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Cost-benefit analysis of NOX control for ships in the Baltic Sea and the North Sea

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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 aimed at decreasing nitrogen oxides (NO_x) emissions from shipping in the Baltic Sea and the North Sea. One instrument is a NO_x emission control area (NECA) in the Baltic Sea and the North Sea; the other is a combination of NECA and a NO_x levy with revenues going back to shipping companies as subsidy for NO_x abatement uptake. Both instruments are assumed to be in force in 2021.

In the analysis, we operate with 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 marine gasoil (MGO) fuelled vessels 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 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 socio-economic perspective, implying low interest rate and long investment lifetime at investment costs' annualization. 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 supporting the European Commission's work on the air pollution abatement strategies and the work of the Convention on Long-Range Transboundary Air Pollution.

Introduction of NECA in the Baltic Sea and the North Sea in 2021 is calculated to result in the total accumulated NO_x emission reductions of ~4500 ktonnes during 2020–2040, on top of the baseline. Socio-economic emission reduction costs are estimated at 1.38 $€_{2010}$/kg NO_x. The accumulated net health benefits (Value of Life Year lost – VOLY) from NECA implementation would amount to ~-210–23500 (central value – 6600) million $€_{2010}$, with the average benefit-cost ratio of 0.99–11.6 (central value – 2.1). Annual reduction in NO_x deposition on land would gradually increase and reaches 60 ktonnes N in 2040.

Combining NECA with the introduction of the NO_x levy and fund effective from 2021 is calculated to result in the accumulated emission reduction over the period 2020–2040 of ~9900 ktonnes NO_x at the cost of 1.68 $€_{2010}$ per kg NO_x. The accumulated net benefits (VOLY) are ~-610–46300 (central value – 11800) million $€_{2010}$, with the average benefit-cost ratio of 0.97–5.2 (central value – 1.7). Reduction in NO_x deposition on land then amounts to ~65–80 ktonnes N per year.

In the sensitivity analysis we consider the case of 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 gross health benefits from implementation of the considered policy instruments are ~30 per cent higher than in the main analysis.

The calculations show that in the short-term perspective (2020—2030) an introduction of levy and fund on top of NECA would result in the accumulated additional net health benefits of ~3400 million $€_{2010}$ (VOLY, central value) attributable primarily to health improvements in population in the coastal countries. Levy and fund appears to be an effective complement to NECA with a potential to bring noticeable health and environmental benefits shortly after its enforcement.

Introduction

Emissions of air pollutants from shipping (NO_x, SO_x, and $PM_{2.5}$) make a significant contribution to the total emissions in Europe and world-wide. According to the analysis by Brandt et al. (2013), shipping emissions cause about 50 thousand premature deaths per year in Europe. Significant share of the sulphur and nitrogen deposition that causes acidification and eutrophication emanates from ship emissions. NO_x emissions contribute to formation of secondary particles and ozone, resulting in increased number of respiratory and cardio-vascular diseases among the population, especially in coastal states.

NO_x 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 ~7820 ktonnes in 2014 (CEIP, 2017) whereas emissions from international shipping in the European seas for the same year are estimated at 3186 ktonnes (EMEP, 2016). As more stringent NO_x emission control is gradually enforced for stationary and mobile sources on land, the share of NO_x emission reduction potential attributable to international shipping is expected to increase in the future.

NO_x emissions from international shipping are regulated by the MARPOL Convention (International Maritime Organization, 2013). The emission reduction system is built as three subsequent Tiers, each of them obliging new-built vessels for further emission reductions compared to the previous Tier. Tier I vessels comprise those constructed between 2000 and 2011, Tier II – vessels constructed after 2011. Tier III requirements apply only in the specially designated areas – NO_x Emission Control Areas (NECAs), and only for vessels built after the implementation year of 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 NECA in the North Sea and the Baltic Sea, with January 1, 2021 as the effective date of Tier III requirements. The final decision is expected to be taken in May 2017 (HELCOM, 2016).

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

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

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

as well as to assess nitrogen deposition and population-weighted secondary $PM_{2.5}$ concentrations, and to provide 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 benefits in monetary terms 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 high sulphur content has dropped in response to the new sulphur emissions regulations valid from January 1, 2015 (Annex VI of the MARPOL Convention, International Maritime Organization, 2013). We assume transport efficiency increase of 1.3–2.25 per cent and 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 the 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 and 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 a catalytic converter (SCR), not by using the exhaust gas recirculation (EGR) technology which is less tested on ships. We estimate that the costs for reducing NO_x are similar for SCR and EGR (at least for new builds) why the use of EGR is not expected to change the results. Levy&fund on top of 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 2021 or later are in fact Tier II vessels since the construction process is often delayed and the implementation date refers to the date the ship is keel-laid. We assume that emission input from these vessels is negligible.

All monetary assessments in the study are expressed in $€_{2010}$. For both costs and benefits, we operate with low, central and high values to take into account uncertainties.

The analysis is conducted from the 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 subsidies introduction and 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.

NO_x emissions

Emission trends

Reliable estimates of emissions from international shipping have been a challenge for a long time. For producing emissions, concentrations and deposition in the EMEP model, data is usually obtained from the Centre on Emission Inventories and Projections (CEIP) and has been based on ENTEC, IIASA or TNO estimates (EMEP, 2016). According to this data, NO_x 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 – ~32 per cent. The trend of increasing emissions continued during 2000–2005.

Table 1. NO_x 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 NO_x 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 NO_x emissions based on AIS data are higher as well. 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).

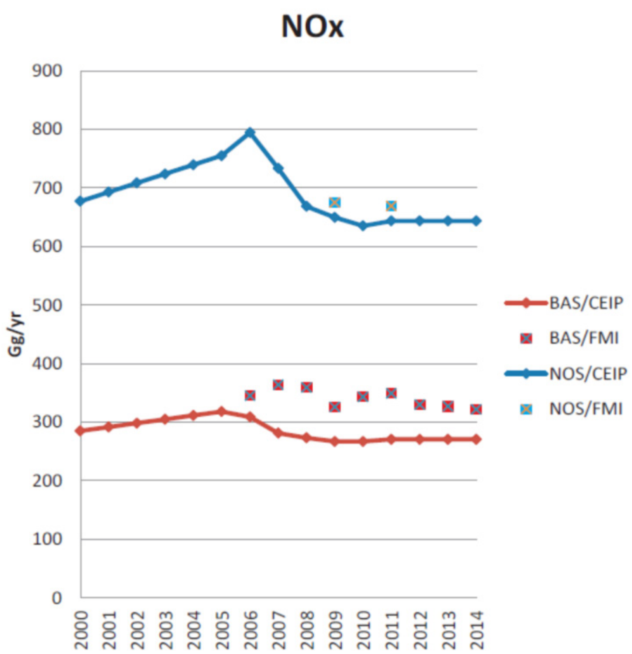


Figure 1. NO_x emissions in the Baltic Sea and the North Sea during 2000–2014. From EMEP (2016).

In the analysis of policy instruments for reducing shipping emissions conducted by Campling et al. (2013) for the European Commission, the EX_TREMIS/EUROSTAT dataset was used to estimate baseline emissions. Campling et al. (2013) estimates base year (2005) NO_x emissions at 220 ktonnes in the Baltic Sea and 518 ktonnes in the North Sea – about 740 ktonnes t in total, which is considerably less than ~1080 ktonnes NO_x in EMEP, 2016.

The trend of increasing NO_x 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 do not longer increase as much as during 1990–2005. The span in the existing estimates of NO_x emissions from international shipping in the Baltic Sea and the North Sea indicates large uncertainties that should be taken into account while choosing base year emission estimates in order to develop projections.

Emission projections and scenarios

A summary of the recent studies estimating NO_x 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 NO_x 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 major part of international and domestic shipping. Estimates by Kalli et al. (2013) are made with 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 NO_x 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 much more flat decline between 2025 and 2040.

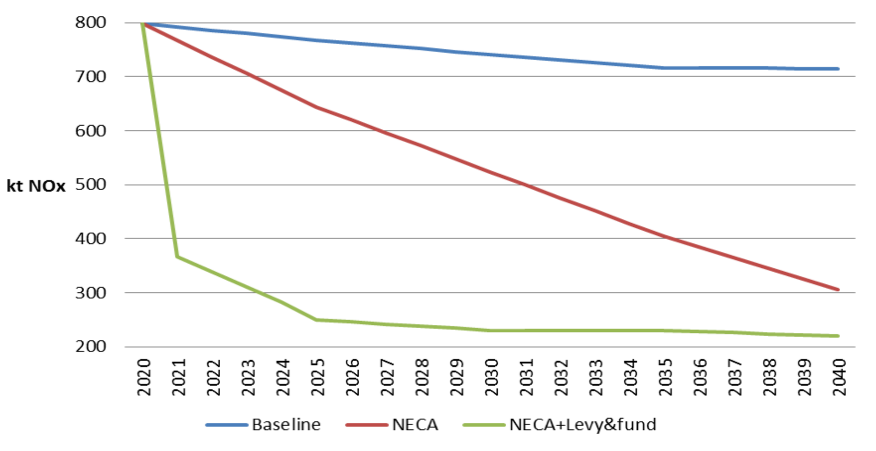


Figure 2. Projections of NO_x emissions according to the three main scenarios: Baseline, NECA, and NECA+Levy&fund.

The 'cut angle' for 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 NO_x 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 NO_x levy introduction (Winnes et al., 2016). Figure 3 also shows a small amount of NO_x emissions emitting 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.

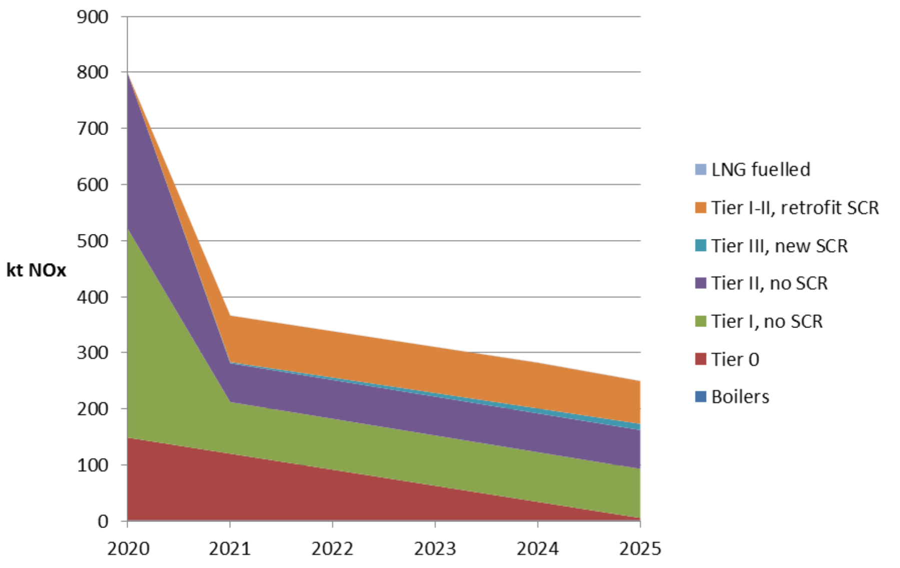


Figure 3. NO_x emissions decline between 2020 and 2025 in the NECA+Levy&fund scenario.

Accumulated NO_x emission reductions (compared to the baseline) over the period 2020–2040 are summarized in Annex 2. In the year 2040, accumulated emission reductions in the NECA + Levy&fund scenario are ~9900 ktonnes – twice as high as emission reductions from the NECA scenario (~4500 ktonnes). Due to 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 the fleet renewal and introduction of vessels obliged to comply with the Tier III requirements. In the NECA+Levy&fund scenario, annual emission reductions slightly increase between 2021 and 2025 (mainly due to phase-out of Tier I vessels) and remain relatively constant (~500 ktonnes NO_x reduced per year) after that. 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 reduction compared to the baseline will be ensured by either installing SCR on new builds 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 annualized with Equation 1 (Bosch et al. 2009):

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

Where
I_{an} = Annual investment costs ($€_{2010}$)
I = Total investment costs ($€_{2010}$)
q = Investment interest rate (shares)
lt = Investment lifetime (years)

In Annex 3, SCR costs together with the costs calculation parameters are specified. Costs in $€_{2010}$ per kg NO_x are calculated via costs in $€_{2010}$ per engine work (kWh) and emission factors presented in Table 2 below.

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

Engine type	Fuel	NO_x 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 via a range of parameters that can be divided into economic parameters and technology parameters. Economic parameters are, e.g. investment per kW engine power, catalyst replacement costs, urea cost, and labour cost. For these parameters we use low-to-high intervals in the analysis. As technology parameters we consider ship category, engine type, installed power per vessel, engine work with abatement equipment being operated, and even NO_x emission reduction achieved by Tier III in comparison to Tiers I/II (since it depends on the engine type as shown in Table 2 above). In the calculation of SCR abatement costs we do not operate with intervals for the technology parameters but instead calculate weighted average values representative for the fleet navigating in the Baltic Sea and the North Sea. The fleet structure for 2030 is summarized 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 parametrization, the following weighted average values are derived:

- Installed engine power, per vessel – 13.4 MW;
- Engine work with abatement equipment being operated, per vessel per year – ~5000 MWh;
- NO_x emission reduction, conversion from Tier II to Tier III – 9.4 kg/MWh
- NO_x emission reduction, conversion from Tier I to Tier III – 11.9 kg/MWh

Annex 3 summarizes both the social and the private investor cost perspectives. Social perspective implies that the decision is made by a public planner and results in maximum benefits for all members of a society. In contrast, a private investor's decisions are mainly driven by economic benefits and risks viewed in a much more short-term perspective. The cost estimate methodologies for these two perspectives differ by applying different interest rate and investment lifetime used for investment cost annualization. For the social cost perspective, the recognized values of 4 per cent interest rate and investment lifetime equal to equipment lifetime are used for annualization (Bosch et al. 2009, Amann et al. 2011). Private investors such as shipping companies usually consider a much shorter time period when annualizing investment costs. Costs are the main factor for companies in their decisions, e.g. choice of a specific abatement technology and whether to use abatement or rather pay levy. There is, however, no common agreement on which values that should be used for private investors' perspective in socio-economic analyses: it is quite subjective and affected by inter alia 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 precautious 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), also presenting 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 display several options for private costs, including the option used in Winnes et al. (2016). For estimating the total costs in the further 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 NO_x 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 particulate policy instrument combination as stimulating SCR uptake by existing Tier II and Tier I vessels but without adding additional costs (except for the cost related to the abatement installation and operation).

The resulting annual total costs are summarized in Annex 5. In the NECA scenario, annual costs gradually increase from ~10–60 (30)[1] million €$_{2010}$ in 2021 to ~200-920 (560) million €$_{2010}$ 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 ~680–1000 (820) million €$_{2010}$ to ~590–1170 (870) million €$_{2010}$ between 2021 and 2025 and then decrease to ~340–1110 (720) million €$_{2010}$ in 2040. The decrease after 2025 is caused by 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 ~2200–10100 (6200) million €$_{2010}$ and ~110000–22500 (16500) million €$_{2010}$, respectively.

With the method described above, investment costs per MWh engine work are calculated via the parameter 'engine work with abatement equipment operated' that 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 NO_X. The other cost component – O&M costs – does not depend on the power use if expressed in € per MWh engine work. This affects the relationship between the total annual abatement costs and hours at sea,

[1] Hereinafter central values are given in parenthesis after the specified intervals

which is not linear: O&M costs increase with more operative hours at sea while investment costs are constant. When calculating costs in € per MWh engine work, only 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 size categories spend more time in the area than the larger vessels. The time spent in the area by small sized vessels has been estimated to be 100% (RoRo/Ferries), 25% (Container vessels), or 50% (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 on installed engine power in the ships. Similar calculations for the larger sized 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 only while navigating NECA area – that was done to enable cost comparisons for different technologies since not all of them are switched off outside 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 of significantly higher costs in both the private and in the socio-economic perspectives, compared to the numbers presented in Winnes et al. (2016).

GAINS model scenario setup

To analyse NO_x deposition and health effects due to exposure to secondary particles, we use the GAINS model (Amann et al. 2011). 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:

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

Equation 2

Where

$PM2.5_j$	= 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, NO_x 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 oxidized nitrogen, sulphur and primary $PM_{2.5}$, for season 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 and described in Amann et al. (2015). It is further updated with more recent information on inter alia 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 the 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 NO_x emissions already 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 (except for one scenario created specifically to estimate effects in 2020, where both ship emissions and land emissions are for 2020). We thus assume that there are no major changes in the 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 in the GAINS input data set divided into zones:

- 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

Compiling the GAINS input data set for international shipping we use emissions as in Campling et al. (2013) for all sea regions except for the Baltic Sea and the North Sea. For them we replace IIASA's data with the calculated emission values for NO_x 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. Hence, a scenario for the Baltic Sea and the North Sea would in the model imply emission reductions in the coast line of for example Mediterranean Sea. 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 hereby 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 data sets in the same way as described in Åström et al. (2014). To account for emissions of other pollutants from domestic shipping, we replace the values from Campling et al. (2013) with our own estimates (as specified in Table 3) also for SO_x, 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 the energy efficiency developments that outweighs traffic increase.

Table 3. Projected emissions of $PM_{2.5}$, SO_x and NMVOC, ktonnes.

Year	$PM_{2.5}$		SO_x		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 SO_x, NMVOC and $PM_{2.5}$ are the same for all the three considered scenarios. For some ships, ammonia emissions associated with SCR use might be treated with a catalyst, resulting also 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.

NO_x deposition

Deposition of oxidized nitrogen on land is estimated with the GAINS model. Deposition maps for 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 from introduction of the considered policy instruments on deposition are mostly seen in the coastal countries. In both policy instrument scenarios, reduction in nitrogen deposition compared to the baseline is noticeable already for 2021, see Figure 4 below.

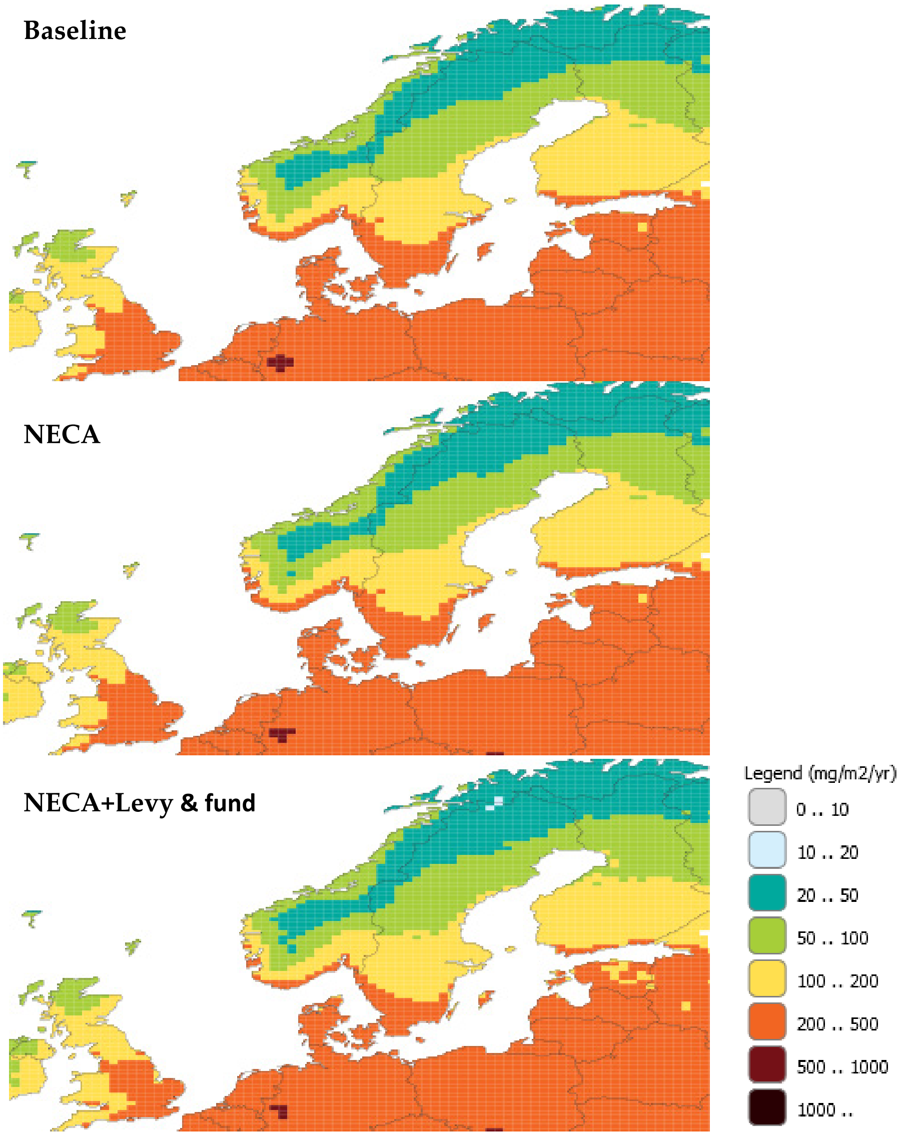


Figure 4. Deposition of oxidised nitrogen in the coastal areas in 2021.

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 oxidized nitrogen are a product of EMEP model simulations analysing relations between emissions in chosen regions (sources) and deposition in other regions (receptors) attributable to 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 NO_x) 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 part of NO_x emitted in the Baltic Sea and North Sea is deposited on land, at least for the 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 summarized in Annex 7. In the NECA scenario, the annual deposition in 2040 is reduced by ~60 ktonnes oxidized nitrogen deposited on land and by ~34 ktonnes oxidized 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[2].

Table 4. European population-weighted concentrations from secondary $PM_{2.5}$, µg/m³.

	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

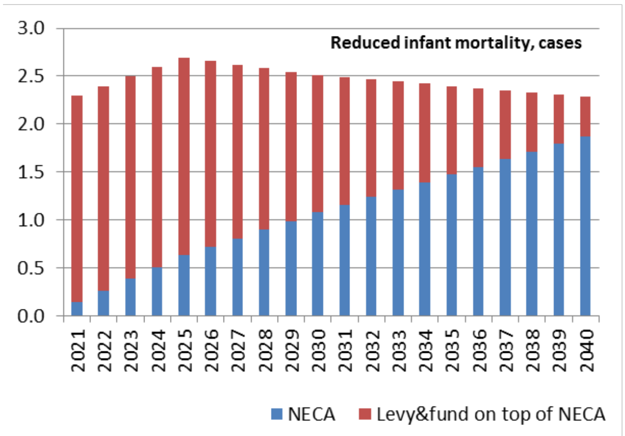
The Alpha-RiskPoll model enables analysis of a wide range of health effects from secondary $PM_{2.5}$ exposure, including mortality in adults and infants, respiratory and cardiac hospital admissions, and restricted activity days. Health effects per country are calculated by combining data on age distribution of population, population-weighted concentrations of secondary $PM_{2.5}$ and effect-specific dose response relationships (Holland et al. 2013). The model operates with population age distribution projected for the years 2020, 2025, 2030 and 2040 – therefore 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 NECA is expected to result in the gradual improvement of the European population health over the period 2020–2040. In the NECA scenario the results from the calculations give that ~1700 premature deaths in adults and ~4100 added cases of bronchitis in small children per year can be avoided in 2040, compared to the baseline scenario.

Combining NECA with the introduction of NO_x levy and fund is found to significantly decrease the number health impacts from air pollution. The calculated marginal impact of the added levy 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 marginal impact of the added levy 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.

[2] 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 whereas the concept of YOLL in GAINS implies accumulated effects in population leaving during a considered year 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.



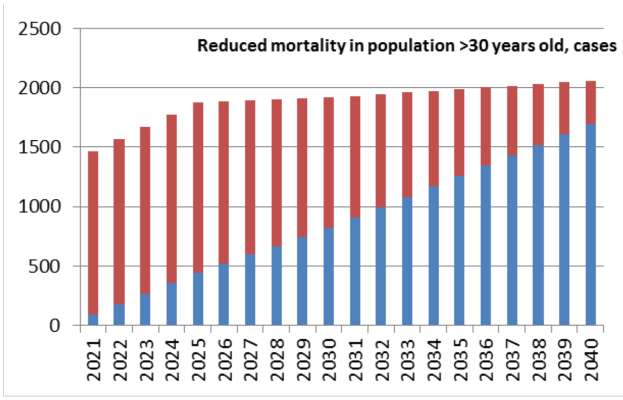


Figure 5. Reduced annual number of premature death cases in Europe.

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

Effect	**Unit**	**NECA**	**NECA + L&F**	**L&F marginal**
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 marginal**
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 inter alia in Holland et al. 2005, Holland et al. 2013, and Holland 2014. 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 metrics 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 those used by the European Commission for its 2013 Clean Air Package (Holland, 2014). The values of reduced adverse health effects are presented in both VOLY and VSL; for each of the metrics, low, central and high values are considered. 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 all European lives are in this study assigned the same economic value.

The results of the cost-benefit analysis for the NECA scenario and for the NECA+Levy&fund scenario are summarized in Tables 7 and 8, respectively. They indicate that already in 2021 introduction of NECA would result in gross health benefits estimated at ~60–300 million $€_{2010}$ per year, and by 2040 this number increases to ~890–2300 million $€_{2010}$. In the NECA+Levy&fund scenario, much higher gross health benefits are expected in 2021 – ~940–4900 million $€_{2010}$. In 2040, the corresponding number would be ~1100–6800 million $€_{2010}$. 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 gross health benefits for these countries are presented in Annex 9. For several countries and years, one can see zero gross 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 too small concentration changes – this effect is seen, in particular, for the European part of Russia where an introduction of NECA does not seem to bring any additional health benefits until 2025-2030.

The calculated accumulated gross health benefits for the period 2020–2040 (valuation in VOLY) are presented in Annex 2. The shapes of the curves are very similar to those of 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 is estimated at ~9900–25700 (12700) million €2010, and in NECA+Levy&fund scenario – at 21900–57300 (28300) million €2010.

Table 7. Costs-benefits analysis, results for the NECA scenario.

Result	Unit	Range end	2021	2025	2030	2035	2040	Acc.
Gross health benefits, VOLY	Million €2010	Low	58	271	480	685	891	9 864
		Central	75	351	621	884	1 147	12 737
		High	153	714	1 257	1 783	2 308	25 717
Gross health benefits, VSL	Million €2010	Low	130	632	1 164	1 772	2 380	-
		Central	244	1 192	2 200	3 361	4 521	-
		High	303	1 480	2 732	4 176	5 620	-
Benefit-cost ratio, VOLY	-	Low	1.04	0.98	0.99	0.98	0.97	0.98*
		Central	2.2	2.1	2.1	2.1	2.0	2.1*
		High	12.5	11.7	11.7	11.6	11.4	11.6*
Benefit-cost ratio, VSL	-	Low	2.3	2.3	2.4	2.5	2.6	-
		Central	7.2	7.0	7.4	7.8	8.0	-
		High	24.8	24.2	25.5	27.1	27.9	-
Net socio-economic benefits, VOLY	Million €2010	Low	2	-7	-7	-14	-27	-209
		Central	41	181	322	455	585	6 558
		High	141	652	1 150	1 629	2 106	23 501
Net socio-economic benefits, VSL	Million €2010	Low	74	354	677	1 072	1 463	-
		Central	210	1 022	1 902	2 931	3 958	-
		High	291	1 419	2 625	4 022	5 418	-

*Average over the period 2020—2040

Table 8. Costs-benefits analysis, results for the NECA+Levy&fund scenario.

Result	Unit	Range end	2021	2025	2030	2035	2040	Acc.
Gross health benefits, VOLY	Million €2010	Low	940	1 150	1 123	1 103	1 082	21 899
		Central	1 221	1 490	1 452	1 423	1 395	28 319
		High	2 487	3 027	2 940	2 873	2 806	57 321
Gross health benefits, VSL	Million €2010	Low	2 099	2 677	2 723	2 807	2 892	-
		Central	3 951	5 051	5 146	5 320	5 494	-
		High	4 902	6 269	6 390	6 610	6 830	-
Benefit-cost ratio, VOLY	-	Low	0.94	0.96	0.96	1.01	0.97	0.97*
		Central	1.5	1.6	1.7	1.9	1.9	1.7*
		High	3.6	4.2	5	6.7	8.3	5.2*
Benefit-cost ratio, VSL	-	Low	2.11	2.23	2.33	2.57	2.61	-
		Central	4.8	5.4	5.9	7	7.6	-
		High	7.2	8.7	10.8	15.4	20.3	-
Net socio-economic benefits, VOLY	Million €2010	Low	-55	-52	-45	10	-28	-611
		Central	402	549	586	668	672	11 772
		High	1 805	2 308	2 350	2 443	2 469	46 279
Net socio-economic benefits, VSL	Million €2010	Low	1 103	1 475	1 555	1 715	1 782	-
		Central	3 133	4 109	4 280	4 565	4 771	-
		High	4 220	5 550	5 800	6 180	6 493	-

*Average over the period 2020—2040

To calculate accumulated values is reasonable for benefit valuation in VOLY but not in 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 to consider in relation to a specific year.

To estimate low and high values of the benefit-cost ratios and the net benefits, we combined low cost values, presented in Annex 5, with high gross benefit values, presented in Tables 7 and 8, and vice versa (the intervals for accumulated costs and benefits for both scenarios are presented in Annex 10).

In both scenarios, benefits from implementation of the policy instruments are at least as high as costs, except for the case with low-end VOLY valuation combined with high-end costs. Benefit-costs ratios presented in Tables 7 and 8 indicate that both policy instruments seem cost-effective. In the NECA scenario, benefit-cost ratio is estimated at 0.97–27.9, with average (over the period 2020—2040) central value in VOLY – 2.1. In the NECA+Levy&fund scenario, the ratio is 0.94–20.3, with average central value in VOLY – 1.7. The average benefit-cost ratio is lower in the NECA+Levy&fund scenario because the significant benefits due to retrofitting a large number of relatively old vessels with SCR are associated with higher costs of retrofit-SCR, compared to an SCR on a new-build.

Net annual socio-economic benefits are the difference between abatement costs and gross 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, with the exception of the case when low-end VOLY valuation is used in combination with high-end costs. The relative difference between net socio-economic benefits in the two scenarios tends to decrease between 2020 and 2040 (except for the low-end VOLY case). Accumulated net benefits in the NECA scenario are ~-210–23500 (6600) million $€_{2010}$; for the NECA+Levy&fund scenario the correspondent numbers are ~-610–46300 (11800) million $€_{2010}$.

The marginal net socio-economic benefits from levy&fund in the NECA+Levy&fund scenario are varying within ~-58–4100 million $€_{2010,}$ depending on the considered year and valuation metrics. The accumulated marginal net benefits over the period 2020–2040 are estimated at ~-400-22 800 (5200) million $€_{2010}$. The marginal benefit-cost ratio averaged over the same time period is 0.97–3.6 (1.5) with the annual variations of 0.94–3.9 (valuation in VOLY) and 2.1–8.9 (valuation in VSL).

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 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 on 1.3–2.25 per cent. Energy efficiency recalculations are loosely based on what is expected to be obtained by IMO's Energy Efficiency Design Index regulations stipulating vessels' energy efficiency improvements 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 NO_x 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) NO_x emission reductions due to the implementation of policy instruments are also higher. Both costs and environmental and health benefits increase in absolute numbers, compared to the main analysis, since larger amounts of emissions may be removed by using SCR.

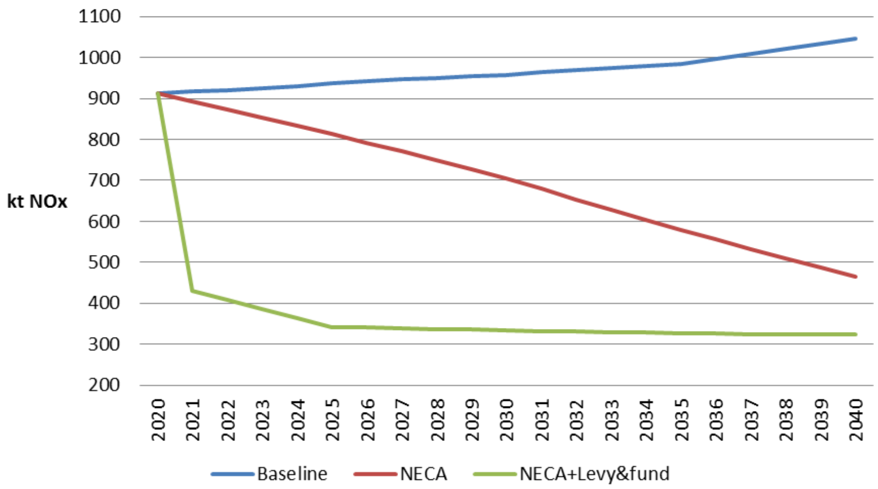


Figure 6. Projections of NO_x emissions – sensitivity analysis.

Table 9. Projected emissions of $PM_{2.5}$, SO_x and NMVOC, ktonnes – sensitivity analysis.

Year	$PM_{2.5}$		SO_x		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 summarized in Annex 11 and also presented in Annex 8 (health effects), Annex 6 (spatial distribution of NO_x deposition), and Annex 10 (gross health benefits by country).

Higher emissions, compared to the main analysis, results in higher deposition of oxidised nitrogen in coastal areas, clearly seen on the maps in Annex 9. 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 (central values) exceed the associated abatement costs (central values) in the sensitivity analysis scenarios so that the net socio-economic 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 gross health benefits in VOLY accumulated over the period 2020—2040 are 27 per cent higher than in the main analysis. This is the average number for the entire Europe; variations in individual coastal countries can be seen in Annex 10.

The results of the sensitivity analysis indicate that if the 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 NECA or NECA in combination with NO_x levy&fund would result in avoidance of more adverse health effects and thus becomes even more relevant.

Discussion

The results of this study indicate that both NECA alone and NECA combined with Levy&fund are cost-effective policy instruments enabling significant reductions of NO_x 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 gross benefits in Europe estimated at 380–2170 million $€_{2010}$ and abatement costs of 233 million $€_{2010}$ (1.4 $€_{2010}$/ kg NO_x). Åström et al. (2014), however, used certain assumptions not taken into account in this analysis. In particular, fuel structure includes a rather large share of heavy fuel oil (it is assumed that vessels are equipped with scrubbers to comply with sulphur emissions regulations). More important assumption concerns extra investments into LNG induced by NECA implementation. This assumption, not considered in this study, looks reasonable. Currently, the main constraint for LNG switch for shipping companies is the price of LNG engines: 220–940 $€_{2010}$/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 an engine, unlike for SCR where costs of catalysts and urea constitute a significant part of the total costs. The most important and yet the most uncertain factor in the future investment decisions is the relationship between the prices of LNG and conventional fuels – primarily MGO. In Åström et al. (2014), the final user fuel price estimates from Danish Maritime Authority (2012) are used – 610 $€_{2010}$ per tonne LNG and 885 $€_{2010}$ per tonne MGO. LNG is thus assumed to be ~30 per cent cheaper than marine gasoil. In January 2016, US LNG contract prices varied from 240 to 375 USD per tonne (for North-Western Europe – 295 USD per tonne) (ICIS, 2017) while global-average MGO price for the same month was around 514 USD per tonne (Bunker Index, 2017). If LNG continues to be a significantly cheaper option, fuel savings will overweight higher engine costs, and the rates of investments into LNG fuelled ships will be much higher than in case if the price difference is small. Switch from conventional fuel to LNG results in reduced emissions of SO_x, 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 structural 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 viable option present on market, often used in combination with water-based technologies 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 NO_x are similar for SCR and EGR (at least for new builds) why 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 on 'no increased LNG use' in the NECA scenario might be too cautious. As discussed above, extra costs for LNG as means to reduce NO_x 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 NO_x 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 socio-economic cost perspective. However, in designing and implementation of NO_x levy and fund the shipping company perspective on SCR investment costs plays an important role for which technology that is preferred. SCR cost is the main factor determining the levy size that encourages a major part of the existing vessel fleet to take up abatement instead of paying levy: the levy should 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 annualization, a levy size needed to overweight 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 not sensitive to levy size because all the revenues are returned to the sector. Thus, the values of interest rate and investment lifetime chosen for private cost perspective do affect the effective levy size but do not affect the total socio-economic costs in case if all the revenue is returned to shipping companies.

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 NO_x levy and fund are summarized in Table 10.

Table 10. Calculated costs and benefits in the NECA scenario and the NECA+Levy&fund scenario, central values, million €$_{2010}$.

Year	NECA					NECA+Levy&fund				
	Gross benefits		Costs	Net benefits		Gross benefits		Costs	Net benefits	
	VOLY	VSL		VOLY	VSL	VOLY	VSL		VOLY	VSL
2021	80	240	30	40	210	1200	4000	820	400	3100
2025	350	1200	170	180	1000	1500	5100	940	550	4100
2030	620	2200	300	320	1900	1500	5100	870	590	4300
2035	880	3400	430	450	2900	1400	5300	760	670	4600
2040	1100	4500	560	580	4000	1400	5500	720	670	4800
2020—2040 accumulated	12700	-	6200	6600	-	28300	-	16500	11800	-

The presented calculations show that an introduction of NECA in the Baltic Sea and the North Sea in 2021 would result in the total accumulated NO_x emission reductions of ~4500 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. Socio-economic emission reduction costs are estimated at 1.38 €$_{2010}$/kg NO_x. Annual costs increase in line with the emission decrease – from ~10–60 (30)[3] million €$_{2010}$ in 2021 to ~200-920 (560) million €$_{2010}$ in 2040, resulting in an accumulated value for the whole period of ~2200–10100 (6200) million €$_{2010}$. The calculated accumulated net socio-economic benefits (VOLY) from NECA implementation would amount to ~-210–23500 (6600) million €$_{2010}$, with a benefit-cost ratio of 0.98–11.6 (central value – 2.1).

Combining NECA with the introduction of the NO_x levy and fund effective from 2021 is expected to enable further emission reductions by stimulating vessels built before 2021 to install retrofit SCR instead of paying levy. Assuming that 75 per cent of existing Tier I and Tier II vessels are retrofitted with SCR, the NO_x emissions would drop to ~370 ktonnes already in 2021 and further decrease to ~220 ktonnes in 2040 (~500 ktonnes lower than in the baseline). The accumulated emission reduction over the period 2020–2040 is estimated at ~9900 ktonnes at the cost of 1.68 €$_{2010}$ per kg NO_x. Annual costs vary between 340 and 1200 (720–940) million €$_{2010}$, resulting in an accumulated cost for the whole period of ~11000–22500 (16500) million €$_{2010}$. The accumulated net socio-economic benefits (VOLY) are ~-610–46300 (11800) million €$_{2010}$, with the benefit-cost ratio of 0.97–5.2 (central value – 1.7).

In both scenarios, improvements in the population health would be primarily experienced in coastal countries. Germany, France and 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 90 per cent of the total gross health benefits resulting from the reduced shipping emissions.

[3] Central values are given in parenthesis after the specified intervals

In addition to improved health, introduction of both policy instruments would bring ecosystem benefits in a form of decreased deposition of oxidised nitrogen. Estimated deposition reduction from an 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. In case of the levy and fund on top of NECA, the numbers for the same year are ~73 ktonnes and ~29 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), both the health and environmental effects in 2040 and the accumulated gross benefits in VOLY due to the implementation of the two considered policy instruments, increase by about a third, compared to the main analysis results.

In the short-time perspective (2020—2030), an introduction of levy as a complement to NECA shows great advantages, compared to the case of NECA introduction alone. The marginal emission reduction in 2021 is estimated at ~400 ktonnes NO_x; in 2030 it will decrease to ~290 ktonnes NO_x. The total accumulated emission reduction over the period 2020—2030 would constitute ~3660 ktonnes, at the cost of additional ~7100 million $€_{2010}$ (central value). The accumulated marginal health benefits associated with this emission reduction are valued at ~10500 million $€_{2010}$ (VOLY, central value), implying the accumulated additional socio-economic net benefits of 3400 million $€_{2010}$. This is inter alia due to the avoidance of ~120 thousand life years lost (all ages), ~37 thousand of added cases of bronchitis in children (6—12 years), and ~4 thousand lost working days (15—64 years) over the period 2020—2030. Levy&fund thus appears to be a very effective complement to NECA with a potential to bring noticeable health and environmental benefits shortly after its enforcement.

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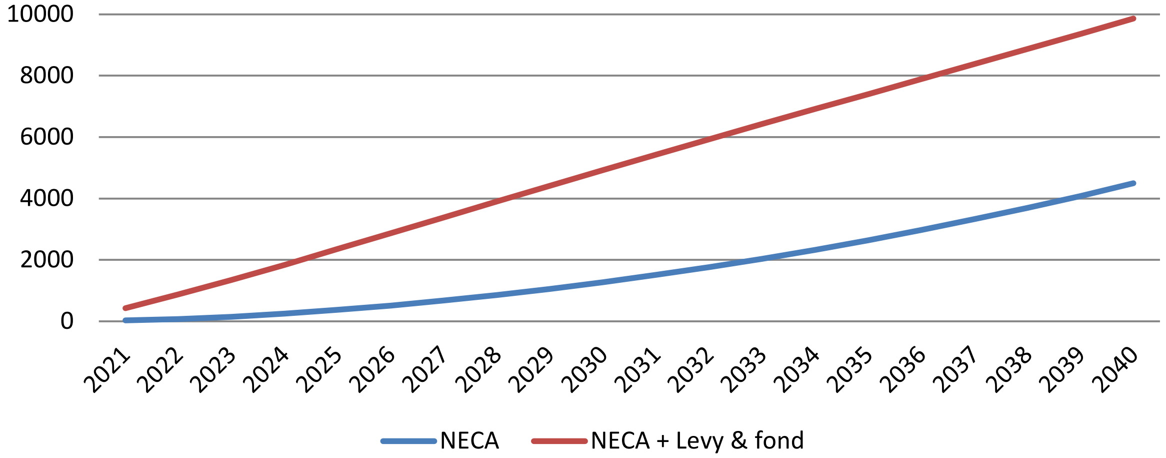
Annex 1. NO_x emissions by categories

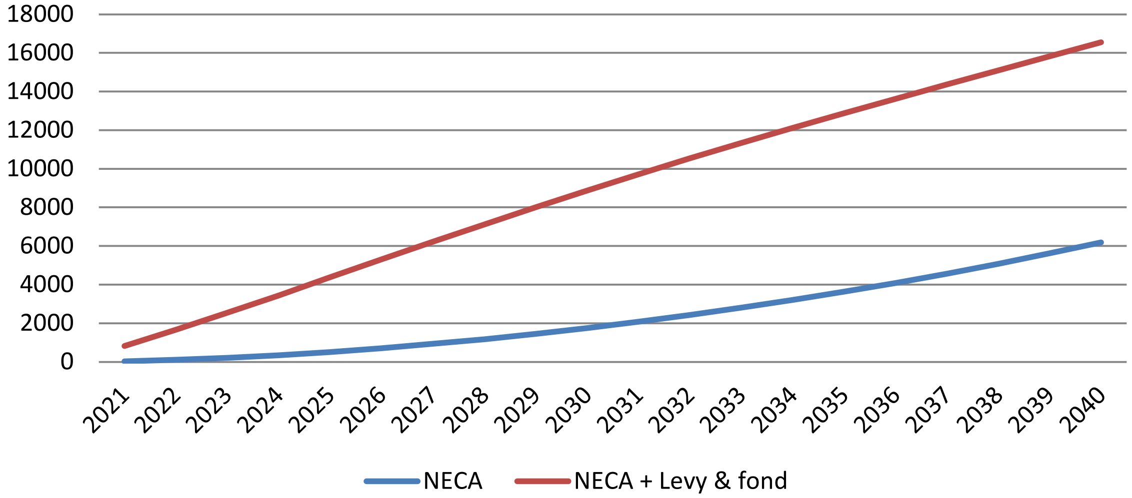
Year	NOx emissions, kt							
	Boilers	Tier 0 No SCR	Tier I No SCR	Tier II No SCR	Tier III (>2021) New SCR	Tiers I, II Retrofit SCR	LNG	Total
2020	1.54	147.3	372.1	277.0	-	-	0.23	798
Baseline								
2021	1.54	118.6	367.6	304.0	-	-	0.25	792
2022	1.54	89.9	363.2	331.1	-	-	0.28	786
2023	1.54	61.3	358.7	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

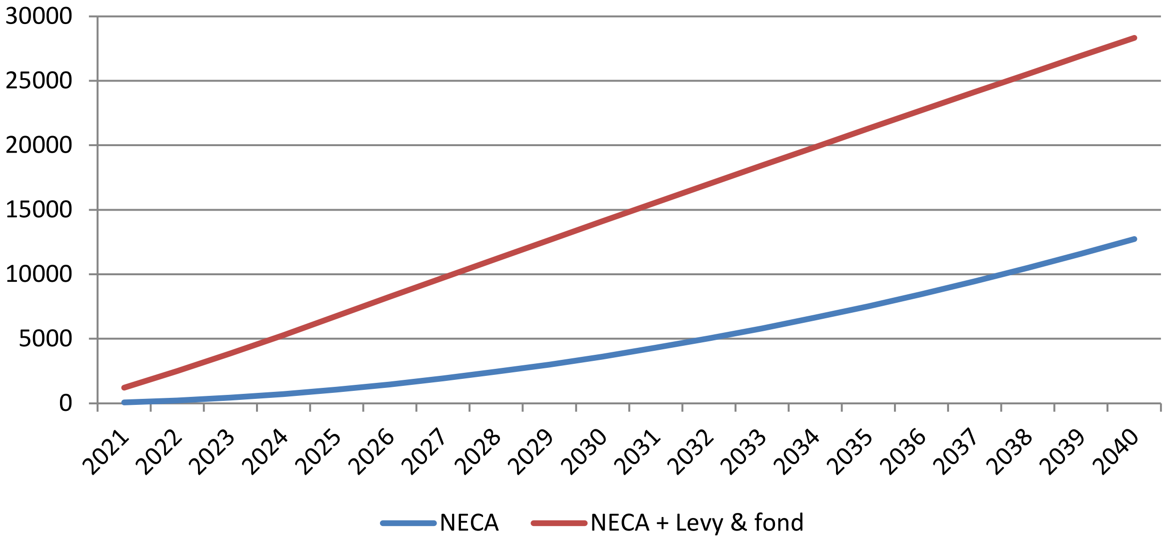
Accumulated NO_x emission reductions, kt



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



Accumulated reduced external costs related to adverse health effects (VOLY), million $€_{2010}$



Annex 3. SCR costs

Technology parameters, weighted average values

- Installed power, per vessel – 13.4 MW,
- Engine work 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,
- NO_x emission reduction for new vessels and Tier II vessels – 9.4 kg/MWh,
- NO_x 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, central values				
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 NO_x				
Social perspective (4%-25 years), low	**€2010/kg NO_x**	**0.49**	**1.57**	**1.74**
Social perspective (4%-25 years), central	**€2010/kg NO_x**	**1.38**	**1.86**	**2.03**
Social perspective (4%-25 years), high	**€2010/kg NO_x**	**2.24**	**2.24**	**2.42**
Private perspective, 5%-15 years, central	€2010/kg NO_x	1.97	2.72	2.16
Private perspective, 7%-12 years, central	€2010/kg NO_x	2.48	3.47	2.75

Parameter	**Unit**	**New SCR**	**Retrofit SCR**	
			on Tier II	**on Tier I**
Private perspective, 10%-10 years, central	$€_{2010}$/kg NO_x	3.13	4.40	3.49
Private perspective, 12%-7 years, central	$€_{2010}$/kg NO_x	4.11	5.82	4.62
Private perspective, 15%-5 years, central	$€_{2010}$/kg NO_x	5.49	7.82	6.20
Private perspective, 7%-5 years, central	$€_{2010}$/kg NO_x	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	2750	110	110
Chemical tanker	26	1534	32	2750	220	220
Container ship	25	3752	84	2750	935	935
General cargo	26	1595	31	1375	110	110
LG tanker	29	222	4	2750	165	165
Oil tanker	26	769	16	2750	440	440
RoRo cargo	27	875	25	2750	1210	1210
Ferry	27	2114	44	5500	5500	5500
Cruise	27	298	6	2750	1045	1045
Vehicle carrier	27	327	18	2750	1210	1210
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

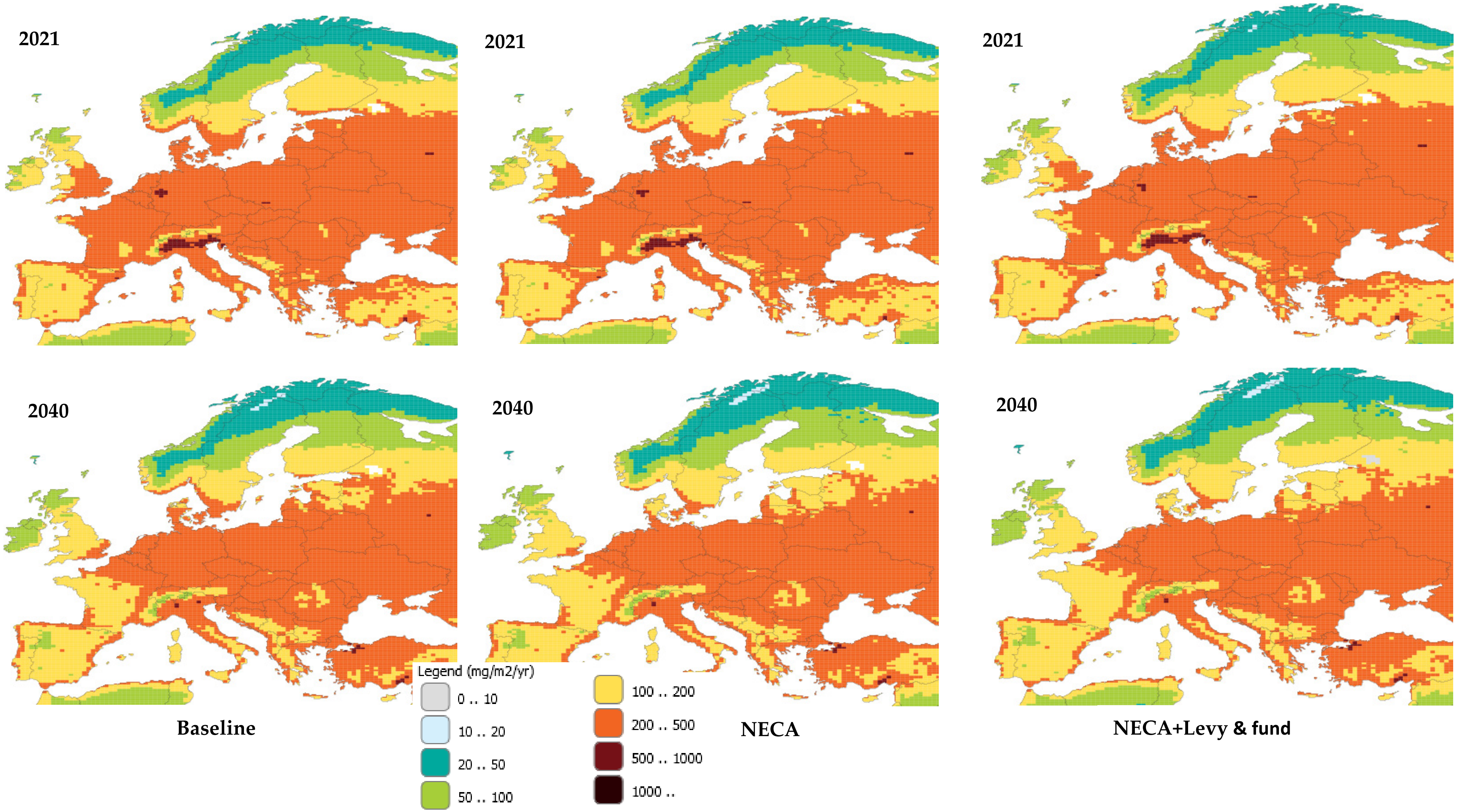
Annex 5. Total annual abatement costs

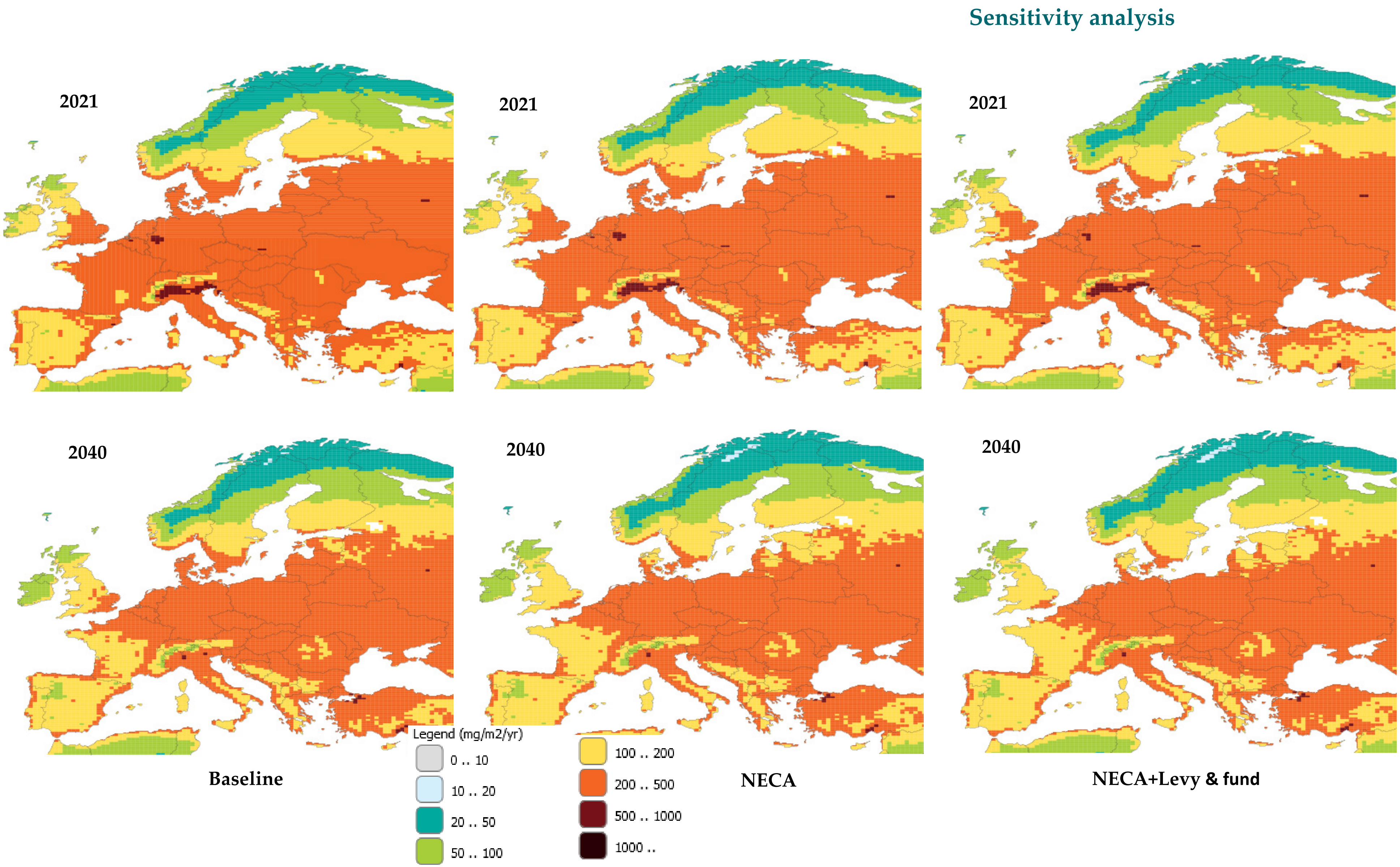
Year	Technology	Costs, million €2010					
		low		central		high	
		NECA	NECA + L&F	NECA	NECA + L&F	NECA	NECA + L&F
2021	nSCR	12	12	34	34	56	56
	rSCR-II	-	261	-	310	-	373
	rSCR-I	-	409	-	475	-	567
	TOTAL	12	682	34	819	56	995
2022	nSCR	24	24	68	68	111	111
	rSCR-II	-	261	-	310	-	373
	rSCR-I I	-	404	-	469	-	560
	TOTAL	24	689	68	847	111	1044
2023	nSCR	37	37	102	102	167	167
	rSCR-II	-	261	-	310	-	373
	rSCR-I	-	399	-	464	-	553
	TOTAL	37	697	102	876	167	1093
2024	nSCR	49	49	136	136	222	222
	rSCR-II	-	261	-	310	-	373
	rSCR-I	-	394	-	458	-	546
	TOTAL	49	704	136	904	222	1142
2025	nSCR	61	61	171	171	278	278
	rSCR-II	-	265	-	310	-	378
	rSCR-I	-	393	-	457	-	545
	TOTAL	61	719	171	941	278	1202
2030	nSCR	107	107	298	298	487	487
	rSCR-II	-	269	-	319	-	384
	rSCR-I	-	214	-	249	-	297
	TOTAL	107	590	298	866	487	1168
2035	nSCR	154	154	429	429	700	700
	rSCR-II	-	251	-	297	-	358
	rSCR-I	-	25	-	29	-	35
	TOTAL	154	430	429	756	700	1092
2040	nSCR	202	202	563	563	917	917
	rSCR-II	-	135	-	160	-	193
	rSCR-I	-	-	-	-	-	-
	TOTAL	202	337	563	723	917	1110

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

Annex 6. NO_x deposition across Europe

Main analysis





Sensitivity analysis
2021
2021
2021
2040
2040
2040
Baseline
NECA
NECA+Levy & fund
Legend (mg/m2/yr)
0 .. 10
10 .. 20
20 .. 50
50 .. 100
100 .. 200
200 .. 500
500 .. 1000
1000 ..

Annex 7. Total NO_x deposition

Year	Emissions, kt NO_x	Deposition of N emitted in the Baltic and North Seas, kt N			Reduction compared to the baseline, kt oxidised 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	469	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. Gross annual health benefits in coastal countries

France

Benefits, million €2010		VOLY			VSL		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	13.0	16.8	34.0	27.7	51.9	64.2
	NECA + L&F	192.5	248.9	503.5	410.5	767.5	950.7
	NECA SA	10.4	13.5	27.2	22.2	41.5	51.4
	NECA + L&F SA	221.1	285.9	578.3	471.5	881.6	1 092.0
2025	NECA	55.1	71.1	143.3	121.5	227.4	281.8
	NECA + L&F	236.2	304.8	614.3	520.6	974.6	1 207.7
	NECA SA	52.5	67.7	136.5	115.7	216.6	268.4
	NECA + L&F SA	270.3	348.8	703.1	595.8	1 115.4	1 382.1
2030	NECA	100.6	129.5	260.1	228.8	428.9	531.6
	NECA + L&F	235.6	303.3	609.2	535.9	1 004.5	1 245.1
	NECA SA	119.1	153.4	308.0	270.9	507.9	629.5
	NECA + L&F SA	288.5	371.5	746.1	656.3	1 230.3	1 524.9
2040	NECA	194.6	249.6	498.3	490.7	925.7	1 148.9
	NECA + L&F	235.1	**301.6**	602.1	593.0	1 118.5	1 388.3
	NECA SA	275.6	353.5	705.9	695.2	1 311.4	1 627.6
	NECA + L&F SA	343.2	440.2	879.0	865.6	1 632.8	2 026.6

United Kingdom

Benefits, million €2010		VOLY			VSL		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	10.7	13.9	28.3	22.5	42.3	52.4
	NECA + L&F	189.2	246.1	502.2	400.0	750.5	930.3
	NECA SA	10.7	13.9	28.3	22.5	42.3	52.4
	NECA + L&F SA	218.5	284.3	580.0	462.0	866.7	1 074.5
2025	NECA	57.0	74.0	150.5	123.9	232.7	288.6
	NECA + L&F	236.0	306.4	623.4	513.3	964.1	1 195.4
	NECA SA	54.2	70.4	143.3	118.0	221.6	274.8
	NECA + L&F SA	268.5	348.7	709.4	584.1	1 097.0	1 360.3
2030	NECA	99.3	128.7	261.1	222.0	417.3	517.6
	NECA + L&F	234.4	303.9	616.6	524.1	985.4	1 222.1
	NECA SA	118.6	153.7	311.9	265.1	498.5	618.3
	NECA + L&F SA	289.6	375.4	761.6	647.4	1 217.2	1 509.7
2040	NECA	192.1	248.0	499.9	463.8	875.3	1 086.5
	NECA + L&F	231.0	**298.3**	601.3	558.0	1 052.9	1 306.9
	NECA SA	272.8	352.2	710.0	658.8	1 243.2	1 543.1
	NECA + L&F SA	336.8	434.9	876.6	813.4	1 534.9	1 905.3

Germany

Benefits, million €2010		VOLY			VSL		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	13.6	17.5	35.3	34.1	64.6	80.3
	NECA + L&F	213.8	275.8	556.7	537.9	1 018.2	1 264.7
	NECA SA	10.2	13.1	26.5	25.6	48.5	60.2
	NECA + L&F SA	244.3	315.2	636.2	614.7	1 163.6	1 445.4
2025	NECA	59.6	76.7	154.4	157.9	299.7	372.4
	NECA + L&F	254.9	328.3	660.4	675.3	1 281.9	1 593.2
	NECA SA	59.6	76.7	154.4	157.9	299.7	372.4
	NECA + L&F SA	291.3	375.1	754.8	771.8	1 465.0	1 820.8
2030	NECA	103.3	132.9	266.5	288.1	548.3	681.8
	NECA + L&F	242.2	311.4	624.6	675.2	1 285.0	1 598.0
	NECA SA	119.5	153.6	308.1	333.1	634.0	788.4
	NECA + L&F SA	297.1	382.0	766.1	828.3	1 576.3	1 960.3
2040	NECA	186.7	239.2	477.3	570.6	1 090.9	1 358.0
	NECA + L&F	227.1	**291.0**	580.7	694.2	1 327.3	1 652.2
	NECA SA	267.5	342.8	684.1	817.8	1 563.6	1 946.4
	NECA + L&F SA	332.9	426.6	851.1	1 017.5	1 945.4	2 421.7

Netherlands

Benefits, million €2010		VOLY			VSL		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	5.5	7.1	14.4	11.5	21.4	26.5
	NECA + L&F	89.1	115.4	234.3	186.3	348.2	431.3
	NECA SA	5.5	7.1	14.4	11.5	21.4	26.5
	NECA + L&F SA	102.8	133.1	270.3	215.0	401.8	497.7
2025	NECA	26.1	33.8	68.4	58.7	110.3	136.8
	NECA + L&F	109.3	141.3	286.1	245.7	461.6	572.3
	NECA SA	25.4	32.9	66.6	57.2	107.4	133.2
	NECA + L&F SA	124.4	160.9	325.7	279.7	525.4	651.5
2030	NECA	45.5	58.7	118.6	109.4	206.4	256.2
	NECA + L&F	107.6	138.8	280.3	258.6	487.8	605.5
	NECA SA	53.1	68.5	138.4	127.6	240.8	298.9
	NECA + L&F SA	131.7	170.0	343.2	316.6	597.3	741.3
2040	NECA	85.4	109.8	220.5	234.1	445.0	553.3
	NECA + L&F	103.8	**133.5**	268.1	284.6	541.2	672.9
	NECA SA	121.6	156.3	313.9	333.3	633.7	787.9
	NECA + L&F SA	150.9	194.1	389.8	413.8	786.8	978.3

Poland

Benefits, million €2010		VOLY			VSL		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	3.5	4.6	9.5	7.4	14.0	17.4
	NECA + L&F	63.0	82.6	170.8	133.8	252.6	313.6
	NECA SA	3.5	4.6	9.5	7.4	14.0	17.4
	NECA + L&F SA	71.8	94.0	194.5	152.4	287.7	357.1
2025	NECA	18.8	24.6	50.7	42.3	80.1	99.5
	NECA + L&F	75.2	98.2	202.6	169.3	320.5	398.1
	NECA SA	17.1	22.3	46.0	38.5	72.8	90.5
	NECA + L&F SA	83.7	109.4	225.6	188.5	356.9	443.3
2030	NECA	30.0	39.1	80.5	71.6	135.9	168.9
	NECA + L&F	71.7	93.5	192.2	171.0	324.7	403.6
	NECA SA	35.0	45.7	93.9	83.5	158.6	197.1
	NECA + L&F SA	86.7	113.1	232.4	206.8	392.7	488.0
2040	NECA	55.7	72.3	147.5	153.5	293.5	365.4
	NECA + L&F	66.8	**86.7**	177.0	184.2	352.2	438.5
	NECA SA	77.9	101.2	206.5	214.9	410.9	511.5
	NECA + L&F SA	97.0	126.0	257.1	267.5	511.5	636.8

Belgium

Benefits, million €2010		VOLY			VSL		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	2.3	3.0	6.0	5.2	9.8	12.2
	NECA + L&F	45.1	58.7	119.6	103.1	194.7	241.7
	NECA SA	2.7	3.6	7.3	6.3	11.8	14.6
	NECA + L&F SA	51.5	66.9	136.6	117.7	222.2	275.9
2025	NECA	13.2	17.1	34.9	31.0	58.6	72.8
	NECA + L&F	54.6	70.9	144.3	128.4	242.6	301.2
	NECA SA	12.8	16.5	33.7	30.0	56.6	70.3
	NECA + L&F SA	62.4	81.0	164.7	146.6	277.0	343.9
2030	NECA	23.2	30.1	61.0	56.0	105.9	131.5
	NECA + L&F	54.1	70.2	142.3	130.7	247.1	306.9
	NECA SA	26.8	34.8	70.6	64.8	122.5	152.2
	NECA + L&F SA	66.0	85.5	173.4	159.2	301.1	374.0
2040	NECA	43.3	55.9	112.7	113.8	216.0	268.5
	NECA + L&F	52.4	**67.6**	136.4	137.7	261.5	325.0
	NECA SA	61.5	79.4	160.1	161.6	307.0	381.6
	NECA + L&F SA	76.6	98.8	199.3	201.2	382.0	474.8

Denmark

Benefits, million €2010		**VOLY**			**VSL**		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	1.4	1.9	3.9	3.1	5.9	7.4
	NECA + L&F	23.4	30.5	62.5	50.9	95.9	119.0
	NECA SA	1.2	1.6	3.2	2.6	4.9	6.1
	NECA + L&F SA	26.7	34.9	71.5	58.2	109.8	136.2
2025	NECA	6.8	8.8	18.0	15.5	29.4	36.5
	NECA + L&F	28.6	37.2	76.1	65.5	123.8	153.7
	NECA SA	6.5	8.5	17.4	15.0	28.3	35.2
	NECA + L&F SA	32.7	42.6	87.0	75.0	141.6	175.9
2030	NECA	12.2	15.8	32.2	29.3	55.5	68.9
	NECA + L&F	28.5	37.0	75.4	68.6	129.8	161.3
	NECA SA	14.1	18.4	37.4	34.0	64.4	80.0
	NECA + L&F SA	34.6	45.0	91.5	83.2	157.6	195.7
2040	NECA	22.5	29.2	59.1	58.6	111.4	138.5
	NECA + L&F	27.1	**35.1**	71.0	70.5	133.9	166.4
	NECA SA	31.7	41.0	82.9	82.3	156.4	194.4
	NECA + L&F SA	39.6	51.2	103.7	102.9	195.5	243.0

Sweden

Benefits, million €2010		**VOLY**			**VSL**		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	1.2	1.5	3.1	2.5	4.8	5.9
	NECA + L&F	16.4	21.1	42.7	35.5	66.5	82.4
	NECA SA	0.8	1.0	2.0	1.7	3.2	3.9
	NECA + L&F SA	18.3	23.6	47.8	39.8	74.4	92.2
2025	NECA	5.2	6.7	13.4	11.7	22.0	27.2
	NECA + L&F	20.3	26.1	52.7	46.0	86.2	106.9
	NECA SA	4.8	6.1	12.4	10.8	20.3	25.2
	NECA + L&F SA	23.0	29.7	59.9	52.3	98.1	121.6
2030	NECA	8.5	10.9	22.0	20.1	37.8	46.8
	NECA + L&F	20.2	26.0	52.3	47.8	89.9	111.5
	NECA SA	10.1	13.0	26.2	23.9	45.0	55.8
	NECA + L&F SA	24.7	31.7	63.9	58.3	109.7	136.0
2040	NECA	16.3	20.8	41.7	41.3	78.0	96.8
	NECA + L&F	19.5	**25.0**	50.0	49.6	93.6	116.2
	NECA SA	23.2	29.7	59.4	58.9	111.2	138.0
	NECA + L&F SA	28.9	37.0	74.0	73.3	138.5	171.9

Russian Federation (European part)

Benefits, million €2010		VOLY			VSL		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	0.0	0.0	0.0	0.0	0.0	0.0
	NECA + L&F	7.9	10.6	22.8	16.6	31.9	39.8
	NECA SA	0.0	0.0	0.0	0.0	0.0	0.0
	NECA + L&F SA	15.9	21.3	45.5	33.3	63.8	79.5
2025	NECA	0.0	0.0	0.0	0.0	0.0	0.0
	NECA + L&F	15.0	20.1	42.9	33.0	63.5	79.1
	NECA SA	7.5	10.1	21.4	16.5	31.7	39.5
	NECA + L&F SA	22.6	30.2	64.3	49.6	95.2	118.6
2030	NECA	7.1	9.5	20.2	16.4	31.5	39.3
	NECA + L&F	14.3	19.0	40.4	32.8	63.1	78.6
	NECA SA	7.1	9.5	20.2	16.4	31.5	39.3
	NECA + L&F SA	21.4	28.6	60.6	49.2	94.6	117.9
2040	NECA	6.6	8.8	18.5	17.0	32.7	40.7
	NECA + L&F	13.2	**17.6**	37.0	33.9	65.3	81.5
	NECA SA	19.9	26.4	55.5	50.9	98.0	122.2
	NECA + L&F SA	19.9	26.4	55.5	50.9	98.0	122.2

Lithuania

Benefits, million €2010		VOLY			VSL		
Year	**Scenario**	**low**	**central**	**high**	**low**	**central**	**high**
2021	NECA	0.5	0.6	1.4	1.1	2.2	2.7
	NECA + L&F	8.6	11.4	24.0	19.9	38.2	47.5
	NECA SA	0.5	0.6	1.4	1.1	2.2	2.7
	NECA + L&F SA	9.7	12.9	27.1	22.5	43.2	53.8
2025	NECA	2.3	3.1	6.4	5.5	10.6	13.2
	NECA + L&F	9.9	13.1	27.5	23.6	45.1	56.2
	NECA SA	2.3	3.1	6.4	5.5	10.6	13.2
	NECA + L&F SA	11.4	15.1	31.8	27.2	52.2	65.0
2030	NECA	4.0	5.3	11.0	9.7	18.6	23.2
	NECA + L&F	9.5	12.5	26.1	23.1	44.2	55.0
	NECA SA	4.7	6.2	13.1	11.5	22.1	27.5
	NECA + L&F SA	11.5	15.2	31.8	28.1	53.9	67.1
2040	NECA	6.8	8.9	18.5	18.1	34.7	43.2
	NECA + L&F	8.3	**10.9**	22.6	22.0	42.3	52.7
	NECA SA	9.8	12.8	26.6	26.0	49.9	62.2
	NECA + L&F SA	12.2	16.0	33.3	32.5	62.4	77.8

Finland

Benefits, million €2010		VOLY			VSL		
Year	Scenario	low	central	high	low	central	high
2021	NECA	0.2	0.3	0.6	0.5	1.0	1.2
	NECA + L&F	3.6	4.7	9.6	8.1	15.3	19.0
	NECA SA	0.2	0.3	0.6	0.5	1.0	1.2
	NECA + L&F SA	4.3	5.6	11.3	9.7	18.2	22.5
2025	NECA	1.1	1.5	3.0	2.7	5.1	6.4
	NECA + L&F	4.5	5.9	11.9	10.8	20.5	25.4
	NECA SA	0.9	1.2	2.4	2.2	4.1	5.1
	NECA + L&F SA	5.2	6.8	13.7	12.5	23.5	29.2
2030	NECA	1.8	2.4	4.8	4.6	8.7	10.8
	NECA + L&F	4.6	5.9	11.9	11.5	21.8	27.1
	NECA SA	2.3	2.9	5.9	5.8	10.9	13.5
	NECA + L&F SA	5.5	7.1	14.3	13.8	26.2	32.5
2040	NECA	3.6	4.6	9.3	10.1	19.2	23.9
	NECA + L&F	4.5	**5.8**	11.6	12.6	24.0	29.9
	NECA SA	5.2	6.6	13.4	14.5	27.6	34.4
	NECA + L&F SA	6.3	8.1	16.3	17.6	33.6	41.8

Latvia

Benefits, million €2010		VOLY			VSL		
Year	Scenario	low	central	high	low	central	high
2021	NECA	0.3	0.4	0.9	0.8	1.5	1.8
	NECA + L&F	4.4	5.8	12.1	10.6	20.3	25.3
	NECA SA	0.3	0.4	0.9	0.8	1.5	1.8
	NECA + L&F SA	5.0	6.6	13.9	12.1	23.3	29.0
2025	NECA	1.2	1.6	3.3	3.0	5.8	7.2
	NECA + L&F	5.0	6.5	13.7	12.4	23.7	29.5
	NECA SA	1.1	1.5	3.1	2.8	5.3	6.6
	NECA + L&F SA	5.8	7.6	15.9	14.4	27.6	34.3
2030	NECA	2.0	2.7	5.5	5.2	9.9	12.3
	NECA + L&F	4.7	6.2	12.9	12.1	23.1	28.8
	NECA SA	2.4	3.2	6.6	6.2	11.8	14.7
	NECA + L&F SA	5.9	7.7	16.1	15.0	28.8	35.9
2040	NECA	3.6	4.7	9.6	9.8	18.9	23.5
	NECA + L&F	4.3	**5.6**	11.6	11.8	22.6	28.2
	NECA SA	5.0	6.5	13.5	13.7	26.4	32.9
	NECA + L&F SA	6.2	8.2	16.9	17.2	33.0	41.1

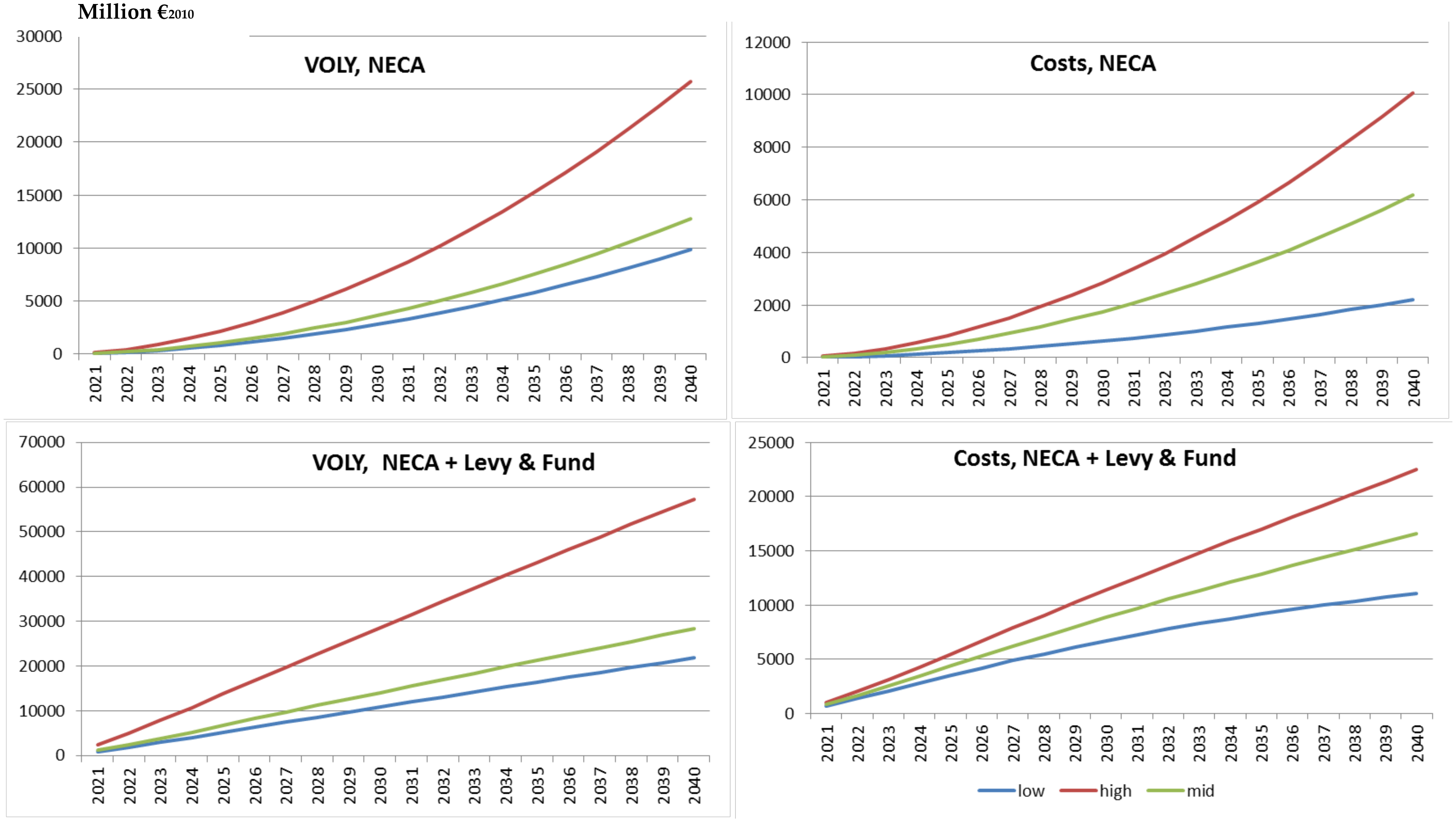
Norway

Benefits, million €2010		VOLY			VSL		
Year	Scenario	low	central	high	low	central	high
2021	NECA	0.2	0.3	0.5	0.4	0.7	0.9
	NECA + L&F	2.3	3.0	6.0	4.4	8.1	10.0
	NECA SA	0.0	0.0	0.0	0.0	0.0	0.0
	NECA + L&F SA	2.5	3.2	6.5	4.8	8.8	10.9
2025	NECA	0.6	0.8	1.7	1.3	2.4	2.9
	NECA + L&F	3.0	3.9	7.8	6.0	11.1	13.7
	NECA SA	0.6	0.8	1.7	1.3	2.4	2.9
	NECA + L&F SA	3.2	4.1	8.3	6.4	11.9	14.7
2030	NECA	1.1	1.4	2.8	2.3	4.3	5.3
	NECA + L&F	2.9	3.7	7.4	6.0	11.1	13.7
	NECA SA	1.5	2.0	4.0	3.2	6.0	7.4
	NECA + L&F SA	3.7	4.8	9.6	7.8	14.5	17.9
2040	NECA	2.3	2.9	5.8	5.3	9.9	12.3
	NECA + L&F	2.7	**3.5**	6.9	6.4	11.9	14.8
	NECA SA	3.4	4.4	8.7	7.9	14.9	18.4
	NECA + L&F SA	4.3	5.5	11.0	10.1	18.9	23.4

Estonia

Benefits, million €2010		VOLY			VSL		
Year	Scenario	low	central	high	low	central	high
2021	NECA	0.1	0.1	0.2	0.1	0.3	0.4
	NECA + L&F	1.8	2.4	5.0	4.3	8.2	10.2
	NECA SA	0.1	0.1	0.2	0.1	0.3	0.4
	NECA + L&F SA	2.1	2.7	5.7	4.9	9.4	11.6
2025	NECA	0.5	0.7	1.5	1.3	2.5	3.2
	NECA + L&F	2.2	2.9	6.0	5.3	10.1	12.6
	NECA SA	0.5	0.6	1.3	1.2	2.3	2.8
	NECA + L&F SA	2.4	3.2	6.7	5.9	11.3	14.0
2030	NECA	0.9	1.2	2.4	2.2	4.2	5.2
	NECA + L&F	2.1	2.7	5.6	5.1	9.8	12.2
	NECA SA	1.0	1.3	2.7	2.5	4.8	5.9
	NECA + L&F SA	2.5	3.3	6.9	6.3	12.0	15.0
2040	NECA	1.6	2.0	4.2	4.1	7.9	9.9
	NECA + L&F	1.9	**2.5**	5.1	5.0	9.6	12.0
	NECA SA	2.2	2.9	6.0	5.9	11.3	14.1
	NECA + L&F SA	2.7	3.6	7.3	7.3	13.9	17.3

Annex 10. Accumulated costs and benefits – intervals



Annex 11. Sensitivity analysis results

Baseline scenario

Parameter	Unit	Main/SA*	2021	2025	2030	2040
Annual NO_x emissions	ktonnes	Main	792	768	741	715
		SA	916	938	958	1047
Annual NO_x deposition on land**	ktonnes N	Main	117	114	110	106
		SA	136	138	146	155
Annual premature mortality, population > 30 years	million years of life lost	Main	360	348	342	345
		SA	360	349	343	346

NECA and NECA+Levy&fund scenarios

Parameter	Unit	Main/SA	NECA		NECA+Levy&fund	
			2030	2040	2030	2040
NO_x emissions, annual	ktonnes	Main	524	306	230	220
		SA	705	465	334	323
NO_x emission reduction, annual	ktonnes	Main	217	409	495	723
		SA	254	582	624	724
NO_x emission reduction, accumulated	ktonnes	Main	1 271	4 492	4 921	9 858
		SA	1 370	5 659	5 767	12 482
NO_x abatement costs, accumulated	million $€_{2010}$	Main	1 748	6 179	8 869	16 547
		SA	1 872	7 773	11 492	23 063
NO_x deposition on land, annual reduction on top of BL	ktonnes N	Main	32	60	80	73
		SA	37	86	89	98
Annual premature mortality, population > 30 years, reduction on top of BL	million years of life lost	Main	0.58	1.10	1.37	1.33
		SA	0.68	1.56	1.68	1.94
Gross health benefits, VOLY, central values, accumulated	million $€_{2010}$	Main	3 632	12 737	14 114	28 319
		SA	3 900	16 203	16 559	35 820
Benefit-cost ratio, VOLY, central values, annual	-	Main	2.1	2.0	1.7	1.9
		SA	2.1	1.5	2.1	1.8
Net socio-economic benefits, VOLY, central values, accumulated	million $€_{2010}$	Main	-	6 558	-	11 772
		SA	-	8 430	-	12 758

* Main or sensitivity analysis scenario
** Only inputs from emissions in the Baltic Sea and the North Sea

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