitrogen deposition on land (in ktonnes N) is up to 30–40 per cent higher in the sensitivity analysis scenarios than in the main analysis.

Health benefits from implementation of the policy instruments exceed the associated abatement costs in the sensitivity analysis scenarios, so that the net health benefits are positive and higher than in the main analysis. The reduction in negative health effects in Europe due to the implementation of the considered policy instruments is up to 30–32 per cent higher than in the case of more optimistic energy efficiency development in the main analysis. The associated health benefits (median VOLY) accumulated over the period 2020—2040 are 27 per cent higher than in the main analysis. This is the average number for the whole of Europe; variations in individual coastal countries can be seen in Annex 9.

The results of the sensitivity analysis indicate that if energy efficiency development does not follow the trend assumed in the main analysis (meaning that future fuel use and emissions are underestimated in the main analysis), implementation of policy instruments such as a NECA or NECA in combination with a NOx levy & fund would result in avoidance of more adverse health effects and thus become even more relevant.

Discussion

The results of this study indicate that both NECA alone and NECA combined with a levy & fund are cost-effective policy instruments enabling significant reductions of NOx emissions and consequent reductions in adverse health effects during 2020–2040. For comparison, the benefit-cost ratio for a 'NECA in the Baltic Sea and the North Sea' scenario presented in Åström et al. (2014) is 1.6–9.3, with health benefits in Europe estimated at $€_{2010}$380–2,170 million and abatement costs of $€_{2010}$233 million ($€_{2010}$1.4/kg NOx). Åström et al. (2014), however, used certain assumptions not taken into account in this analysis. In particular, the fuel mix includes a rather large share of heavy fuel oil (it is assumed that vessels are equipped with scrubbers to comply with sulphur emission regulations). A more significant assumption concerns extra investments into LNG induced by NECA implementation. This assumption, not considered in this study, looks reasonable. Currently, the main constraint that discourages shipping companies from switching to LNG is the price of LNG engines: $€_{2010}$220–940/kW on top of the price of a conventional engine, according to Winnes et al. (2016). At the same time, there are no indications of high maintenance costs for such engines, unlike for SCR where the costs of catalysts and urea constitute a significant part of the total costs. The most important and yet the most uncertain factor in future investment decisions is the price difference between LNG and conventional fuels – primarily MGO. Åström et al. (2014), uses the end-user fuel price estimates from the Danish Maritime Authority (2012) – $€_{2010}$610 per tonne for LNG and $€_{2010}$885 per tonne for MGO.

LNG is thus assumed to be ~30 per cent cheaper than marine gasoil. In January 2016, US LNG contract prices varied from USD240 to 375 per tonne (USD295 per tonne for north-western Europe) (ICIS, 2017), while the global-average MGO price for the same month was around USD514 per tonne (Bunker Index, 2017). If LNG continues to be a significantly cheaper option, fuel savings will outweigh higher engine costs, and the rate of investment in LNG-fuelled ships will be much higher than if the price difference were smaller. Switching from conventional fuel to LNG results in reduced emissions of SOx particles and CO_2, and is consequently a suitable option to comply with requirements in existing and considered regulations on these three pollutants. It is, however, associated with higher emissions of methane and a range of constraints such as limited availability and extra space requirements (Winnes et al. 2016).

In this study, we have not considered alternatives to SCR to comply with NECA requirements, such as EGR and alternative fuels (LNG, methanol). EGR is a viable option that is commercially available and is often used in combination with water-based technologies, according to Winnes et al. (2016). It is however a much less established technology than SCR and its costs are associated with larger uncertainties. We estimate that the costs for reducing NOx are similar for SCR and EGR (at least for new builds), so the use of EGR is not expected to change the results significantly. Methanol-fuelled ships are too new on the market and the cost data is too scarce and uncertain. Our assumption of 'no increased LNG use' in the NECA scenario might be too cautious. As discussed above, extra costs for LNG as a means to reduce NOx emissions might be lower than SCR costs, which means we might overestimate the total abatement costs in the NECA and the NECA + levy & fund scenarios – and underestimate the associated health benefits. Introducing a NOx levy and fund might further encourage increased slow steaming – a measure to decrease levy-associated costs by reducing emissions.

The total costs in this study are estimated from the social cost perspective. However, when designing and implementing a NOx levy and fund it is important to consider the costing perspective adopted by shipping companies when making investment decisions. SCR cost is the main factor determining the size of levy that will encourage most of the existing vessel fleet to take up abatement instead of paying the levy The levy should therefore be at least as high as net retrofit SCR costs. Depending on the investment interest rate and investment lifetime chosen by a particular shipping company for cost annualisation, the size of the levy needed to outweigh the perceived SCR cost estimate will vary. At the same time, as concluded in Winnes et al. (2016), the total costs in the NECA + levy & fund scenario are virtually insensitive to levy size because all the revenues are returned to the sector. Thus, the values of interest rate and investment lifetime chosen for the private cost perspective do affect the effective levy size but do not affect the total social costs if all the revenue is returned to shipping companies.

The cost-benefit analysis in this study is limited to the effects attributable to exposure to concentrations of secondary $PM_{2.5}$. Other impacts, e.g. exposure to elevated ground-level ozone levels or NO_2 levels, are left outside the scope of the analysis due to the lack of input data. This means that potential benefits due to introduction of new policy instruments are underestimated.

Conclusions

The estimated costs and benefits due to the potential implementation of NECA and NECA combined with NOx levy and fund are summarised in Table 10.

Table 10. Calculated costs and benefits in the NECA scenario and the NECA + levy & fund scenario using median VOLY and mean VSL, €$_{2010}$million.

Year	NECA					NECA + levy & fund				
	Benefits		Costs	Net benefits		Benefits		Costs	Net benefits	
	VOLY	VSL		VOLY	VSL	VOLY	VSL		VOLY	VSL
2021	80	240	30	40	210	1,220	3,950	820	400	3,130
2025	350	1,190	170	180	1,020	1,490	5,050	940	550	4,110
2030	620	2,200	300	320	1,900	1,450	5,150	870	590	4,280
2035	880	3,360	430	450	2,930	1,420	5,320	760	670	4,560
2040	1,150	4,520	560	580	3,960	1,390	5,490	720	670	4,770
2020–2040 accumulated	12,700	-	6,200	6,600	-	28,300	-	16,500	11,800	-

The presented calculations show that the introduction of a NECA in the Baltic Sea and the North Sea in 2021 would result in total accumulated NOx emission reductions of 4,500 ktonnes during 2020–2040, on top of the baseline. Emissions gradually decrease from 800 ktonnes in 2020 to 310 ktonnes in 2040 (a reduction by 410 ktonnes compared to the baseline value in 2040), following the annual fleet renewal rates. Emission reduction costs (from a social perspective) are estimated at €$_{2010}$1.38/kg NOx. Annual costs increase in line with the declining emissions – from €$_{2010}$30 million in 2021 to 560 million in 2040, resulting in an accumulated value for the whole period of €$_{2010}$6,200 million. The calculated accumulated net health benefits (median VOLY) from NECA implementation would amount to €$_{2010}$6,600 million, with a benefit-cost ratio of 2.1.

Combining a NECA with the introduction of the NOx levy and fund effective from 2021 is expected to enable further emission reductions by encouraging the retrofitting of SCR to vessels built before 2021, instead of paying the levy. Assuming that 75 per cent of existing Tier I and Tier II vessels are retrofitted with SCR, the NOx emissions would drop to 370 ktonnes as early as 2021 and further decrease to 220 ktonnes in 2040 (500 ktonnes lower than the baseline). The accumulated emission reduction over the period 2020–2040 is estimated at 9,900 ktonnes at a cost of €$_{2010}$1.68 per kg NOx. Annual costs vary between €$_{2010}$720 and 940 million, resulting in an accumulated cost for the whole period of €$_{2010}$16,500 million. The accumulated net health benefits (median VOLY) are €$_{2010}$11,800 million, with a benefit-cost ratio of 1.7.

In both scenarios, health improvements would primarily be experienced in coastal countries. Germany, France and the United Kingdom are expected to benefit the most. Together, the fourteen coastal states around the Baltic Sea and the North Sea are expected to account for more than 90 per cent of the total health benefits resulting from the reduced shipping emissions.

In addition to improved health, introduction of both policy instruments would bring ecosystem benefits in the form of decreased deposition of oxidised nitrogen. The estimated deposition reduction from the introduction of a NECA would be 60 ktonnes N on land and 34 ktonnes N in the Baltic Sea and the North Sea in 2040. If a levy & fund were introduced in addition to the NECA, the numbers for the same year would be 73 ktonnes and 42 ktonnes, respectively.

If the annual increase in energy efficiency is 35 per cent lower than assumed in the main analysis (the case considered in the sensitivity analysis), the health and environmental effects in 2040 and the accumulated health benefits (median VOLY) due to the implementation of the two considered policy instruments, would both increase by about a third, compared to the main analysis results.

In the short-term perspective (2020–2030), the introduction of a levy & fund to complement a NECA shows great advantages, compared to the case of NECA introduction alone. The additional emission reduction in 2021 is estimated at 400 ktonnes NOx; in 2030 it will decrease to 290 ktonnes NOx. The total accumulated additional emission reduction over the period 2020–2030 would constitute 3,660 ktonnes, at an additional cost of $€_{2010}$ 7,100 million. The accumulated additional health benefits associated with this emission reduction are valued at $€_{2010}$10,500 million (median VOLY), implying accumulated additional net health benefits of $€_{2010}$3,400 million. This is due, among other things, to the avoidance of about 120 thousand life years lost (all ages), 37 thousand additional cases of bronchitis in children (6–12 years), and 4 thousand lost working days (15–64 years) over the period 2020–2030. A levy & fund thus appears to be a very effective complement to a NECA with the potential to bring noticeable health and environmental benefits shortly after its enforcement.

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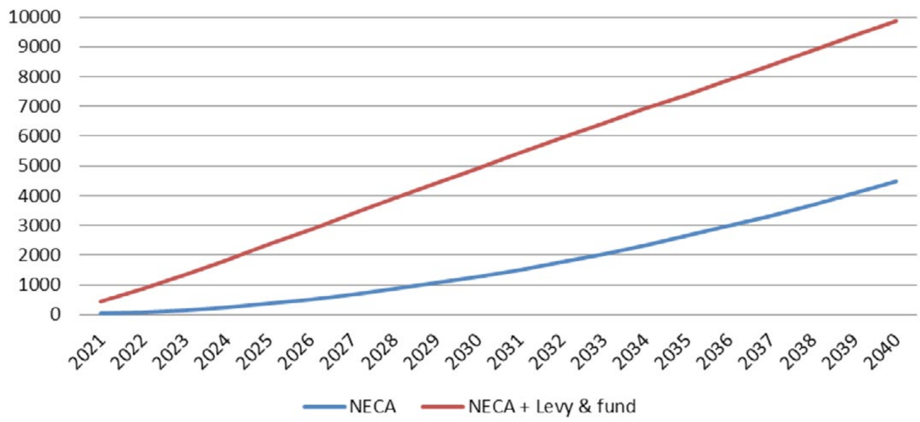
Annex 1. NOx emissions by categories

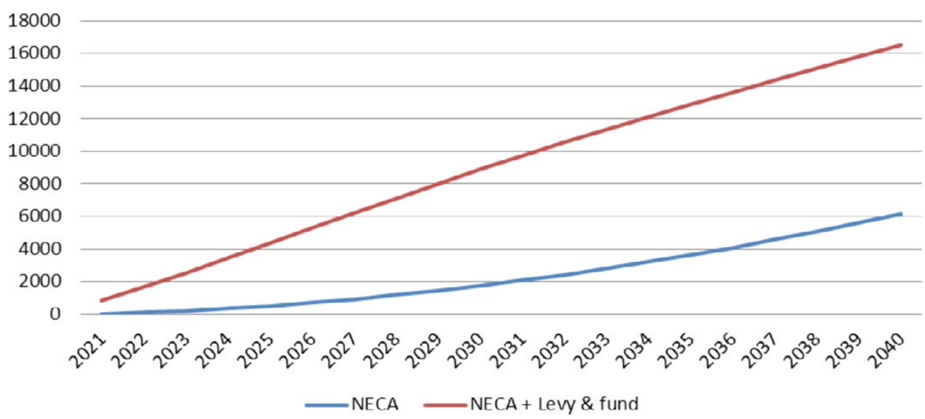
Year	NOx emissions, kt							
	Boilers	Tier 0	Tier I	Tier II	Tier III (>2021)	Tiers I, II	LNG	Total
		No SCR	No SCR	No SCR	New SCR	Retrofit SCR		
2020	1.54	147.3	372.1	277.0	-	-	0.23	798
Baseline								
2021	1.54	118.6	367.6	304.0	-	-	0.25	792
2022	1.54	89.9	363.2	331.1	-	-	0.28	786
2023	1.54	61.3	358.7	358.2	-	-	0.30	780
2024	1.53	32.6	354.3	385.3	-	-	0.32	774
2025	1.53	4.0	349.8	412.4	-	-	0.34	768
2030	1.52	-	188.7	550.4	-	-	0.44	741
2035	1.51	-	23.6	690.3	-	-	0.54	716
2040	1.50	-	-	712.9	-	-	0.65	715
NECA								
2021	1.54	118.6	367.6	277.1	2.1	-	0.25	767
2022	1.54	89.9	363.2	277.1	4.4	-	0.28	736
2023	1.54	61.3	358.7	277.2	6.6	-	0.30	706
2024	1.53	32.6	354.3	277.2	8.8	-	0.32	675
2025	1.53	4.0	349.8	277.3	11.1	-	0.34	644
2030	1.52	-	188.7	278.1	55.2	-	0.44	524
2035	1.51	-	23.6	279.4	99.0	-	0.54	404
2040	1.50	-	-	161.5	142.3	-	0.65	306
NECA + levy & fund								
2021	1.54	118.6	91.9	69.26	2.1	82.9	0.25	367
2022	1.54	89.9	90.8	69.28	4.4	82.4	0.28	339
2023	1.54	61.3	89.7	69.29	6.6	81.9	0.30	311
2024	1.53	32.6	88.6	69.31	8.8	81.4	0.32	283
2025	1.53	4.0	87.4	69.32	11.1	76.3	0.34	250
2030	1.52	-	47.2	69.54	55.2	56.1	0.44	230
2035	1.51	-	5.9	69.85	99.0	53.2	0.54	230
2040	1.50	-	-	40.38	142.3	35.1	0.65	220

Annex 2. Accumulated results

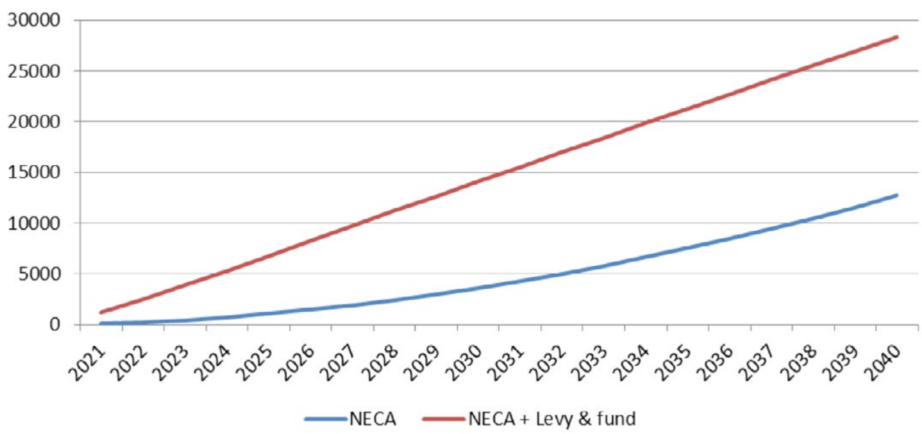
Accumulated NOx emission reductions, kt



Accumulated abatement costs on top of baseline, million €$_{2010}$



Accumulated health benefits (median VOLY), million €$_{2010}$



Annex 3. SCR costs

Technology parameters, weighted average values

- Installed power, per vessel – 13.4 MW,
- Engine work output with abatement equipment being operated, per vessel – ~5000 MWh,
- Equipment lifetime for new vessels and Tier II vessels – 26 years,
- Equipment lifetime for Tier I retrofit vessels – 15 years,
- NOx emission reduction for new vessels and Tier II vessels – 9.4 kg/MWh,
- NOx emission reduction for Tier I retrofit vessels – 11.9 kg/MWh

Other parameters and resulting costs

Method and data sources for estimating the low, central and high values of these cost components are described in detail in Winnes et al. (2016).

Parameter	Unit	New SCR	Retrofit SCR	
			on Tier II	on Tier I
Cost parameters				
Investment costs, total	€$_{2010}$/kW	61.3	88.7	88.7
Investment costs, total	€$_{2010}$/vessel	711,348	1,029,251	1,029,251
Urea consumption	kg/MWh	11.5	11.5	11.5
Urea cost	€$_{2010}$/kg	0.18	0.18	0.18
Catalyst replacement	€$_{2010}$/MWh	0.6	0.6	0.6
Labour demand	hours/year	8.0	8.0	8.0
Labour cost	€$_{2010}$/hour	36.0	36.0	36.0
O&M costs	€$_{2010}$/MWh	2.7	2.7	2.7
Investment costs, annual, social perspective	€$_{2010}$/MWh	9.4	13.5	19.4
Investment costs, annual, 5%-15 years	€$_{2010}$/MWh	15.8	22.9	22.9
Investment costs, annual, 7%-12 years	€$_{2010}$/MWh	20.7	29.9	29.9
Investment costs, annual, 10%-10 years	€$_{2010}$/MWh	26.7	38.6	38.6
Investment costs, annual, 12%-7 years	€$_{2010}$/MWh	36.0	52.0	52.0
Investment costs, annual, 15%-5 years	€$_{2010}$/MWh	49.0	70.8	70.8
Investment costs, annual, 7%-5 years	€$_{2010}$/MWh	40.0	57.9	57.9
Total annual costs per kg removed NOx				
Social perspective (4%-25 years), low	€$_{2010}$/kg NOx	0.49	1.57	1.74
Social perspective (4%-25 years), central	€$_{2010}$/kg NOx	1.38	1.86	2.03
Social perspective (4%-25 years), high	€$_{2010}$/kg NOx	2.24	2.24	2.42
Private perspective, 5%-15 years, central	€$_{2010}$/kg NOx	1.97	2.72	2.16
Private perspective, 7%-12 years, central	€$_{2010}$/kg NOx	2.48	3.47	2.75
Private perspective, 10%-10 years, central	€$_{2010}$/kg NOx	3.13	4.40	3.49
Private perspective, 12%-7 years, central	€$_{2010}$/kg NOx	4.11	5.82	4.62
Private perspective, 15%-5 years, central	€$_{2010}$/kg NOx	5.49	7.82	6.20
Private perspective, 7%-5 years, central	€$_{2010}$/kg NOx	4.54	6.44	5.11

Annex 4. Fleet structure

Ship category-specific parameters, values assumed for 2030

Ship category	Lifetime, years	Fuel consumption, kt		Hours at sea in the Baltic Sea and the North Sea		
		MGO	LNG	Small	Medium	Large
Bulk carrier	26	697	14	2,750	110	110
Chemical tanker	26	1,534	32	2,750	220	220
Container ship	25	3,752	84	2,750	935	935
General cargo	26	1,595	31	1,375	110	110
LG tanker	29	222	4	2,750	165	165
Oil tanker	26	769	16	2,750	440	440
RoRo cargo	27	875	25	2,750	1,210	1,210
Ferry	27	2,114	44	5,500	5,500	5,500
Cruise	27	298	6	2,750	1,045	1,045
Vehicle carrier	27	327	18	2,750	1,210	1,210
TOTAL	-	12,183	274	-	-	-

Distribution of MGO consumption by engine type and ship size within a ship category

Ship category	Slow-speed diesel engine			Medium-speed diesel engine			High-speed diesel engine			Of total MGO*
	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large	
Bulk carrier	3%	48%	29%	0%	1%	1%	1%	8%	5%	97%
Chemical tanker	15%	33%	5%	4%	9%	1%	7%	14%	2%	90%
Container ship	1%	9%	64%	0%	0%	3%	0%	2%	17%	96%
General cargo	21%	6%	1%	33%	9%	2%	20%	5%	1%	98%
LG tanker	5%	10%	33%	3%	6%	21%	2%	3%	12%	95%
Oil tanker	3%	14%	50%	0%	0%	1%	1%	5%	18%	92%
RoRo cargo	4%	3%	10%	11%	7%	25%	9%	6%	21%	96%
Ferry	0%	0%	1%	15%	9%	33%	10%	6%	23%	97%
Cruise	0%	0%	2%	4%	4%	60%	1%	1%	21%	93%
Vehicle carrier	1%	34%	41%	0%	2%	2%	0%	8%	9%	97%

* The remaining marine gasoil (2–10%, depending on the ship category) is consumed in boilers

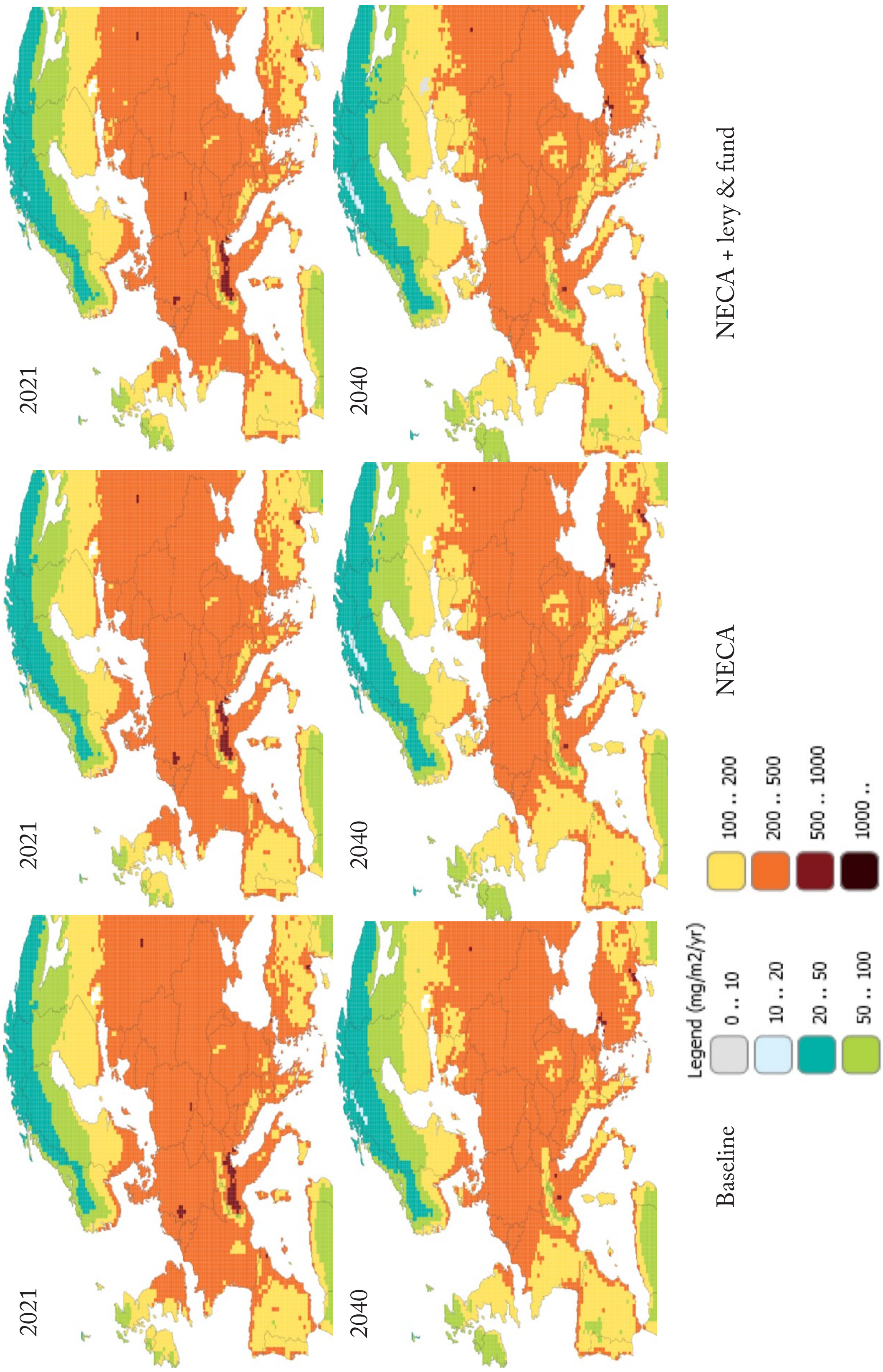
Annex 5. Total annual abatement costs

Year	Technology	Costs, million $€_{2010}$					
		low		central (used in CBA)		high	
		NECA	NECA + L&F	NECA	NECA + L&F	NECA	NECA + L&F
2021	nSCR	12	12	34	34	56	56
	rSCR-II	-	261	-	310	-	373
	rSCR-I	-	409	-	475	-	567
	TOTAL	12	682	34	819	56	995
2022	nSCR	24	24	68	68	111	111
	rSCR-II	-	261	-	310	-	373
	rSCR-I I	-	404	-	469	-	560
	TOTAL	24	689	68	847	111	1,044
2023	nSCR	37	37	102	102	167	167
	rSCR-II	-	261	-	310	-	373
	rSCR-I	-	399	-	464	-	553
	TOTAL	37	697	102	876	167	1,093
2024	nSCR	49	49	136	136	222	222
	rSCR-II	-	261	-	310	-	373
	rSCR-I	-	394	-	458	-	546
	TOTAL	49	704	136	904	222	1,142
2025	nSCR	61	61	171	171	278	278
	rSCR-II	-	265	-	310	-	378
	rSCR-I	-	393	-	457	-	545
	TOTAL	61	719	171	941	278	1,202
2030	nSCR	107	107	298	298	487	487
	rSCR-II	-	269	-	319	-	384
	rSCR-I	-	214	-	249	-	297
	TOTAL	107	590	298	866	487	1,168
2035	nSCR	154	154	429	429	700	700
	rSCR-II	-	251	-	297	-	358
	rSCR-I	-	25	-	29	-	35
	TOTAL	154	430	429	756	700	1,092
2040	nSCR	202	202	563	563	917	917
	rSCR-II	-	135	-	160	-	193
	rSCR-I	-	-	-	-	-	-
	TOTAL	202	337	563	723	917	1,110

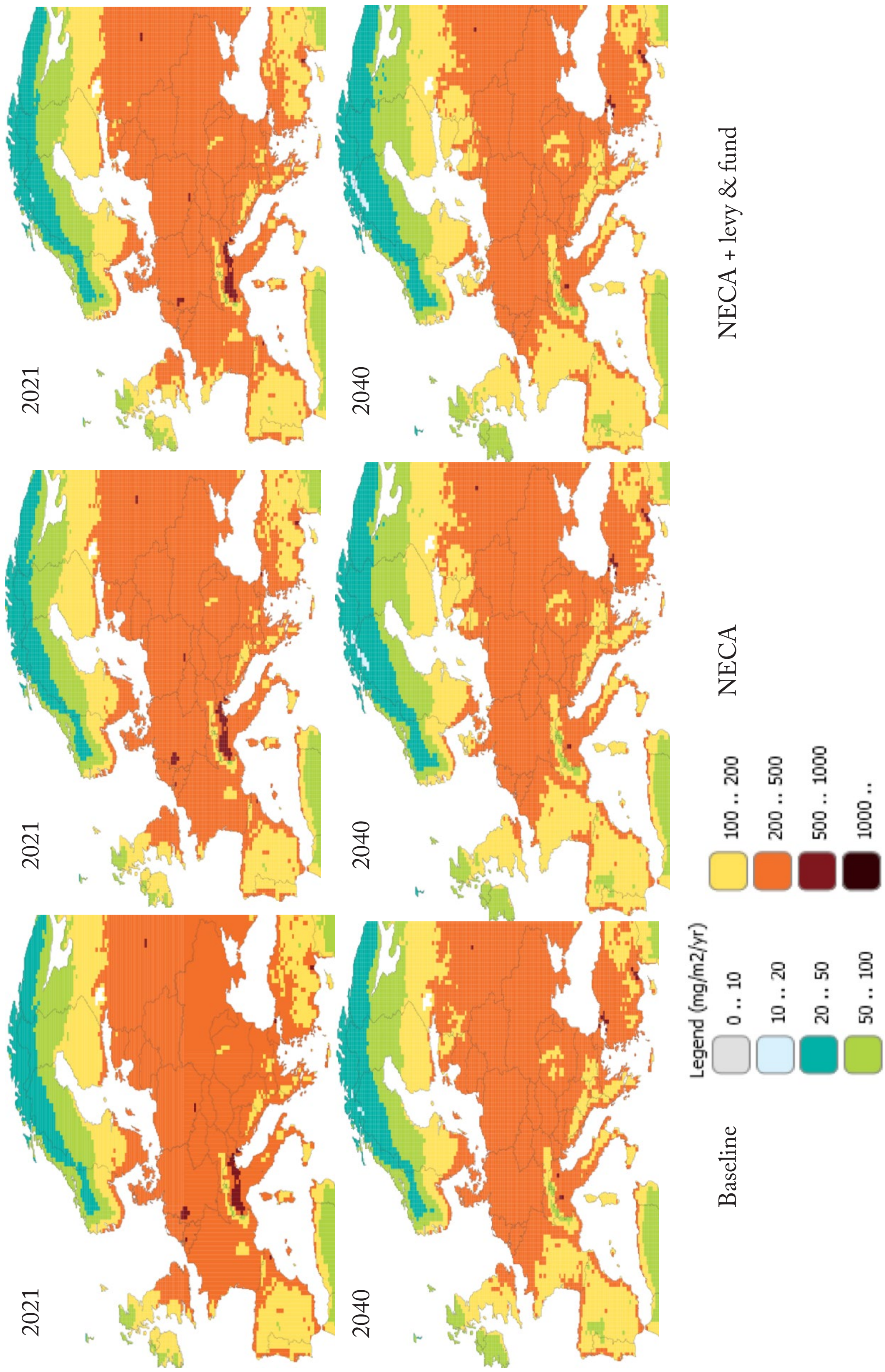
nSCR – SCR on new vessels, rSCR-II and rSCR-I – retrofit SCR – conversion from Tier II and Tier I

Annex 6. NOx deposition across Europe

Main analysis



Sensitivity analysis



Annex 7. Total NOx deposition

Year	Emissions, kt NOx	Deposition of N emitted in the Baltic and North Seas, kt N			Reduction compared to the baseline, kt N		
		on Ba, No*	on other seas	on land	on Ba, No*	on other seas	on land
				Baseline			
2020	798	66.9	47.4	118.0	-	-	-
2021	792	66.4	47.0	117.1	-	-	-
2022	786	65.9	46.7	116.2	-	-	-
2023	780	65.4	46.3	115.3	-	-	-
2024	774	64.9	46.0	114.5	-	-	-
2025	768	64.4	45.6	113.6	-	-	-
2030	741	62.1	44.0	109.6	-	-	-
2035	716	60.0	42.5	105.9	-	-	-
2040	715	59.9	42.4	105.7	-	-	-
				NECA			
2021	767	64.3	45.5	113.4	2.1	1.5	3.7
2022	736	61.7	43.7	108.9	4.2	2.9	7.3
2023	706	59.1	41.9	104.3	6.2	4.4	11.0
2024	675	56.5	40.1	99.8	8.3	5.9	14.7
2025	644	54.0	38.2	95.2	10.4	7.4	18.3
2030	524	43.9	31.1	77.5	18.2	12.9	32.1
2035	404	33.9	24.0	59.7	26.1	18.5	46.1
2040	306	25.6	18.2	45.2	34.3	24.3	60.5
				NECA + levy & fund			
2021	367	30.7	21.8	54.2	36.1	25.6	63.8
2022	339	28.4	20.1	50.1	38.0	26.9	67.0
2023	311	26.0	18.4	45.9	39.8	28.2	70.3
2024	283	23.7	16.8	41.8	41.7	29.5	73.5
2025	250	20.9	14.8	37.0	43.9	31.1	77.5
2030	230	19.3	13.7	34.0	45.1	31.9	79.6
2035	230	19.3	13.7	34.0	42.8	30.3	75.6
2040	220	18.4	13.1	32.5	41.6	29.4	73.3

*The Baltic Sea and the North Sea

Annex 8. Annual reductions in health effects in Europe caused by exposure to concentrations of secondary $PM_{2.5}$

Effect	Mortality, all ages, 1000 life years lost	Mortality, >30 years, premature deaths	Infant mortality, premature deaths	Chronic Bronchitis, >27 years, cases	Bronchitis in children, 6-12 years, added cases	Respiratory Hospital Admissions, all ages, cases	Cardiac Hospital Admissions, >18 years, cases	Restricted Activity Days, all ages, 1000 days	Asthma symptom days, children 5-19 years, 1000 days	Lost working days, 15-64 years, 1000 days
2021										
NECA	0.9	90	0.1	74	260	32	24	102	3	26
NECA + L&F	14.0	1,463	2.3	1,198	4,232	524	385	1,667	46	421
NECA SA	0.8	80	0.1	66	232	28	21	92	3	23
NECA + L&F SA	16.1	1,689	2.7	1,382	4,886	606	444	1,924	54	485
2025										
NECA	4.0	443	0.6	354	1,235	154	113	496	14	119
NECA + L&F	16.9	1,875	2.7	1,497	5,222	652	477	2,095	57	504
NECA SA	3.9	436	0.6	346	1,206	152	111	484	13	116
NECA + L&F SA	19.4	2,144	3.1	1,709	5,965	746	546	2,393	65	575
2030										
NECA	7.0	819	1.1	639	2,200	277	202	899	24	206
NECA + L&F	16.4	1,915	2.5	1,495	5,153	647	472	2,104	57	482
NECA SA	8.2	955	1.3	746	2,575	323	235	1,052	28	240
NECA + L&F SA	20.2	2,359	3.1	1,839	6,339	797	580	2,590	70	592
2040										
NECA	12.8	1,692	1.9	1,234	4,119	528	385	1,749	45	372
NECA + L&F	15.6	2,057	2.3	1,498	4,999	642	4v69	2,123	55	452
NECA SA	18.3	2,423	2.7	1,764	5,888	757	552	2,501	65	532
NECA + L&F SA	22.7	3,007	3.3	2,189	7,306	939	685	3,104	81	661

Annex 9. Annual health benefits in coastal countries

France

Benefits, million $€_{2010}$		Median VOLY	Mean VSL
Year	Scenario		
2021	NECA	16.8	51.9
	NECA + L&F	248.9	767.5
	NECA SA sensitivity analysis	13.5	41.5
	NECA + L&F sensitivity analysis	285.9	881.6
2025	NECA	71.1	227.4
	NECA + L&F	304.8	974.6
	NECA SA	67.7	216.6
	NECA + L&F SA	348.8	1,115.4
2030	NECA	129.5	428.9
	NECA + L&F	303.3	1,004.5
	NECA SA	153.4	507.9
	NECA + L&F SA	371.5	1,230.3
2040	NECA	249.6	925.7
	NECA + L&F	301.6	1,118.5
	NECA SA	353.5	1,311.4
	NECA + L&F SA	440.2	1,632.8

United Kingdom

Benefits, million $€_{2010}$		Median VOLY	Mean VSL
Year	Scenario		
2021	NECA	13.9	42.3
	NECA + L&F	246.1	750.5
	NECA SA sensitivity analysis	13.9	42.3
	NECA + L&F sensitivity analysis	284.3	866.7
2025	NECA	74.0	232.7
	NECA + L&F	306.4	964.1
	NECA SA	70.4	221.6
	NECA + L&F SA	348.7	1,097.0
2030	NECA	128.7	417.3
	NECA + L&F	303.9	985.4
	NECA SA	153.7	498.5
	NECA + L&F SA	375.4	1,217.2
2040	NECA	248.0	875.3
	NECA + L&F	298.3	1,052.9
	NECA SA	352.2	1,243.2
	NECA + L&F SA	434.9	1,534.9

Germany

Benefits, million €$_{2010}$		Median VOLY	Mean VSL
Year	**Scenario**		
2021	NECA	17.5	64.6
	NECA + L&F	275.8	1,018.2
	NECA SA sensitivity analysis	13.1	48.5
	NECA + L&F sensitivity analysis	315.2	1,163.6
2025	NECA	76.7	299.7
	NECA + L&F	328.3	1,281.9
	NECA SA	76.7	299.7
	NECA + L&F SA	375.1	1,465.0
2030	NECA	132.9	548.3
	NECA + L&F	311.4	1,285.0
	NECA SA	153.6	634.0
	NECA + L&F SA	382.0	1,576.3
2040	NECA	239.2	1,090.9
	NECA + L&F	291.0	1,327.3
	NECA SA	342.8	1,563.6
	NECA + L&F SA	426.6	1,945.4

Netherlands

Benefits, million €$_{2010}$		Median VOLY	Mean VSL
Year	**Scenario**		
2021	NECA	7.1	21.4
	NECA + L&F	115.4	348.2
	NECA SA sensitivity analysis	7.1	21.4
	NECA + L&F sensitivity analysis	133.1	401.8
2025	NECA	33.8	110.3
	NECA + L&F	141.3	461.6
	NECA SA	32.9	107.4
	NECA + L&F SA	160.9	525.4
2030	NECA	58.7	206.4
	NECA + L&F	138.8	487.8
	NECA SA	68.5	240.8
	NECA + L&F SA	170.0	597.3
2040	NECA	109.8	445.0
	NECA + L&F	133.5	541.2
	NECA SA	156.3	633.7
	NECA + L&F SA	194.1	786.8

Poland

Benefits, million $€_{2010}$		Median VOLY	Mean VSL
Year	**Scenario**		
2021	NECA	4.6	14.0
	NECA + L&F	82.6	252.6
	NECA SA sensitivity analysis	4.6	14.0
	NECA + L&F sensitivity analysis	94.0	287.7
2025	NECA	24.6	80.1
	NECA + L&F	98.2	320.5
	NECA SA	22.3	72.8
	NECA + L&F SA	109.4	356.9
2030	NECA	39.1	135.9
	NECA + L&F	93.5	324.7
	NECA SA	45.7	158.6
	NECA + L&F SA	113.1	392.7
2040	NECA	72.3	293.5
	NECA + L&F	86.7	352.2
	NECA SA	101.2	410.9
	NECA + L&F SA	126.0	511.5

Belgium

Benefits, million $€_{2010}$		Median VOLY	Mean VSL
Year	**Scenario**		
2021	NECA	3.0	9.8
	NECA + L&F	58.7	194.7
	NECA SA sensitivity analysis	3.6	11.8
	NECA + L&F sensitivity analysis	66.9	222.2
2025	NECA	17.1	58.6
	NECA + L&F	70.9	242.6
	NECA SA	16.5	56.6
	NECA + L&F SA	81.0	277.0
2030	NECA	30.1	105.9
	NECA + L&F	70.2	247.1
	NECA SA	34.8	122.5
	NECA + L&F SA	85.5	301.1
2040	NECA	55.9	216.0
	NECA + L&F	67.6	261.5
	NECA SA	79.4	307.0
	NECA + L&F SA	98.8	382.0

Denmark

Benefits, million €$_{2010}$		Median VOLY	Mean VSL
Year	Scenario		
2021	NECA	1.9	5.9
	NECA + L&F	30.5	95.9
	NECA SA sensitivity analysis	1.6	4.9
	NECA + L&F sensitivity analysis	34.9	109.8
2025	NECA	8.8	29.4
	NECA + L&F	37.2	123.8
	NECA SA	8.5	28.3
	NECA + L&F SA	42.6	141.6
2030	NECA	15.8	55.5
	NECA + L&F	37.0	129.8
	NECA SA	18.4	64.4
	NECA + L&F SA	45.0	157.6
2040	NECA	29.2	111.4
	NECA + L&F	35.1	133.9
	NECA SA	41.0	156.4
	NECA + L&F SA	51.2	195.5

Sweden

Benefits, million €$_{2010}$		Median VOLY	Mean VSL
Year	Scenario		
2021	NECA	1.5	4.8
	NECA + L&F	21.1	66.5
	NECA SA sensitivity analysis	1.0	3.2
	NECA + L&F sensitivity analysis	23.6	74.4
2025	NECA	6.7	22.0
	NECA + L&F	26.1	86.2
	NECA SA	6.1	20.3
	NECA + L&F SA	29.7	98.1
2030	NECA	10.9	37.8
	NECA + L&F	26.0	89.9
	NECA SA	13.0	45.0
	NECA + L&F SA	31.7	109.7
2040	NECA	20.8	78.0
	NECA + L&F	25.0	93.6
	NECA SA	29.7	111.2
	NECA + L&F SA	37.0	138.5

Russian Federation (European part)

Benefits, million $€_{2010}$		Median VOLY	Mean VSL
Year	Scenario		
2021	NECA	0.0	0.0
	NECA + L&F	10.6	31.9
	NECA SA sensitivity analysis	0.0	0.0
	NECA + L&F sensitivity analysis	21.3	63.8
2025	NECA	0.0	0.0
	NECA + L&F	20.1	63.5
	NECA SA	10.1	31.7
	NECA + L&F SA	30.2	95.2
2030	NECA	9.5	31.5
	NECA + L&F	19.0	63.1
	NECA SA	9.5	31.5
	NECA + L&F SA	28.6	94.6
2040	NECA	8.8	32.7
	NECA + L&F	17.6	65.3
	NECA SA	26.4	98.0
	NECA + L&F SA	26.4	98.0

Lithuania

Benefits, million $€_{2010}$		Median VOLY	Mean VSL
Year	Scenario		
2021	NECA	0.6	2.2
	NECA + L&F	11.4	38.2
	NECA SA sensitivity analysis	0.6	2.2
	NECA + L&F sensitivity analysis	12.9	43.2
2025	NECA	3.1	10.6
	NECA + L&F	13.1	45.1
	NECA SA	3.1	10.6
	NECA + L&F SA	15.1	52.2
2030	NECA	5.3	18.6
	NECA + L&F	12.5	44.2
	NECA SA	6.2	22.1
	NECA + L&F SA	15.2	53.9
2040	NECA	8.9	34.7
	NECA + L&F	10.9	42.3
	NECA SA	12.8	49.9
	NECA + L&F SA	16.0	62.4

Finland

Benefits, million €$_{2010}$		Median VOLY	Mean VSL
Year	**Scenario**		
2021	NECA	0.3	1.0
	NECA + L&F	4.7	15.3
	NECA SA sensitivity analysis	0.3	1.0
	NECA + L&F sensitivity analysis	5.6	18.2
2025	NECA	1.5	5.1
	NECA + L&F	5.9	20.5
	NECA SA	1.2	4.1
	NECA + L&F SA	6.8	23.5
2030	NECA	2.4	8.7
	NECA + L&F	5.9	21.8
	NECA SA	2.9	10.9
	NECA + L&F SA	7.1	26.2
2040	NECA	4.6	19.2
	NECA + L&F	5.8	24.0
	NECA SA	6.6	27.6
	NECA + L&F SA	8.1	33.6

Latvia

Benefits, million €$_{2010}$		Median VOLY	Mean VSL
Year	**Scenario**		
2021	NECA	0.4	1.5
	NECA + L&F	5.8	20.3
	NECA SA sensitivity analysis	0.4	1.5
	NECA + L&F sensitivity analysis	6.6	23.3
2025	NECA	1.6	5.8
	NECA + L&F	6.5	23.7
	NECA SA	1.5	5.3
	NECA + L&F SA	7.6	27.6
2030	NECA	2.7	9.9
	NECA + L&F	6.2	23.1
	NECA SA	3.2	11.8
	NECA + L&F SA	7.7	28.8
2040	NECA	4.7	18.9
	NECA + L&F	5.6	22.6
	NECA SA	6.5	26.4
	NECA + L&F SA	8.2	33.0

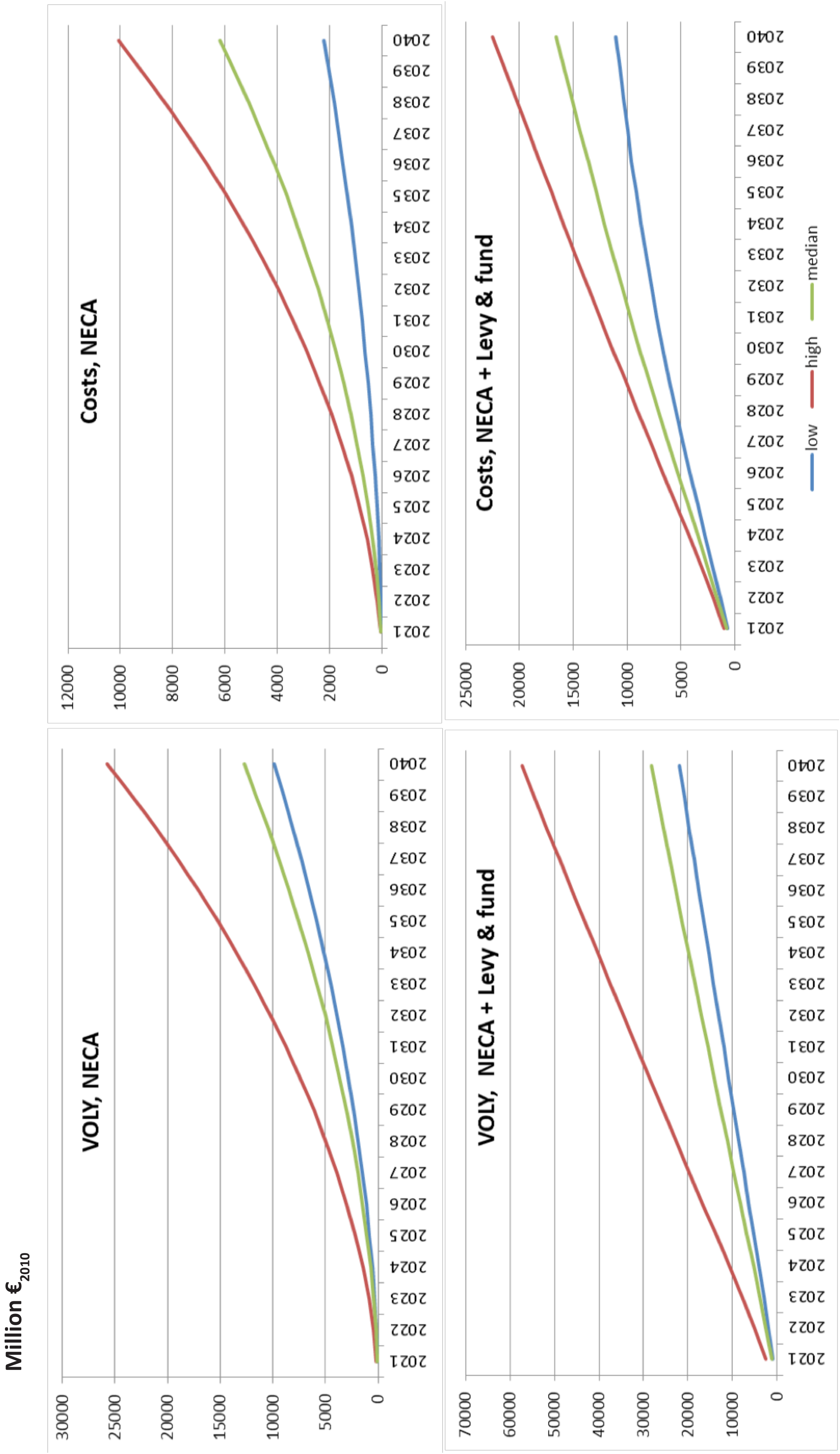
Norway

Benefits, million $€_{2010}$		Median VOLY	Mean VSL
Year	Scenario		
2021	NECA	0.3	0.7
	NECA + L&F	3.0	8.1
	NECA SA sensitivity analysis	0.0	0.0
	NECA + L&F sensitivity analysis	3.2	8.8
2025	NECA	0.8	2.4
	NECA + L&F	3.9	11.1
	NECA SA	0.8	2.4
	NECA + L&F SA	4.1	11.9
2030	NECA	1.4	4.3
	NECA + L&F	3.7	11.1
	NECA SA	2.0	6.0
	NECA + L&F SA	4.8	14.5
2040	NECA	2.9	9.9
	NECA + L&F	3.5	11.9
	NECA SA	4.4	14.9
	NECA + L&F SA	5.5	18.9

Estonia

Benefits, million $€_{2010}$		Median VOLY	Mean VSL
Year	Scenario		
2021	NECA	0.1	0.3
	NECA + L&F	2.4	8.2
	NECA SA sensitivity analysis	0.1	0.3
	NECA + L&F sensitivity analysis	2.7	9.4
2025	NECA	0.7	2.5
	NECA + L&F	2.9	10.1
	NECA SA	0.6	2.3
	NECA + L&F SA	3.2	11.3
2030	NECA	1.2	4.2
	NECA + L&F	2.7	9.8
	NECA SA	1.3	4.8
	NECA + L&F SA	3.3	12.0
2040	NECA	2.0	7.9
	NECA + L&F	2.5	9.6
	NECA SA	2.9	11.3
	NECA + L&F SA	3.6	13.9

Annex 10. Accumulated costs and benefits – intervals



Annex 11. Sensitivity analysis results

Baseline scenario

Parameter	Unit	Main/SA*	2021	2025	2030	2040
Annual NOx emissions	ktonnes	Main	792	768	741	715
		SA	916	938	958	1,047
Annual NOx deposition on land**	ktonnes N	Main	117	114	110	106
		SA	136	138	146	155

NECA and NECA + levy & fund scenarios

Parameter	Unit	Main/SA	NECA		NECA + levy & fund	
			2030	2040	2030	2040
NOx emissions, annual	ktonnes	Main	524	306	230	220
		SA	705	465	334	323
NOx emission reduction, annual	ktonnes	Main	217	409	495	723
		SA	254	582	624	724
NOx emission reduction, accumulated	ktonnes	Main	1,270	4,490	4,920	9,860
		SA	1,370	5,660	5,770	12,480
NOx abatement costs, accumulated	million $€_{2010}$	Main	1,750	6,180	8,870	16,550
		SA	1,870	7,770	11,490	23,060
NOx deposition on land, annual reduction on top of BL	ktonnes N	Main	32	60	80	73
		SA	37	86	89	98
Health benefits, median VOLY, accumulated	million $€_{2010}$	Main	3,600	12,700	14,100	28,300
		SA	3,900	16,200	16,600	35,800
Benefit-cost ratio, median VOLY, average over 2020-2040	-	Main	2.1	2.0	1.7	1.9
		SA	2.1	1.5	2.1	1.8
Net health benefits, median VOLY, accumulated	million $_{2010}$	Main	1,900	6,600	5,200	11,800
		SA	2,000	8,400	5,100	12,800

* Main or sensitivity analysis scenario

** Only inputs from emissions in the Baltic Sea and the North Sea

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