Nordic Council
of Ministers

# Damage Costs of Nordic emissions of Short-Lived Climate Pollutants and $CO_2$

## Scenarios for 2015–2050

# Contents

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# Foreword

This report constitutes the final deliverable of the project "*Analysing current and future damage costs of Nordic emissions of greenhouse gases, short-lived climate pollutants, and other air pollutants*" (agreement no: NKL-2406), financed by the Nordic working group for Climate and Air (NKL) under the auspices of the Nordic Council of Ministers (NCM). The project has been led by Stefan Åström, and project collaborators have been Krister Mars from Anthesis AB, Henrik Lindhjem and Ståle Navrud from Menon Economics, as well as Mikko Savolahti, Niko Karvosenoja and Tommi Forsberg from the Finnish Environment Institute. The contact person for NKL has been Anna Gran.

We would like to thank NKL for active involvement in the project. We would also like to thank the workshop participants Thomas Sterner (Gothenburg University) and Mike Holland (EMRC). With the approval by NKL of this report, the project is considered completed. The conclusions and recommendations presented in this report do not represent the position of the Nordic working group for Climate and Air (NKL) under the auspices of the Nordic Council of Ministers (NCM). All errors are the authors' own.

# List of abbreviations

| Abbreviation | Full Term |
|---|---|
| **BC** | Black Carbon |
| **BSL** | Baseline Scenario (from CIAM & TFIAM) |
| **$CH_4$** | Methane |
| **CIAM** | Centre for Integrated Assessment Modelling |
| **$CO_2$** | Carbon Dioxide |
| **EEA** | European Environment Agency |
| **EPA** | Environmental Protection Agency |
| **GHG** | Greenhouse Gases |
| **GTP100** | Global Temperature change Potential over 100 Years |
| **GWP100** | Global Warming Potential over 100 Years |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **MTFR** | Maximum Technically Feasible Reduction Scenario |
| **$NH_3$** | Ammonia |
| **NMVOC** | Non-Methane Volatile Organic Compounds |
| **$No_x$** | Nitrogen Oxides |
| **OC** | Organic Carbon |
| **OECD** | Organisation for Economic Co-operation and Development |
| **PM_other** | Other Particulate Matter (non-carbon PM2.5) |
| **PM2.5** | Particulate Matter ≤2.5 micrometers in diameter |

| | |
|---|---|
| **SCC** | Social Cost of Carbon |
| **SC-GHG** | Social Cost of Greenhouse Gases |
| **SCM** | Social Cost of Methane |
| **SCN** | Social Cost of Nitrous Oxide |
| **SLCF** | Short-Lived Climate Forcers |
| **SLCP** | Short-Lived Climate Pollutants |
| **$SO_2$** | Sulphur Dioxide |
| **TFIAM** | Task Force on Integrated Assessment Modelling |
| **UNECE** | United Nations Economic Commission for Europe |
| **VOLY** | Value of Life Year Lost |
| **VSL** | Value of Statistical Life |
| **WAM** | With Additional Measures (scenario) |
| **WEM** | With Existing Measures (scenario) |

# Svensk sammanfattning

Nordiska utsläpp av växthusgaser och luftföroreningar orsakar fortfarande stor skada på klimatet, den naturliga miljön, folkhälsan, och ekonomin. Men det saknas kunskap om hur stora skadekostnaderna är och kan bli i framtiden, och klimatrelaterade skadekostnader för luftföroreningar är fortfarande exkluderade i befintliga akademiska och statliga riktlinjevärden för skadekostnader. Beräkningen och användningen av skadekostnader är en viktig input för regeringar och företag vid utformning av nya miljöpolicyer eller mer hållbara produkter och tjänster. Ofullständiga skadekostnader kan därför leda till felaktiga beslut, och det är därför viktigt att sträva efter mer fullständiga skadekostnader än vad som för närvarande finns tillgängligt.

I projektet som redovisas i denna rapport har vi gjort en insats för att göra skattade skadekostnader av de luftföroreningar som har klimatpåverkan (SLCF) mer kompletta genom att lägga till skattningar av deras klimatrelaterade skadekostnader till redan fastställda skadekostnader och beräkna totala och scenariospecifika skadekostnader för de nordiska länderna. Vi använde offentligt tillgängliga data och prognoser av Nordiska SLCF-utsläpp, fackgranskade data om klimatpåverkan från SLCF, samt de senaste uppdateringarna av data om klimatrelaterade skadekostnader per ton metanutsläpp. För de mer kortlivade utsläppen justerade vi de klimatrelaterade skadekostnaderna för att bättre återspegla skadeförloppet över tid. Vi diskuterade också de viktigaste osäkerheterna kopplat till våra beräkningar. Slutligen jämförde vi våra beräkningar med motsvarande beräkningar för $CO_2$-skadekostnader och beräknade de ekonomiska fördelarna med att minska SLCF-utsläpp ytterligare.

Våra resultat visar att de klimatrelaterade skadekostnaderna för SLCF är betydande och sannolikt kommer att öka i framtiden, trots förväntade utsläppsminskningar. Till 2040 visar vår scenariosanalys att klimatrelaterade skadekostnader för SLCF kommer att uppgå till cirka 600 miljoner $€_{2020}$ per år, ~250 miljoner per år, ~600 miljoner per år och 240 miljoner per år för Danmark, Finland, Norge och Sverige. Dessa kostnader utgör cirka 15–25 % av de totala skadekostnaderna för SLCF-utsläpp från dessa länder, medan de återstående 75–85 % härrör från skador på hälsa och miljö. Island är ett intressant undantag med höga nivåer av kylande $SO_2$-utsläpp. För Island är de klimatrelaterade skadekostnaderna för SLCF därför negativa år 2040 (dvs. socioekonomiskt gynnsamma). När vi jämför med kvarvarande $CO_2$-skadekostnader i ambitiösa nationella $CO_2$-scenarier, utgör $CO_2$-utsläpp 70 % av skadekostnaderna och SLCF-utsläpp 30 %. Men OM $CO_2$-utsläppen fortsätter att minska enligt nationella prognoser för Danmark, Finland, Island och Sverige, kommer skadekostnaderna för SLCF-utsläpp att vara lika viktiga som kvarvarande $CO_2$-skadekostnader år 2050.

Våra viktigaste slutsatser och rekommendationer är i korthet att:

- Nuvarande skadekostnader för SLCF-utsläpp är underskattade,
- Inkludering av klimatrelaterade skadekostnader skulle konservativt öka skadekostnaderna för SLCF med cirka 15–25 %,
- Mer forskning om klimatpåverkan från nordiska SLCF-utsläpp behövs fortfarande.

Vi föreslår att Luft- och klimatgruppen inom Nordiska ministerrådet:

- Uppmuntrar nationella regeringar att komplettera sina riktlinjevärden för socioekonomiska skadekostnader för SLCF-utsläpp med uppskattningar av deras klimatrelaterade skadekostnader,
- Förbättrar det vetenskapliga underlaget för klimatpåverkan från nordiska SLCF-utsläpp,
- Kompletterar de globala genomsnittliga värdena för klimatskadekostnader med värden som bättre är anpassade till nordiska förhållanden för inhemska analyser,
- Överväger att främja en ökning av nationella/nordiska ambitionsnivåer för utsläppsminskningar, eftersom de socioekonomiska fördelarna är större än tidigare känt, särskilt för de SLCF som har en uppvärmande effekt.

# English summary


Nordic emissions of greenhouse gases and air pollution still cause great damage to the climate, the natural environment, public health and the wider economy. But there is a lack of knowledge about how large the damage costs are and may become in the future, and the climate damage costs of air pollution are still excluded in existing academic and governmental guideline values on damage costs. The calculation and use of damage cost is an important input for governments as well as companies when designing new environmental policies or more sustainable products and services. Incomplete damage costs can therefore lead to misguided decisions, and it is therefore important to strive for more complete damage costs than currently available.

In the project presented in this report we have made an effort to make current damage cost estimates of the air pollutants known as short-lived climate forcers (SLCF) more complete by adding their climate change damage costs on top of already established damage costs to calculate total and scenario-specific damage costs for the Nordic countries. We used publicly available data and projections on Nordic SLCF emissions, peer-reviewed data on climate impact of SLCF, as well as the latest updated data on climate change damage costs per tonne of methane-equivalent emissions. For the more short-lived emissions, we adjusted the climate change damage cost to better reflect the temporal profile of the damages. We also discussed key uncertainties related to our calculations. Finally, we compared our calculations with corresponding calculations for $CO_2$ damage costs and calculated monetary benefits of reducing SLCF emissions further.

Our results show that climate damage costs of SLCFs are substantial and are likely to become higher in the future, despite projected emission reductions. By 2040, our scenario analysis show that SLCF climate damage costs will be ~600 million $€_{2020}$ per year, ~250 million per year, ~600 million per year, and ~240 million per year for Denmark, Finland, Norway, and Sweden. These costs constitute some 15–25% of the total damage costs of SLCF emissions from these countries, the remaining 75–85% origins from damages to human health and the environment. Iceland is an interesting exception with high levels of cooling $SO_2$ emissions. For Iceland the SLCF climate damage costs are therefore in 2040 negative (i.e. socio-economically beneficial). When comparing with remaining $CO_2$ damage costs in ambitious national $CO_2$ scenarios, $CO_2$ emissions constitute 70% of the damage and SLCF emissions 30%. But if $CO_2$ emissions will continue to go down as nationally projected by Denmark, Finland, Iceland, and Sweden, the damage costs of SLCF emissions will be as important as remaining $CO_2$ damage costs by 2050.

Our most important conclusions and recommendations are in brief that:

- Current SLCF emission damage costs are underestimations,
- Including climate damage costs would conservatively increase SLCF damage costs by around 15–25%.
- More research, on the climate impact of Nordic SLCF emissions is still needed.

We suggest that the Air & Climate group of the Nordic Council of Ministers:

- Propose to national governments that they complement their guideline values for socio-economic damage costs of SLCF emissions with estimates of their climate damage costs,
- Improve the scientific underpinning of the climate impact of Nordic SLCF emissions,
- Complement the global average social cost of carbon and social cost of methane estimates with values better adjusted for intra-Nordic circumstances,
- Consider promoting an increase in national/Nordic emission abatement ambition levels since the socio-economic benefits are larger than previously known, especially for the SLCFs that are 'warming'.

# 1. Introduction

Mitigating emissions of gases and particles inducing climate change is an imperative to limit the effects of global warming. Most important is the greenhouse gas $CO_2$. According to IPCCs Sixth Assessment Report urgent near-term actions will slow global warming and "*secure a livable and sustainable future for all*" (IPCC, 2023). In addition to the climate change urgency, the same sources cause emissions of gases and particles often referred to as air pollutants. These emissions are globally the main drivers of illness and mortality due to non-communicative diseases (Health Effects Institute, 2024). Studies show that the annual effect of air pollution on current global welfare loss has been estimated from $4.6 trillion to $5.11 trillion (Peszko et al. 2023) and ~7–8 million people die prematurely each year due to air pollution (Mathew et al. 2024; Health Effects Institute, 2024). Even though air pollution problems are more severe in other regions they still cause problems in the pan-European region, despite much progress since the peak pollution years of the 1970s and 1980s. In 2018, for example, some 417,000 premature fatalities per year occurred in Europe due to fine particulate matter in ambient air (European Environment Agency, 2020). In Sweden the number of fatalities directly linked to exposure to fine particulate matter is estimated to some 4,700 in 2015 and in addition the number of fatalities linked to vehicle exhaust is estimated to 2,850 (Gustafsson et al. 2018). For the other Nordic countries, the corresponding number is 2,600–3,500 for Denmark, 1,500-1,900 for Finland, 60-70 for Iceland, and 1,400–2,100 for Norway (Lehtomäki et al. 2020). In addition, a recent study shows that Oslo is the Nordic capital with the worst air quality (Soares et al. 2023).

Emissions of several air pollutants are identified to have short term and regionally varied impact on climate change. In general, fine particulate matter in ambient air (PM2.5), including secondary particles like Sulphur aerosols as well as coarser fractions of particulate matter contribute negatively to the radiative forcing of the climate system, while some sub-fractions of PM2.5 like black carbon (BC) as well as tropospheric ozone increase the radiative forcing. Ozone ($O_3$) is a secondary pollutant formed in the troposphere from emissions of nitrogen oxides ($NO_x$), methane ($CH_4$), as well as non-methane volatile organic compounds (NMVOC). On a global scale, today's atmospheric concentration of particulate matter (including Sulphur aerosols) currently counteracts (masks) global warming to an extent corresponding to a radiative forcing (RF) of -0.9 Watt/$m^2$. Current $CO_2$ concentrations have an RF of ~1.82 W/$m^2$. The global average for particulate matter does however hide large regional variation, and the impact of the aerosol components varies (Myhre et al. 2013). As an example, Bond et al. (2013) find that the global average direct RF of BC is 0.9 W/$m^2$, with indirect effects adding more unquantified warming. This number has later been revised down to 0.4 $W/m^2$ (Myhre et al. 2013) and 0.11 $W/m^2$ (Szopa et al. 2021). Emissions that act as ozone precursors currently cause an RF of 0.5 $W/m^2$ (Myhre et al. 2013).

The air pollutant gaining most attention recently for its impact on climate change is BC, a soot sub-fraction of PM2.5. One ton BC of emissions is considered to have an impact on radiative forcing equivalent to 120–3,200 ton of $CO_2$ emissions, dependent on climate metric (Myhre et al. 2013). Recent estimates downplay the climate importance of particles (Szopa et al. 2021) but is yet not specified what this implies for climate metric values. Climate change impact has been identified for all the above presented air pollutants, as well as for the effect of $CH_4$ emissions on ozone formation (Etminan et al. 2016).

Air pollutants emitted from natural systems and anthropogenic sources with effects on climate change are usually referred to as short-term climate forcers (SLCFs) (Szopa et al. 2021), although other terms such as short-lived climate pollutants and near-term climate forcers can also be found in the literature. SLCF include pollutants such as black carbon, methane ($CH_4$), tropospheric ozone, and fluorinated gases such as hydrofluorocarbons (HFCs) (Szopa et al. 2021).

Control of SLCF emissions has been calculated to enable a reduction in the speed of global warming, contingent that $CO_2$ emissions are reduced (D. Shindell et al. 2012; Bowerman et al. 2013; Shoemaker et al. 2013). Even without $CO_2$ emission reduction, fast reduction of SLCF emissions, particularly hydrofluorocarbons (HFCs), methane, and black carbon can reduce global warming with up to 0.6 °C by 2050 (Sun et al. 2022).

However, the generalization of SLCF impacts is not straightforward. The impacts have a regional nature (Borgar Aamaas et al. 2016) and can be located in other regions than the emission source region (Acosta Navarro et al. 2016).

There is an increased global recognition of the importance of addressing SLCF in global mitigation programs and policies. However, most current air pollution policies and regulations fall short in integrating the climate and pollution challenges of SLCF emissions into a common policy framework, although there is emerging work emphasising this need in different sectors (e.g. the agricultural sector, cf. Valinia et al. (2024)). Poorly designed policies have been linked to a temporary increase in air pollution emissions. An example is policies that drive up fuel prices, which in some cases have been observed to discourage operation of technologies used to control air pollution (Peszko et al. 2023). Even if integrated policies are yet to be implemented, there are several known technologies and other solutions that can reduce both air pollution and radiative forcing from SLCFs. IPCC highlights several measures with inter alia: "*implementation of energy efficiency measures, methane capture and recovery from solid-waste management and the oil and gas industry, zero-emissions vehicles, efficient and clean stoves for heating and cooking,* *filtering of soot (particulate matter) for diesel vehicles, cleaner brick-kiln technology, practices that reduce burning of agricultural waste (super), as well as the eradication of burning of kerosene for lighting*" (Szopa et al. 2021). Other studies highlight air pollution solutions that accentuate PM2.5 emission reductions from sources that are especially BC-intensive, thus enabling co-benefits between human health and climate change (UNECE, 2021). Overall, the general message from applied research is that: "*climate and air pollution policies should be developed in an integrated manner. This will ideally enable win-win policies between human health and climate change, and at worst mitigate the risk of mitigating one problem whilst aggravating another*" (Peszko et al. 2023).

Air pollution governance has since long been aided by valuing external costs of pollution in monetary terms (monetization), since this allows both the market mechanism to self-adjust via environmental taxes and fees, as well as provides identification of weighing costs against benefits with air pollution control. Further, monetization of external costs of pollution provides an easy way of communicating environmental challenges with finance departments in governments and companies. But as stated above, effects on climate change are hitherto rarely included in the monetization of the externalities of air pollution. To help the development of integrated air pollution policies it is therefore useful to monetize not only the effect on air quality, but also effects on climate change. The effects are however uncertain, and variable dependent on region and time-of-year, so uncertainty estimates are needed to ensure robustness in policy advice from monetization.

## 1.1. What is known from earlier studies

Few studies have presented monetized estimates of the climate change effects of SLCF emissions in a manner consistent with the monetized estimates of the health effects of air pollution. D. T. Shindell (2015) concludes that mitigation of emissions affecting climate change should target a broad range of emissions affecting climate change, not only $CO_2$. The illustrative calculations of the environmental damages of "atmospheric release" is in Shindell estimated to $330-970 billion per year for electricity generation in the United States. Åström and Källmark (2023) proposed unit costs of certain of the air pollutants and compared with external costs on human health for selected countries. However, no study has made an assessment of the combined social externalities of $CO_2$ emissions and air pollution emissions or made national-scale analysis. Correspondingly, little is known about the current and future total external costs of air pollution acting as SLCFs and other greenhouse gas emissions.

## 1.2. Purpose of this report

In this report, we present the results from a project aimed to fill at least some of the gaps in the literature. In the project we have studied current and future damage costs of Nordic emissions of greenhouse gases and SLCFs. To maximise the policy relevance of our results we have based our scenario analysis on the emission forecasts and scenarios reported from the Nordic countries to the EU and UNFCCC, as well as on the latest policy scenarios under discussion at the UNECE Air Convention, in which all the Nordic countries are parties. In addition, the project has strived to analyse and present the key remaining uncertainties of importance for Nordic policy makers engaged in air pollution and climate change policies informed by monetization of emissions.

The emissions considered SO2, NOx, PM2.5, BC, OC, and other non-carbon PM2.5 emissions (PM_other). Since HFC6-emissions are of little or no concern for impacts related to air pollution, the work excludes HFC from the analysis.

# 2. Method and data

The calculation of damage costs associated with emissions of SLCFs is adapted to data availability, especially considering comparability between the Nordic countries, and computational availability. In this chapter we first present the overall method for the calculations and present the data needed for the calculations.

## 2.1. Calculating total Nordic SLCF damage costs

The calculation of total SLCF damage cost for a specific SLCF is made by multiplying the amount of emissions with the sum of unit climate effect given by a specific emission metric (Table 1) with the economic marginal climate damage cost for the specific pollutant and year (Figure 4) plus the other marginal SLCF damage costs (Table 3):

$$\textit{SLCF damage cost}_{p,m,t,i} = E_{p,t} \times (CI_{p,m} \times CDC_{p,t,i} + ODC_{p,t,i})$$

where:

*SLCF damage cost* (€$_{2020}$/tonne pollutant)

*E* = emissions (kton)

*CI* = climate impact specified per SLCF (*p*) and per emission metric (*m*) (equivalent per tonne pollutant)

*CDC* = marginal climate damage cost specified per pollutant (*p*), year (*t*) and discount rate (*i*) (€$_{2020}$ per equivalent)

*ODC* = marginal other damage cost specified per pollutant (*p*), year (*t*) and discount rate (*i*) (€$_{2020}$ per tonne)

The calculations are made in Microsoft Excel.

## 2.2. Data used in the calculations

The data used for this report consists of three parts. Nordic emissions of greenhouse gases and SLCFs, climate impact metrics to describe the effect on climate change of the emissions, as well assessments of economic externalities of climate change and air pollution.

### 2.2.1. Emission scenarios

The emission data and scenarios are for $CO_2$ taken from the latest available nationally reported emission data and scenarios to the European Environment Agency (EEA) for $CO_2$ (European Environment Agency, 2024c; 2024a), including gap filling made by EEA (Figure 1). All data are total emissions excluding effects of land use and land-use change and forestry (LULUCF).

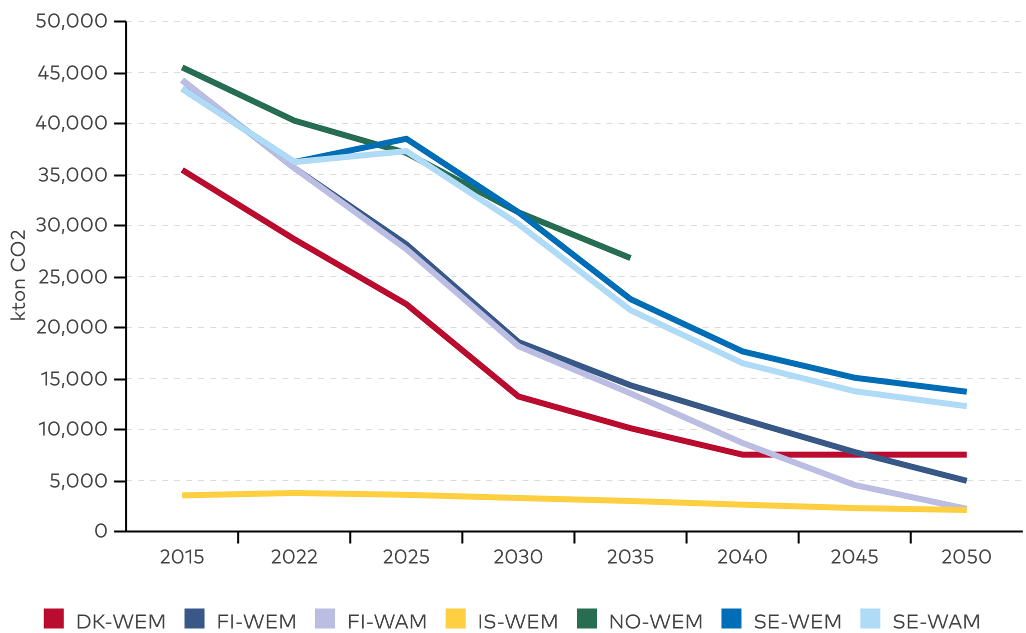
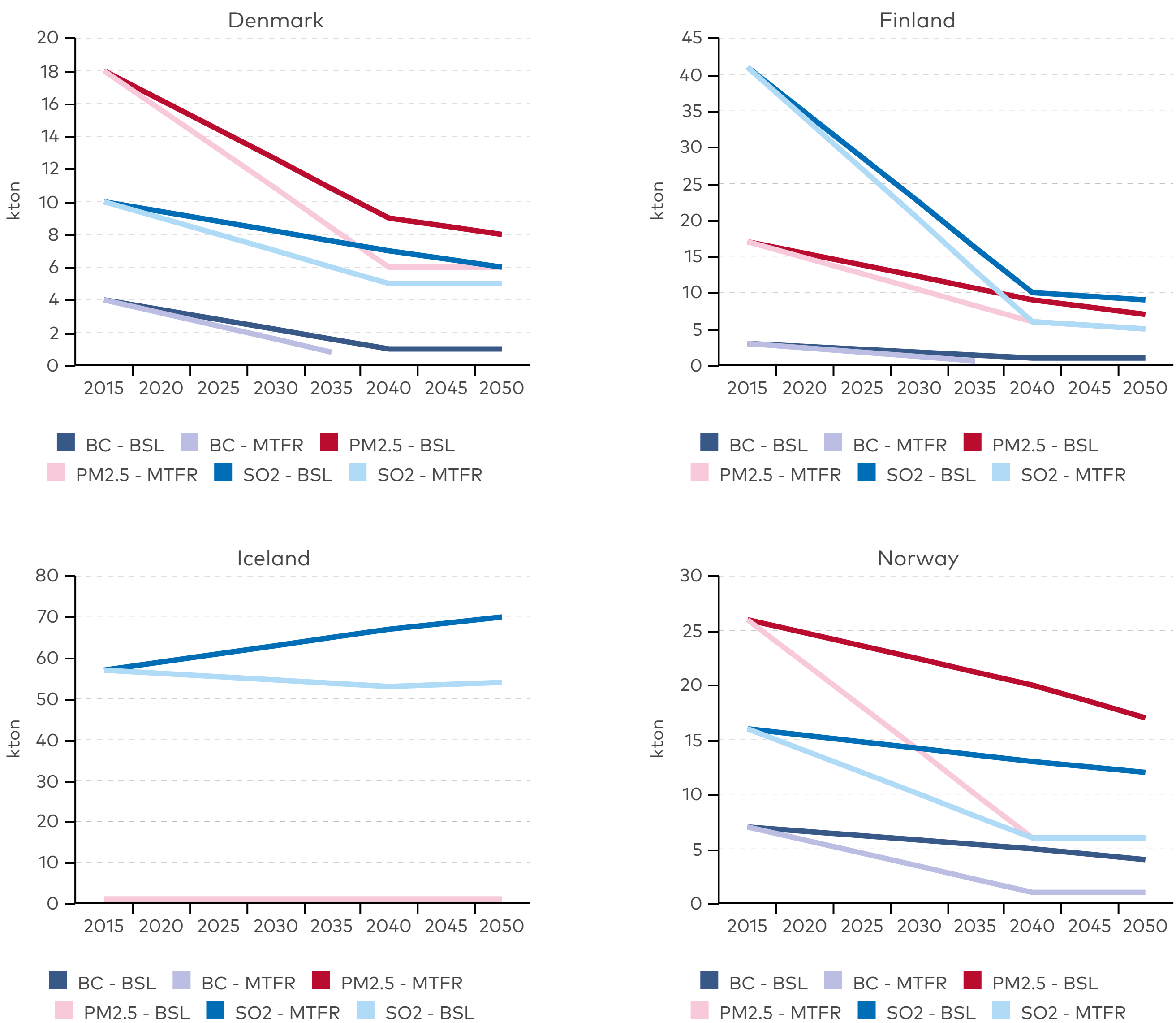



**Figure 1** Nationally projected $CO_2$ emissions as reported to the (European Environment Agency, 2024c) for the scenarios With Existing Measures (WEM) and With Additional Measures (WAM). Notice that only Finland and Sweden have reported WAM emission scenarios.

As can be noted, the scenarios registered by EEA are for different duration, where Norway stands out as only reporting $CO_2$-projections until 2035. Furthermore, only Sweden and Finland report low emission scenarios (WAM).

The SLCFs data is taken from the latest UNECE Air Convention policy brief produced by the Centre for Integrated Assessment Modelling (CIAM) and the Task Force on Integrated Assessment Modelling (TFIAM), which is used as negotiation support material during the ongoing revision of the UNECE Air Convention Gothenburg Protocol (CIAM and TFIAM, 2024). National scenarios for SLCFs were not used since they vary with respect to target year and the availability of high-policy-ambition emission scenarios, which makes them less relevant for policy support analysis. However, the scenarios produced by CIAM and TFIAM have undergone national consultation with official Nordic experts, and are checked against official statistics on fuel use, use of emission control technologies, as well as energy system fuel mixes etc. The emission scenarios from CIAM are presented in Figure 2 and Figure 3. As can be seen in the figures, the CIAM and TFIAM estimates indicate that there are substantial technical emission reduction potentials for all Nordic countries and all pollutants over the years. This potential can be seen through the comparison of the emissions in an air pollution policy baseline scenario (BSL) and a scenario in which all known emission control technologies are fully implemented (MTFR). The modelling and the scenarios suggest that Norway has the relatively largest emission reduction potential.



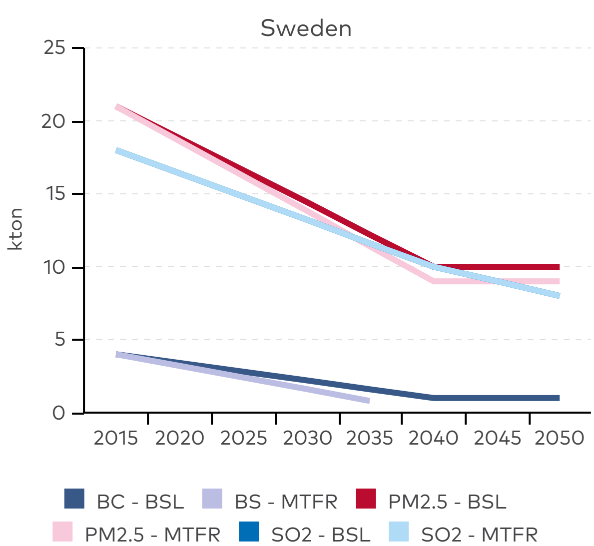
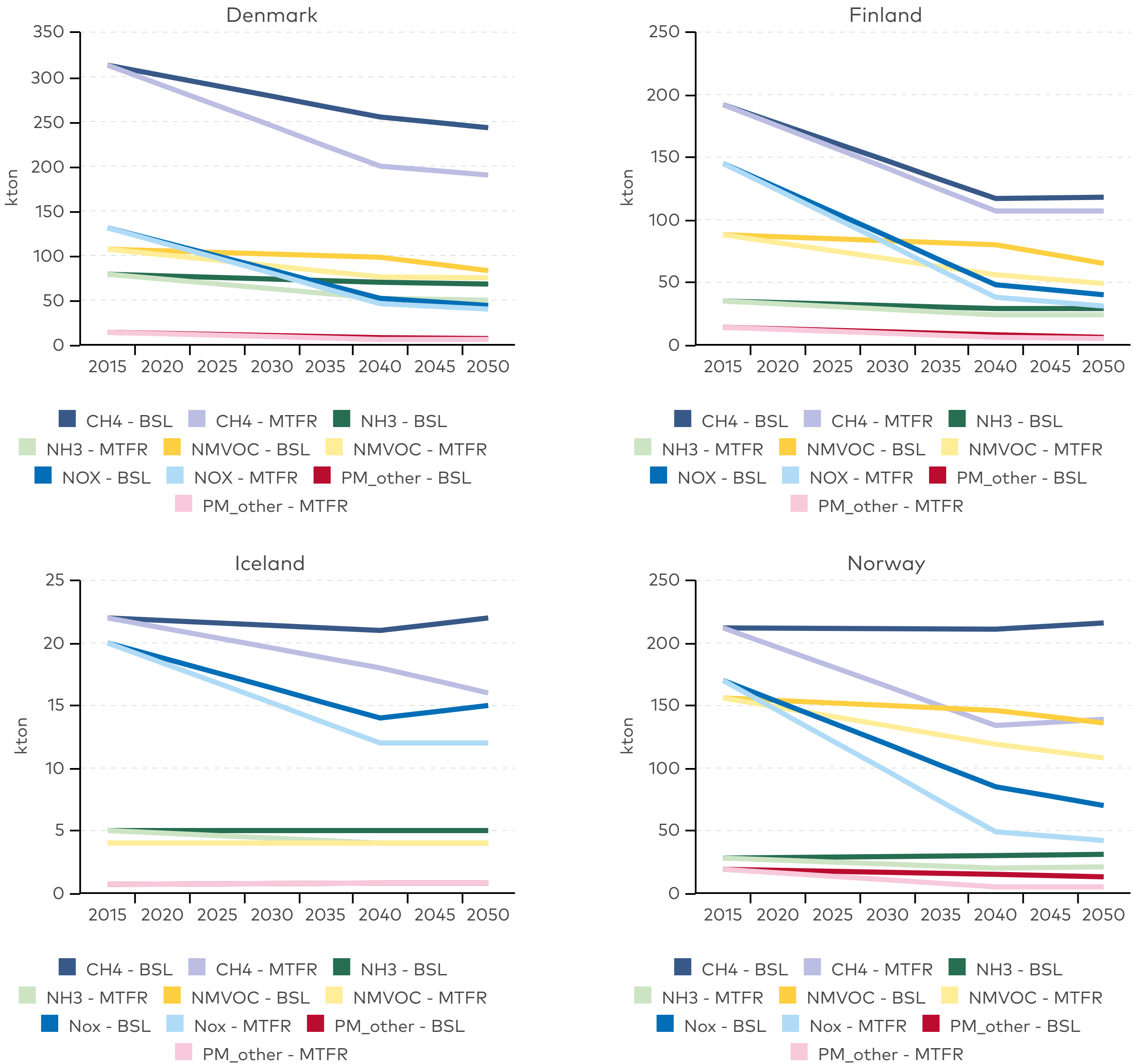




**Figure 2** BSL and MTFR emission scenarios for the pollutants BC, PM2.5 and $SO_2$ (CIAM and TFIAM, 2024). In the figure, the values for the years 2020–2035 and 2045 are derived by interpolating the values for 2015, 2040, and 2050. When a line is not seen in the graph, the difference between BSL and MTFR is too small to be visible.



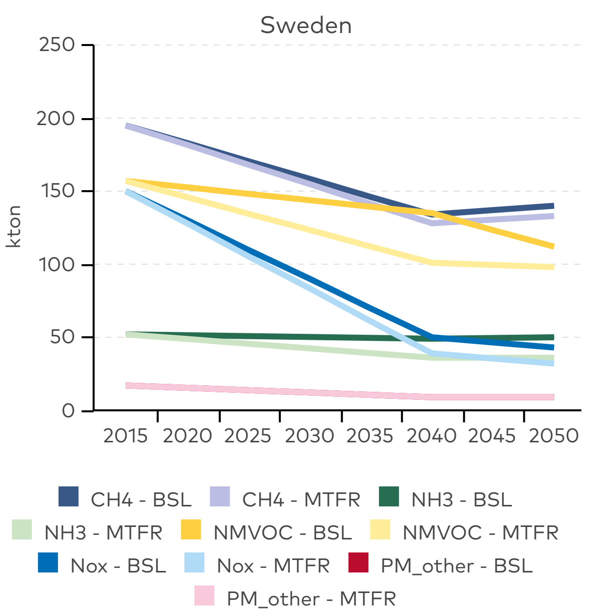




**Figure 3** BSL and MTFR emission scenarios for the pollutants $CH_4$, $NH_3$, NMVOC, $NO_x$, and PM_other (CIAM and TFIAM, 2024). In the figure, the values for the years 2020–2035 and 2045 are derived by interpolating the values for 2015, 2040, and 2050.

The BSL and MTFR emission scenarios are not exactly similar to the nationally reported emission scenarios as they were reported in 2023. But they are similar enough for them to be useful for later policy recommendations. And as a reminder, these scenarios have been undergoing bilateral discussions with country representatives from the governments in the countries. In Appendix I to this report, we show a comparison between the BLE and the officially reported NFR emission projections to the Air Convention Centre for Emission Inventories and Projections (CEIP, 2023).

### 2.2.2. Climate impact

The climate impact of SLCF emissions is complicated to estimate and calculate. It also requires a large amount of computational power, a scarce resource despite fast growing computational capacity. In response to this, climate metrics are used to allow for quick comparisons and calculations of climate change effects of changes in emissions. In practice these metrics work as "exchange rates" to enable comparability between different types of emissions. The choice of which climate metric to use is largely dependent on political priorities and purpose of the analysis (Tanaka, Peters, and Fuglestvedt 2014). In the work leading to this report, we compiled data on several climate metrics and time horizons as presented in Table 1. Due to policy relevance, we have chosen to present results for the climate metric Global Warming Potential over a 100-year time horizon ($GWP_{100}$). As in Åström and Källmark (2023), we are normalising SCLF climate impact towards $CH_4$ emissions ($CH_4$-equivalents) since the climate characteristics of the long-lived and well-mixed greenhouse gas $CO_2$ are too different from poorly mixed and short-lived SLCFs like black carbon.

**Table 1:** Metric values for European SLCF emissions as $CH_4$-equivalences and $CO_2$-equivalences per pollutant and emission metric considered in the analysis. Due to lack of consistent data, values for $SO_2$ and $NH_3$ are for global emissions.

| **$CH_4$ equivalents** | | | | | | |
|---|---|---|---|---|---|---|
| | **$GWP_{20}$** | | | **$GWP_{100}$** | | |
| | **$5^{th}$ perc.** | **Mid** | **$95^{th}$ perc.** | **$5^{th}$ perc.** | **Mid** | **$95^{th}$ perc.** |
| **PM-other** | -1.02[a] | -2.05[a] | -2.60[a] | -0.759[a] | -1.66[a] | -2.22[a] |
| **BC** | 3.91[b] | 17.6[b] | 25.0[b] | 2.90[b] | 14.3[b] | 21.3[b] |
| **OC** | -1.02[b] | -2.05[b] | -2.60[b] | -0.759[b] | -1.66[b] | -2.22[b] |
| **NMVOC** | 0.0559[c] | 0.175[c] | 0.240[c] | 0.0357[c] | 0.154[c] | 0.227[c] |
| **$CH_4$** | 1[c,d] | 1[c,d] | 1[c,d] | 1[c,d] | 1[c,d] | 1[c,d] |
| **$NO_x$** | -0.0675[c] | -0.173[c] | -0.229[c] | -0.101[c] | -0.195[c] | -0.254[c] |
| **$SO_2$** | 2.18[d] | -3.19[d] | -6.08[d] | 1.65[d] | -2.55[d] | -5.15[d] |
| **$NH_3$** | 0.69[d] | -0.52[d] | -1.17[d] | 0.528[d] | -0.415[d] | -1.00[d] |
| | **GTP20** | | | **GTP100** | | |
| | **$5^{th}$ perc.** | **Mid** | **$95^{th}$ perc.** | **$5^{th}$ perc.** | **Mid** | **$95^{th}$ perc.** |
| **PM-other** | -0.829[a] | -0.866[a] | -1.00[a] | -1.53[a] | -1.78[a] | -3.48[a] |
| **BC** | 7.67[b] | 7.91[b] | 7.97[b] | 14.7[b] | 16.3[b] | 27.5[b] |
| **OC** | -0.829[b] | -0.866[b] | -1.00[b] | -1.53[b] | -1.78[b] | -3.48[b] |
| **NMVOC** | -0.0737[c] | 0.142[c] | 0.146[c] | -0.0169[c] | 0.151[c] | 0.174[c] |
| **$CH_4$** | 1[a,c] | 1[c] | 1[a,c] | 1[c] | 1[c] | 1[c] |
| **$NO_x$** | -0.253[b] | -0.264[b] | -0.305[b] | -0.123[b] | -0.212[b] | -0.225[b] |
| **$SO_2$** | -0.641[b] | -0.642[b] | -0.646[b] | -1.17[b] | -1.34[b] | -2.14[b] |
| **$NH_3$** | 0.553[a,e] | -0.283[d] | -0.507[a,e] | 1.88[a,e] | -0.568[d] | -0.918[a,e] |

| $CO_2$ equivalents | | | | | | |
|---|---|---|---|---|---|---|
| | $GWP_{20}$ | | | $GWP_{100}$ | | |
| | 5th perc. | Mid | 95th perc. | 5th perc. | Mid | 95th perc. |
| **PM-other** | -60.1[a] | -172[a] | -284[a] | -16.2[a] | -46.5[a] | -76.7[a] |
| **BC** | 230[b] | 1480[b] | 2730[b] | 62.1[b] | 400[b] | 737[b] |
| **OC** | -60.1[b] | -172[b] | -284[b] | -16.2[b] | -46.5[b] | -76.7[b] |
| **NMVOC** | 3.29[c] | 14.7[c] | 26.2[c] | 0.764[c] | 4.31[c] | 7.85[c] |
| **$CH_4$** | 58.8[c,d] | 84.0[c,d] | 109[c,d] | 21.4[c,d] | 28.0[c,d] | 7.85[c] |
| **$NO_x$** | -3.97[c] | -14.5[c] | -25.1[c] | -2.17[c] | -5.47[c1] | -8.78[c] |
| **$SO_2$** | 128[d] | -268[d] | -664[d] | 35.3[d] | -71.4[d] | -178[d] |
| **$NH_3$** | 40.3[d] | -43.6[d] | -128[d] | 11.3[d] | -11.6[d] | -34.5[d] |
| | **GTP20** | | | **GTP100** | | |
| | 5th perc. | Mid | 95th perc. | 5th perc. | Mid | 95th perc. |
| **PM-other** | -28.4[a] | -58.0[a] | -87.6[a] | -3.48[a] | -7.10[a] | -10.7[a] |
| **BC** | 217[b] | 530[b] | 843[b] | 27.5[b] | 65.3[b] | 103[b] |
| **OC** | -28.4[b] | -58.0[b] | -87.6[b] | -3.48[b] | -7.10[b] | -10.7[b] |
| **NMVOC** | -2.09[c] | 9.50[c] | 15.4[c] | -0.0169[c] | 0.602[c] | 1.22[c] |
| **$CH_4$** | 28.3[a,c] | 67.0[c] | 106[a,c] | 1.00[c] | 4.00[c] | 7.00[c] |
| **$NO_x$** | -8.65[b] | -17.7[b] | -26.7[b] | -0.123[b] | -0.847[b] | -1.57[b] |
| **e** | -18.3[b] | -43.0[b] | -67.7[b] | -2.14[b] | -5.36[b] | -8.20[b] |
| **$NH_3$** | 15.7[a,e] | -18.9[d] | -53.6[a,e] | 1.88[a,e] | -2.27[d] | -6.43[a,e] |

a: Own assumption that non-carbonaceous PM2.5 have RF identical to OC, b: Collins et al. (2013), c: Myhre et al. (2013), d: G. Myhre et al. (2013) supplementary material, e: D. T. Shindell et al. (2009)

### 2.2.3. Estimating marginal climate external costs of SLCF

To quantify the welfare effects of emissions of SLFCs one needs to calculate the marginal damage (external cost) of each pollutant that in the next step can be multiplied with tonnes or kilos of emissions for each of the Nordic countries (cf. the SLFC cost function above). We first present how marginal damage of climate change is valued (monetized), and then other marginal costs (e.g. diseases caused by air pollution).

#### Marginal social costs of greenhouse gas emissions

Since climate change is a global problem and the damage of emissions are (almost) independent of where the emissions of greenhouse gases occur, the standard approach in cost-benefit analysis is to value (monetize) the climate change-related damage of an extra tonne of GHG emitted by estimates of the social cost of GHGs that is the same across countries (Dong, Tol, and Wang 2024; Ricke et al. 2018). The social cost of GHGs (SC-GHG) is defined as the "*monetary value of the net harm to society from emitting a metric ton of that GHG into the atmosphere in a given year*" (US Environmental Protection Agency, 2023). The SC-GHG is sometimes broken down into social cost of carbon (SCC, i.e. $CO_2$-specific), methane (SCM) and nitrous oxide (SCN) (US Environmental Protection Agency, 2023). This is because the damage from one tonne emitted of each of these GHGs has very different damage costs, due to e.g. lifetime in the atmosphere and a different temporal profile. As noted by US Environmental Protection Agency (2023), "*In principle, SC-GHG is a comprehensive metric that includes the value of all future climate change impacts (both negative and positive), including changes in net agricultural productivity, human health effects, property damage from increased flood risk, changes in the frequency and severity of natural disasters, disruption of energy systems, risk of conflict, environmental migration, and the value of ecosystem services.*" In practice, however, it has not been possible to date to calculate all these effects with a reasonable degree of certainty, so estimates of SC-GHG is often seen as conservative (negative effects are likely higher than positive of the ones that have not been included) (US Environmental Protection Agency, 2023). The damages that are now considered explicitly or implicitly represented by US Environmental Protection Agency (2023) are mortality and morbidity effects from heat/cold and extreme weather events, labor supply effects, energy consumption and production, loss of coastal land, buildings and infrastructure and effects on food production. In other words, there is no risk of double counting with those damage costs conventionally estimated for air pollutants. Many (most) of these effects are valued using adjusted market prices. Mortality effects are valued using estimates of the value of statistical life (VSL) of the USA, extrapolated to other countries in the world using GDP/capita adjustment (e.g. lower values in lower income countries).[1]

Typically, SC-GHG is estimated using integrated assessment models, such as the well-known DICE (Nordhaus, 2017) and other models, sometimes combined with other methods, that integrate the climatic system with economic models.

Åström and Källmark (2023), that this report builds and extends upon, use estimates of SC-GHGs from the report by the US Interagency Working Group on Social Cost of Greenhouse Gases (2021). Since then, USEPA has built on that report and produced new SC-GHG estimates published in November 2023, that we use in the current report (US Environmental Protection Agency, 2023). The US Environmental Protection Agency (2023) presents annual estimates of SCC, SCM and SCN in USD 2020 from 2020 until 2080, with three alternative discount rates (2.5%, 2% and 1.5%). These rates are lower than in earlier guideline values, which corresponds well to newer research on discount rates (Rennert et al. 2022; Carleton et al., n.d.; P. H. Howard and Sterner, 2017).

We have extracted the relevant SCC-GHG (specifically SCC and SCM) numbers for each five-year period from 2020 to 2050, matching the years for our emission scenarios of the Nordic countries (USEPA 2013, Table A.5.1, Appendix 5, pages 154–155). USD 2020 amounts are converted to Euro 2020 using exchange rate of 0.876 $_{2020}$ per $\text{USD}_{2020}$ as in Åström and Källmark (2023).

Note that the SC-GHG estimates are not presented with confidence bounds to account for uncertainty. Instead, they represent so-called certainty equivalents based on incorporating risk aversion,[2] that can be used in cost-benefit analysis. These certainty-equivalents are based on an averaging of uncertainty (using e.g. Monte Carlo analysis) across the three damage modules.[3] Table 2 presents the resulting social cost of carbon (SCC) and social cost of methane (SCM) used in the calculations.

1. It has not been possible in this report to update VSL estimates for the Nordic context. There is, however, work ongoing by the OECD to update their recommendations for which VSL values could be used for assessing mortality effects of policies (OECD, forthcoming).
2. Certainty equivalent of a risky cost (benefit) is the sure cost (benefit) that the consumer (i.e. in this case: society) considers just as good. Note that in many standard CBAs the decision maker is assumed to be risk neutral, in which case the certainty equivalent is just equal to the expected value. However, in the calculated SC-GHG, risk aversion is incorporated (see e.g. discussion in USEPA (2023, pages 73–76).
3. USEPA (2023, p1): "The estimation process generates nine separate distributions of discounted marginal damages per metric ton – the product of using three damage modules and three near-term target discount rates – for each gas in each emissions year. These distributions have long right tails reflecting the extensive evidence in the scientific and economic literature that shows the potential for lower-probability but higher-impact outcomes from climate change, which would be particularly harmful to society. The uncertainty grows over the modeled time horizon. Therefore, under cases with a lower near-term target discount rate – that give relatively more weight to impacts in the future – the distribution of results is wider. To produce a range of estimates that reflects the uncertainty in the estimation exercise while also providing a manageable number of estimates for policy analysis, this report combines the multiple lines of evidence on damage modules by averaging the results across the three damage module specifications."

**Table 2:** Social cost of methane (SCM) and carbon (SCC) in $€_{2020}$/tonne $CH_4$ and $€_{2020}$/tonne $CO_2$

| Discount rate | Comparator | Scenario year | Damage cost (Euro per metric tonne emission) |
|---|---|---|---|
| 2.5% | SCC | 2020 | 105 |
| 2.5% | SCC | 2030 | 123 |
| 2.5% | SCC | 2040 | 149 |
| 2.5% | SCC | 2050 | 175 |
| 2.0% | SCC | 2020 | 166 |
| 2.0% | SCC | 2030 | 201 |
| 2.0% | SCC | 2040 | 237 |
| 2.0% | SCC | 2050 | 272 |
| 1.5% | SCC | 2020 | 298 |
| 1.5% | SCC | 2030 | 333 |
| 1.5% | SCC | 2040 | 377 |
| 1.5% | SCC | 2050 | 420 |
| 2.5% | SCM | 2020 | 1139 |
| 2.5% | SCM | 2030 | 1664 |
| 2.5% | SCM | 2040 | 2365 |
| 2.5% | SCM | 2050 | 3066 |
| 2.0% | SCM | 2020 | 1402 |
| 2.0% | SCM | 2030 | 2102 |
| 2.0% | SCM | 2040 | 2891 |
| 2.0% | SCM | 2050 | 3679 |
| 1.5% | SCM | 2020 | 2015 |
| 1.5% | SCM | 2030 | 2803 |
| 1.5% | SCM | 2040 | 3679 |
| 1.5% | SCM | 2050 | 4643 |

### Adjusting for differences in atmospheric lifetime of pollutants

Although SCM is a more suitable metric than SCC, methane has a longer lifetime in the atmosphere and a different temporal profile (how long after an emission pulse that the temperature response occurs) than the other SLCFs. Since future values are discounted, it is reasonable to adjust the SCC values with respect to difference in temporal profiles. To do this we use the results from EPA (2023) and information from Figure 6.15 in Szopa et al. (2021) and the following assumptions:

- An emission pulse of an SLCF has no significant surface air temperature response after 400 years,
- The net-present values of SCM given by IWG are based on similar surface air temperature response temporal profiles as reported for gases with a 10-year lifetime as in figure 6.15,
- Mitigating and exacerbating SLCFs with the same lifetime have the same global mean surface air temperature response in absolute terms.

The corresponding $CH_4$-normalised climate damage costs per tonne SLCF emissions are seen in Figure 4.

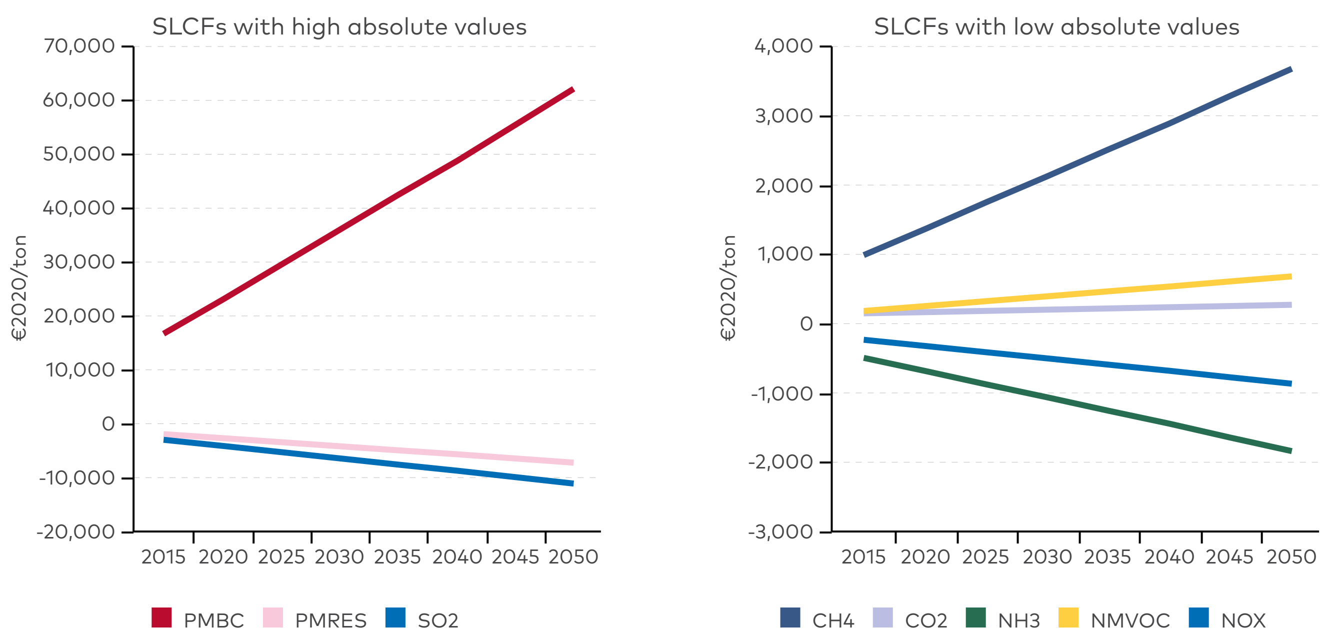



**Figure 4:** Social climate damage cost of one tonne of SLCF emissions emitted from the period 2015 to 2050 for the mid estimate of $GWP_{100}$ and with an initial discount rate of 2%.

### 2.2.4. Estimating other marginal SLCF externalities

Although this report is focused on assessing climate damage costs of SLCF emissions, the established damage costs of SLCF emissions are associated with health and environmental effects. To present a more complete picture of the total climate, health, and environmental damage cost of SLCF emissions, we complement the SLCF climate damage cost calculations with published data on other health and environmental damage costs of SLCF emissions. The latest and most authoritative estimate of these damage costs are published by the European Environment Agency (2024b). To enhance policy relevance, we utilise the damage costs as assessed when valuing effects on mortality with the value of a life year lost (VOLY) metric, just as was done by the European Commission in their presentation of a proposal for a revised NEC Directive (European Commission 2013). The alternative would be to use the metric value of statistical life (VSL) – as done when calculating the social cost of GHGs above. This is conceptually equally valid and allows for equal value being assigned to median persons as to elderly and weak persons. As a rule of thumb, the use of VSL instead of VOLY would render health and environmental damage costs to be a bit more than twice as high as when using VOLY (European Environment Agency, 2024b).

**Table 3:** Health and environmental damage costs of Nordic SLCF emissions from industrial sources in 2020

| Country | Pollutant | 2020 | Unit |
|---|---|---|---|
| Norway | $NO_x$ | 8,938 | Euro/tonne $NO_x$ (VOLY) |
| Norway | PM2.5 | 27,050 | Euro/tonne PM2.5 (VOLY) |
| Norway | $SO_2$ | 10,850 | Euro/tonne $SO_2$ (VOLY) |
| Norway | NMVOC | 824 | Euro/tonne NMVOC (VOLY) |
| Norway | $NH_3$ | 6,402 | Euro/tonne $NH_3$ (VOLY) |
| Sweden | NOx | 7,975 | Euro/tonne NOx (VOLY) |
| Sweden | PM2.5 | 36,366 | Euro/tonne PM2.5 (VOLY) |
| Sweden | $SO_2$ | 11,546 | Euro/tonne $SO_2$ (VOLY) |

| | | | |
|---|---|---|---|
| Sweden | NMVOC | 931 | Euro/tonne NMVOC (VOLY) |
| Sweden | $NH_3$ | 10,499 | Euro/tonne $NH_3$ (VOLY) |
| Finland | $NO_x$ | 4,936 | Euro/tonne $NO_x$ (VOLY) |
| Finland | PM2.5 | 45,471 | Euro/tonne PM2.5 (VOLY) |
| Finland | $SO_2$ | 8,626 | Euro/tonne $SO_2$ (VOLY) |
| Finland | NMVOC | 560 | Euro/tonne NMVOC (VOLY) |
| Finland | $NH_3$ | 6,014 | Euro/tonne $NH_3$ (VOLY) |
| Iceland | $NO_x$ | 977 | Euro/tonne $NO_x$ (VOLY) |
| Iceland | PM2.5 | 19,547 | Euro/tonne PM2.5 (VOLY) |
| Iceland | $SO_2$ | 3,944 | Euro/tonne $SO_2$ (VOLY) |
| Iceland | NMVOC | 665 | Euro/tonne NMVOC (VOLY) |
| Iceland | $NH_3$ | -1,306 | Euro/tonne $NH_3$ (VOLY) |
| Denmark | $NO_x$ | 11,132 | Euro/tonne $NO_x$ (VOLY) |
| Denmark | PM2.5 | 59,066 | Euro/tonne PM2.5 (VOLY) |
| Denmark | $SO_2$ | 21,960 | Euro/tonne $SO_2$ (VOLY) |
| Denmark | NMVOC | 1,278 | Euro/tonne NMVOC (VOLY) |
| Denmark | $NH_3$ | 15,168 | Euro/tonne $NH_3$ (VOLY) |

Since a large part of the health and environmental damage costs are estimated through the use of willingness-to-pay studies, it is important to adjust for increases in income for future years. In our work, we increase the health and environmental damage costs over time for the parts of the damage costs that is associated with willingness-to-pay (70% in 2020) in accordance with recommendations in (Atkinson et al. 2018). The increase corresponds to an assumed 2% growth in real income per year from the year 2020 until 2050, and a WTP-elasticity of 1.

## 2.3. Uncertainties

We discuss the uncertainties related to the key hypotheses (called Key Claims) that typically motivate emission reduction measures, and serve as input to the most important knowledge gaps related to the results presented in this report. The main purpose of the uncertainty discussion is to provide input to potential needs for more knowledge on the input parameters used in the rest of the report. As a framework for the uncertainty analysis, we use as inspiration the guidance for lead authors in past IPCC Working Group 3 assessment reports (Mastrandrea et al. 2011). In the framework, the following dimensions are used to assess the validity of a finding: the type, amount, quality and consistency of evidence and the degree of agreement (Figure 5). When applicable in the IPCC work, this is then extended to express *confidence* (from "very low" to "very high") and further to assign likelihood (from "exceptionally unlikely" to "virtually certain") for quantifying the probability of an event. We focus the uncertainty discussion on air pollution and associated effects, since much of the climate change evidence is summarised in IPCC assessment reports etc.

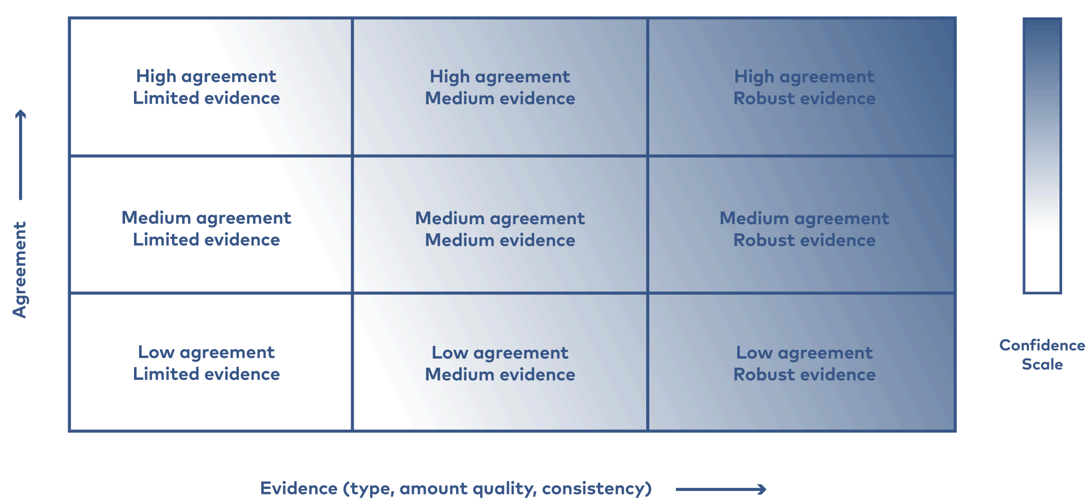



**Figure 5:** A depiction of evidence and agreement statements and their relationship to confidence. Confidence increases towards the top-right corner as suggested by the increasing strength of shading. Copied from Mastrandrea et al. (2011).

Through a joint project group discussion, we identified four key claims of relevance for air pollution aspects important for this report and its results. These key claims were then discussed regarding their robustness and the agreement of the scientific evidence supporting the claims.

# 3. Results

The results of the analysis are in this chapter given for the mid-estimate values of the components of the analysis. The results from high- and low estimates are presented in Appendix II. We first present the climate damage costs over time of Nordic SLCF emissions. We then present how these climate damage costs compare to more established health and environmental costs of the same emissions. After this we present a comparison of how the total climate, health, and environmental damage costs in the CIAM & TFIAM (2024) BSL scenario compared to the $CO_2$ climate damage costs as presented in the nationally projected With Existing Measures (WEM) scenarios. Finally, we show results from the calculations of the monetary value of the climate, health and environmental benefits in the Nordic countries of reducing emissions from a Baseline (BSL) emission level into an Maximum Technical Feasible Reduction (MTFR) emission level, i.e. when all known emission control technologies are fully implemented.

## 3.1. Climate damage costs of Nordic SLCFs

As can be guessed from the climate damage costs per tonne pollutant presented above, the total climate damage costs of Nordic SLCFs will increase for future years, despite projected emission reductions in the BSL scenario (Figure 6). Of course, climate damage costs of SLCF emissions with a negative warming impact will be reduced over time. In Figure 6 we show for each Nordic country the climate damage cost associated with the national total emissions for each SLCF considered in this report. Some curves are below zero, which indicates that they have a 'cooling' climate impact. The dotted lines show the net total effect when adding the positive and negative trends.

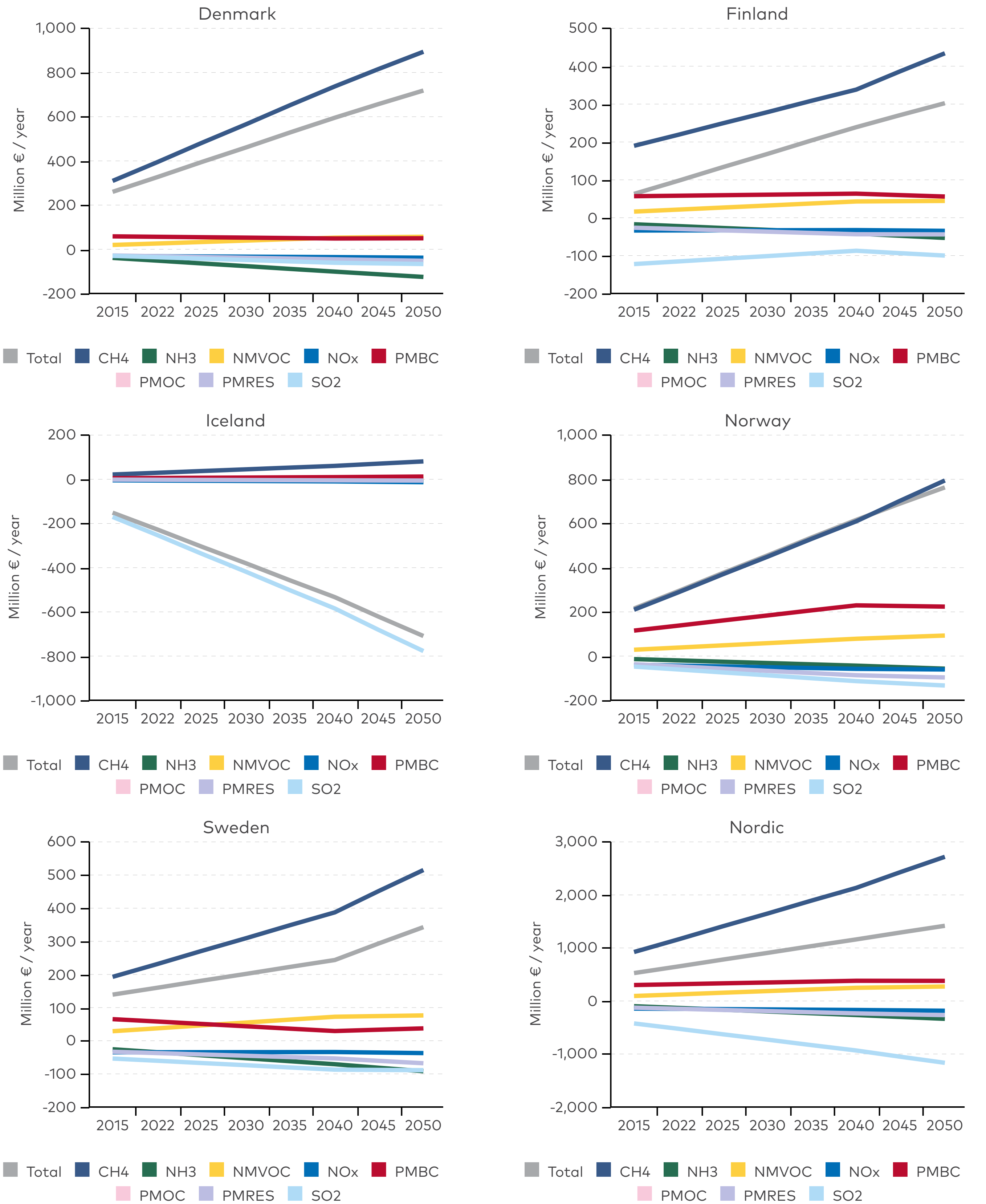



**Figure 6** SLCF climate damage costs from BSL emissions for the Nordic countries. Split per SLCP and summarized as Total. All values in million $€_{2020}$ per year for the mid values of damage costs and climate impact and with a 2% start year discount rate.

There is a relatively large variation between the Nordic countries. For Iceland, the climate damage costs of BSL emissions are overall negative mostly due to large $SO_2$ emissions, but for both Denmark and Finland, the climate damage costs will correspond to some 800 million $€_{2020}$ per year in 2050.

## 3.2. Total damage costs of Nordic SLCFs

In addition to the climate damage costs of SLCF emissions, there are the well-established health and environmental damage costs. As can be expected, in the BSL scenario, the health and environmental damage costs are larger than the climate damage costs (Figure 7). The figure shows the total climate, health and environmental damage costs associated with the BSL emission scenario for SCLF emissions. Note that the climate damage costs have been aggregated together into one block (corresponds to the dotted curve in Figure 6). Note that the climate damage costs are increasing over time at a rate faster than the emission reductions. This is because of the increasing damages of each additional tonne $CO_2$ emitted in a warmer world and because of richer populations in the future.

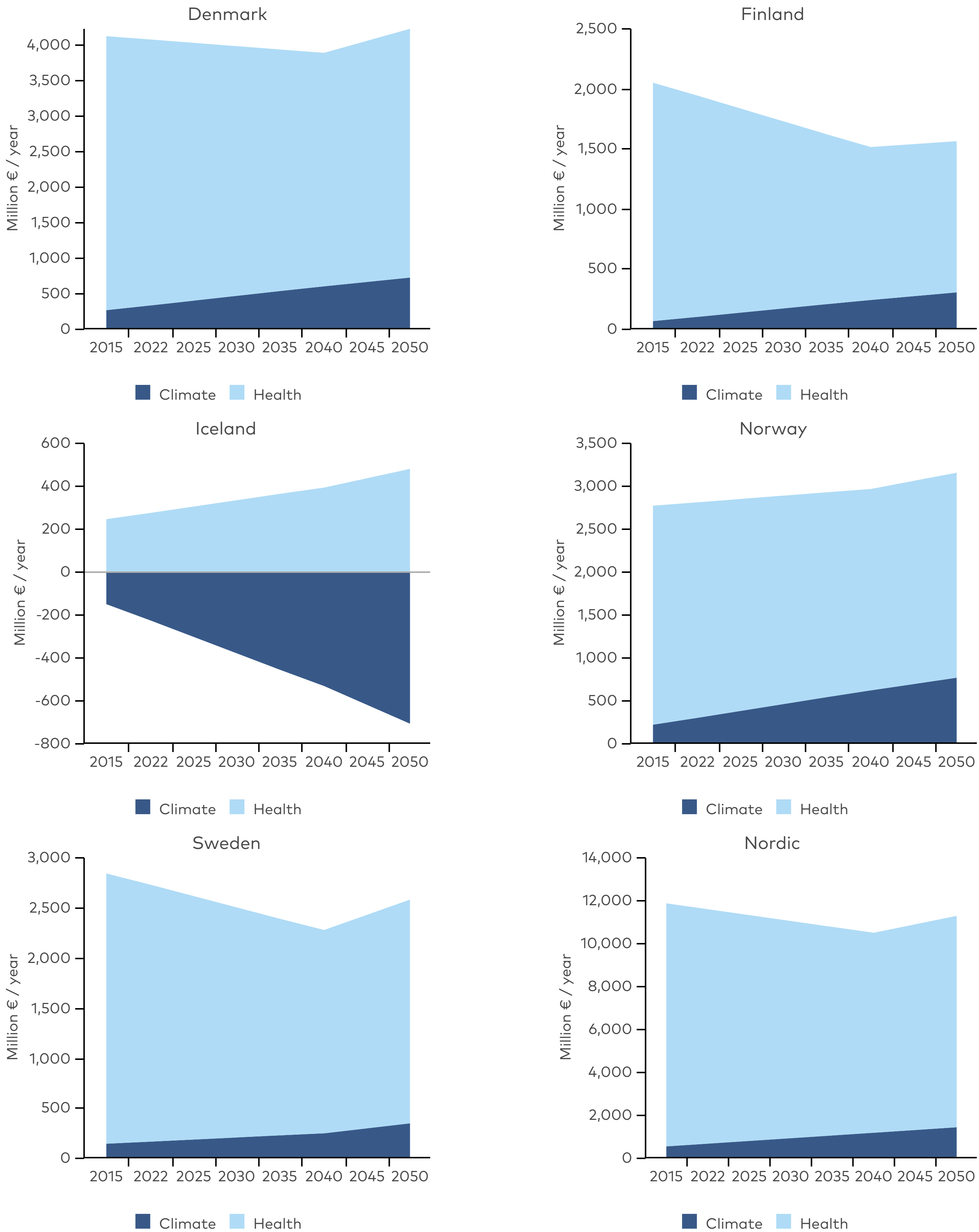



**Figure 7:** SLCF climate damage costs and health damage costs from BSL emissions for the Nordic countries 2015–2050 as in the BSL-scenario. Split per effects on climate change and on human health and the environment. All values in million $€_{2020}$ per year for the mid values of damage costs and climate impact and with a 2% start year discount rate. Health values are based on the economic value of a life year lost (VOLY).

For the Nordic countries except for Iceland, by 2050, the climate damage costs of SLCF emissions will constitute around 15-20% of the total SLCF damage costs in the BSL scenario. Interestingly enough, the total damage costs from SLCF emissions remains relatively stable for the Nordic countries, with Finland as an exemption.

## 3.3. Total damage costs of SLCFs in the BSL scenario and Nordic $CO_2$ in the WEM scenario

When comparing the scenario-specific Nordic climate, health, and environmental damage costs of SLCF emissions in the BSL scenario, with the $CO_2$ damage costs in the WEM scenario, the relative importance of SLCF damage costs will increase over time. This change in relative importance is much due to the assumed successful $CO_2$ emission reduction in the WEM scenario (Figure 8). The figure sums together all SLCF damage costs presented in Figure 7, and adds also the $CO_2$ damage costs based on nationally reported WEM emission scenarios.

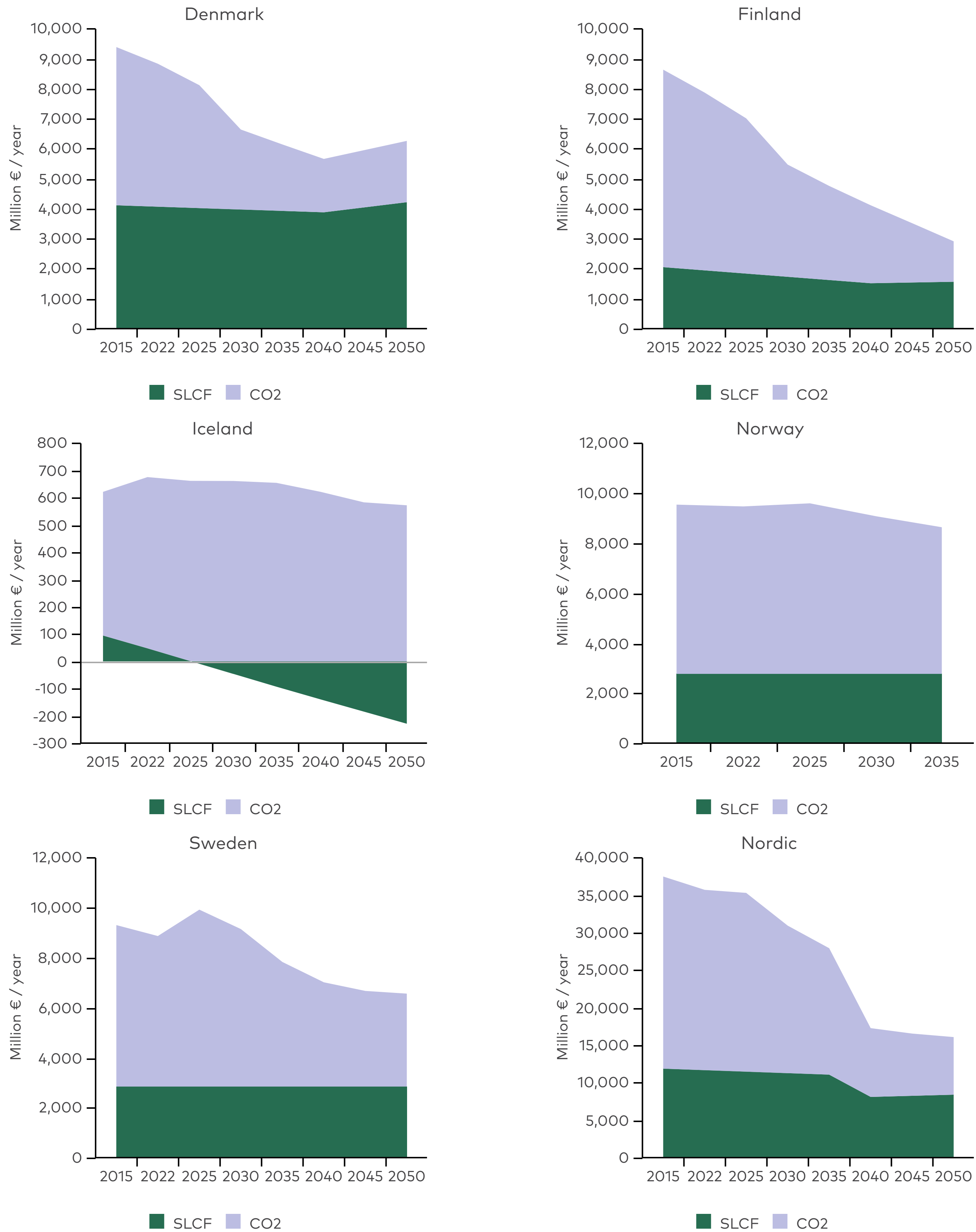



**Figure 8:** Socio-economic damage costs from SLCF emissions as in the BSL scenario and $CO_2$ emissions as in the nationally reported WEM scenario. All values in million $€_{2020}$ per year for the mid values of damage costs and climate impact and with a 2% start year discount rate. Health values are based on the economic value of a life year lost (VOLY). The Norwegian and Total Nordic values are for the time period 2015–2035 due to the limit to the Norwegian WEM scenario.

As can be seen, most countries expect $CO_2$ emissions that are so large that the total climate damage costs are expected to decrease in the future. This decrease leads to the interesting result that damage costs of SLCFs will become as high as for $CO_2$ in the future. Again, the major exception to the rule is Iceland. For Iceland, the relatively high $SO_2$ emissions change the relationship between SLCF and $CO_2$ damage costs compared to the other Nordic countries. In addition, as can be expected, Denmark with high relatively high population density and proximity to continental Europe will have relatively high SLCF damage costs. On average for the Nordic countries, the SLCF damage costs are more than 40% of the total SLCF and $CO_2$ damage costs in 2050.

## 3.4. Marginal effect of MTFR SLCF emission reductions

Of additional policy interest is the monetary value of emission reductions associated with the Nordic countries reducing emissions from a BSL scenario emission level down to an MTFR scenario emission level. Figure 9 presents the difference in emissions between the BSL and MTFR scenario and the corresponding changes in damage costs, split per climate damage and damage to health and the environment. As can be seen in the country-specific charts in Figure 9, the majority of the monetary benefits of emission reductions are due to health and environmental benefits. Again, the deviation is Iceland. Another interesting observation is that the Swedish SLCF emission reductions when going from BSL to MTFR is relatively climate neutral, which is basically what was proposed by Hansson et al. (2023). The results per sector are varying between countries. Agricultural emission reductions provide highest benefits for Denmark and Sweden, whilst emission reductions from stationary sources provides highest benefits for Finland and Norway. Results per sector are presented in Appendix III.

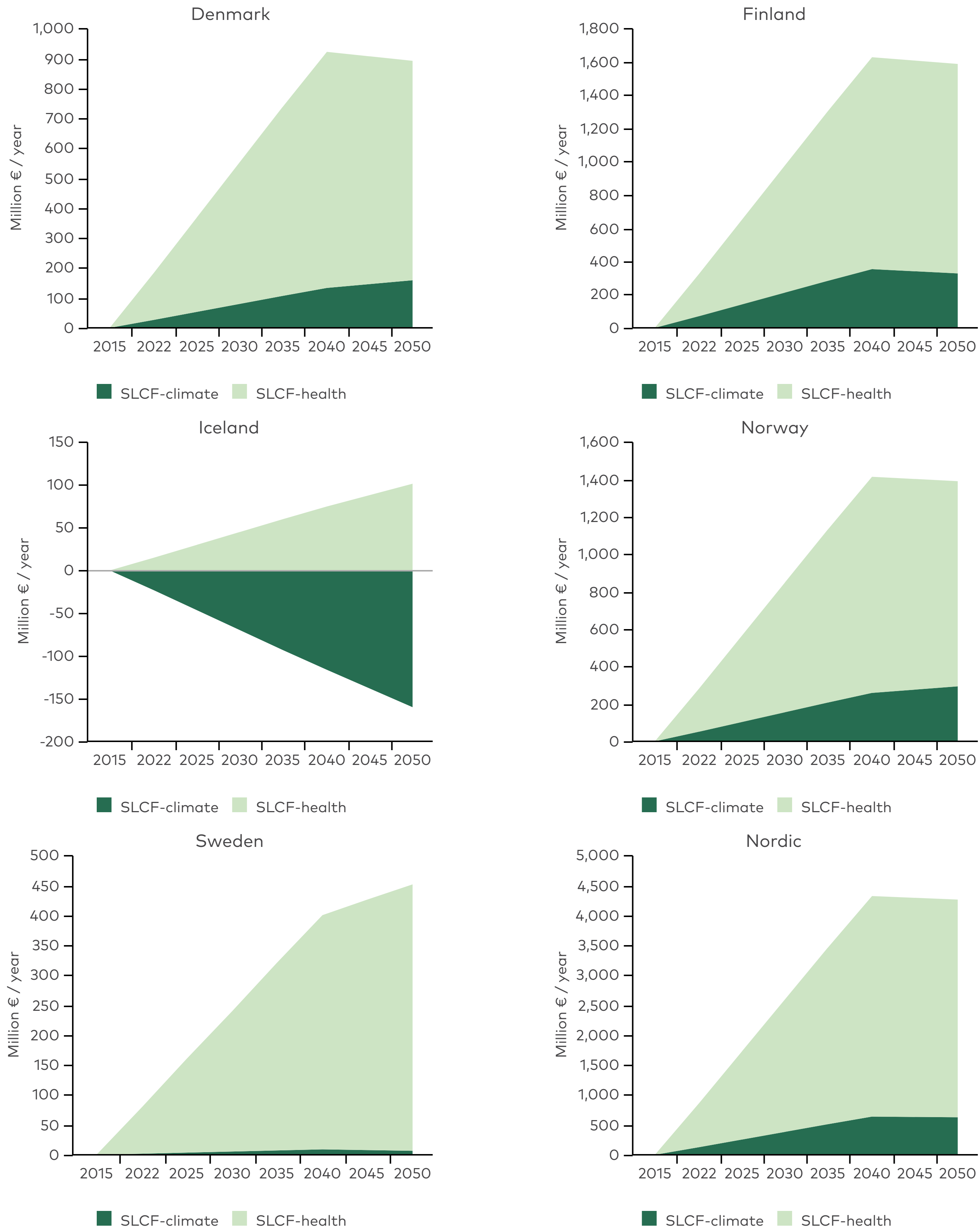



**Figure 9** Monetary benefit per Nordic country from the emission reductions in the MTFR scenario compared to the BSL scenario. Split per effects on climate change and on human health and the environment. All values in million $€_{2020}$ per year for the mid values of damage costs and climate impact and with a 2% start year discount rate. Health values are based on the economic value of a life year lost (VOLY).

# 4. Uncertainty discussion

In this chapter we discuss the underlying uncertainties in the hypotheses that motivate emission reduction measures and physical and monetary impacts of these. We have discussed the validity of four key claims using the approach described in Chapter 2.3.

## 1. Human activity increases air pollution concentrations in Nordic countries

Claim #1 can be assessed using observational and modelling studies, which provides a good possibility for solid validity. Measurements show that air quality is worse in close proximity to human activities such as heavy traffic or industries. Chemical/optical analysis of pollutants gathered from ambient air indicate their origin as anthropogenic rather than natural (examples of natural would include dust, sea salt etc.). Observational and modelling studies agree that both long-range transported and locally produced emissions from human activities contribute to concentrations in Nordic countries.

## 2. Increased air pollution concentrations cause health problems in Nordic countries

Increased concentrations of air pollution, especially fine particulate matter, $NO_X$ and ozone, have been connected to various health hazards in numerous population and toxicological studies. In the scientific literature, there is agreement regarding the claim that increased concentrations cause health problems in Nordic countries. However, there is higher uncertainty or at least variability regarding the effects on human health when concentration levels in ambient air are relatively low.

## 3. Emissions of short-lived climate forcers from Nordic countries affect climate change

The short-lived climate forcers considered in this report are estimated to impact the climate by altering the atmosphere's radiative forcing. This impact can be either warming (most notably for BC) or cooling (most notably for $SO_2$ and OC). The impacts can be measured in labs (Bond et al. 2013). Larger scale assessments are modelled, and there are no "source apportionment" methods for determining what has caused the rise in measured temperatures in ambient air.

In general, the literature suggests variance on the estimated climate impact of air pollutants, depending on the model being used. The studies also always include uncertainties due to limitations of the models and understanding of the physical processes involved. The issue is complex, because the impact of a given emission is estimated to vary greatly depending on the location and season, which affect the albedo and meteorology in the area of impact (Borgar Aamaas et al. 2016; Sand et al. 2020; Räisänen et al. 2022). Another problem in determining impacts of local emissions is a low signal-to-noise ratio in model runs. This means that for a small amount of emissions, such as those coming from Europe for example, a strong upward scaling is typically needed to see impacts in the models as in Sand et al. (2020).

## 4. Increased/decreased air pollution concentrations cause economic losses/gains in Nordic countries

It is clear from numerous health economic assessment studies that the health problems lead to economic losses of some kind. Episodes of poor air quality have been observed to increase mortality and hospital admissions. However, a purely utilitarian and time ignorant economic assessment (abandoned in environmental impact assessments) can show that health problems such as premature death can give economic benefits through reduced health care costs and payment of pensions (Heinzerling and Ackerman 2002). This is one of the reasons why willingness-to-pay studies are used to estimate the economic value of health effects. There is however no scientific consensus on which monetary metric or value to use in analysis, so there is a variance in the health cost estimates. In addition to health hazards, air pollution has been shown to negatively impact materials, crop production and the natural environment. However, these costs are typically estimated to be notably lower than health damage costs. Finally, the literature does not suggest any non-linearities, so improved air quality will provide benefits. Whether the benefits are larger than the costs of course will depend on the costs of the measures used to improve air quality. The overall assessment from the discussion on air pollution is found in Table 4.

**Table 4:** Key Claims on air pollution. Validity assessment assessed considering our knowledge on type, amount, quality and consistency of scientific evidence.

| Claim | | Validity |
|---|---|---|
| 1 | Human activity increases air pollution concentrations in Nordic countries | Robust evidence, High agreement |
| 2 | Increased air pollution concentrations cause health problems in Nordic countries | Medium to robust evidence, High agreement |
| 3 | Emissions of short-lived climate forcers from Nordic countries affect climate change (either warming or cooling impact) | Limited evidence, Medium agreement |
| 4 | Increased air pollution concentrations cause economic losses in Nordic countries | Medium to robust evidence, High agreement |

As is suggested by Table 4, our understanding is that the main uncertainty in our results relates to the climate change impact of Nordic emissions. This area of knowledge could benefit from more lab analysis, monitoring, and modelling.

# 5. Discussion, conclusions & recommendations

In this report we present for the Nordic region, country- and scenario-specific socio-economic damage costs of the air pollutants classified as short-lived climate forcers, including methane. For the first time, the damage costs consider the emissions' effects on climate change, health, and the environment. Further, we compare these costs with climate damage costs of Nordic $CO_2$ emissions for the same scenario period. Finally, we calculate the socio-economic benefits of reducing SLCF emissions from what the UNECE Air Convention currently considers to be a likely emission pathway given current air pollution legislation (BSL), into an emission pathway that corresponds to a maximal introduction of technically feasible emission reduction measures (MTFR).

The results of the mid-value analysis show significant variation between the Nordic countries, where Iceland is an outlier. This is understandable since Iceland is an island remote from other populations and with relatively large $SO_2$ emissions. All in all, our results show that SLCF climate damage costs constitute a significant and increasing share of total SLCF damage costs for the Nordic countries (contingent on increasing global temperatures in the future). The damage costs due to health effects and effects on the environment still dominate the total damage costs, but climate damage costs provide significant additions to the total.

In addition, based on similar but not identical, $CO_2$ scenarios from the Nordic countries (WEM) and SLCF scenarios from CIAM & TFIAM (BSL), the calculations suggest that damage costs of SLCF emissions and $CO_2$ emissions will be of almost equal magnitude in the future. Comparing the BSL with the WEM scenario for the year 2035 (the last all-Nordic WEM-scenario year), SLCF damage costs constitute ~40% of the total $CO_2$ and SLCF damage costs by 2035.

Furthermore, the comparison of damage costs between the CIAM & TFIAM BSL and MTFR scenario shows that all Nordic countries would have substantial benefits from SLCF emission reductions corresponding to the difference between BSL and MTFR. Again, there are differences between the countries. The Icelandic emission reductions would imply socio-economic losses due to the net effect of Icelandic emissions on climate change. The Danish, Finnish, and Norwegian emission reduction benefits will to 13%–20% be due to climate change effects.

## 5.1. Discussion

As per usual, the results of our analysis are subject to scientific uncertainty and scenario-dependency. As we suggest from the uncertainty discussion, the most important uncertainty relates to the Nordic-specific climate impact of SLCF emissions. The literature is well aligned in its suggestion that the position of emissions with respect to both latitude and longitude will affect climate impact. More dedicated studies on these types of questions would be beneficial to establish the robustness of our results.

The scenario-dependency will affect the results and corresponding conclusions. Due to incompleteness in the data across the Nordics, we did not use national scenarios, but instead used the latest and policy-relevant scenarios from CIAM & TFIAM. For the applicable years, we have controlled the BSL scenario against nationally reported emission scenarios (Appendix I). To our understanding, at least on a national level, the BSL and national scenarios are sufficiently similar for our results to be policy relevant.

In addition to the scientific uncertainty and the 'Knightian uncertainty' about the future (Knight 1921), there are also uncertainties related to the economic parts of the results. First, as is standard when discussing damage costs of air pollution: the fact that we base our main analysis on the normative choice of VOLY instead of VSL for air pollution-induced health effects, implies that the relative importance of climate damage costs is higher than if we would have compared with the VSL metric. As a reminder, we chose VOLY since this is the metric preferred by inter alia the EU in air quality policy processes, and since it was not possible for us in this project to update VSL values based on the available information in the report used for SCM (US Environmental Protection Agency, 2023).

Second, as noted in Chapter 2.2.3, the mortality cost component of SCC and SCM is based on an estimate of the value of statistical life (VSL) from USA. This estimate is then extrapolated to countries in the rest of the world by normalizing GDP/capita. An improvement in future updates of the estimates of the damage of Nordic emissions would be to use new global VSL estimates that will soon be made available by the OECD. The authors of this report are engaged in the development of this OECD report (OECD, forthcoming).

Third, we are using economic damage costs of climate change derived from climate-economic models. These models rarely estimate 'external costs' of climate change in a manner similar to standard environmental economic theory. Instead, they often provide a numerical estimate corresponding to an intertemporal equilibrium point between emission abatement/mitigation costs and emission abatement/mitigation benefits. So if the emission scenario being analysed with a certain SCC/SCM value does not correspond to the temperature increase that was implied when originally deriving the SCC/SCM value, the results will be somewhat biased up or down.

Fourth, the climate change damage costs we use do not correspond to the governmental guideline values for damage costs of $CO_2$. For example, the Swedish Road Administration suggests using a $CO_2$ damage cost corresponding to ~650 $€_{2020}$/tonne$CO_2$ (Swedish Road Administration, 2020). This value is more than twice as high as the SCC-values used in our analysis, even for 2050. In Norway, the Ministry of Finance, has a set of carbon price paths that are recommended for use in cost-benefit analysis. However, to our understanding, the scientific underpinning of the US EPA 2023 values is more solid than the values suggested by the Swedish Road Administration or the Norwegian Ministry of Finance. The Norwegian carbon values, for example, are based on costs of climate measures to reach climate targets and not assessment of damage costs. The carbon cost values we use may still, however, be incomplete in that they are not able to capture all the expected damages fully (as noted in Chapter 2, in US Environmental Protection Agency (2023) or for other reasons (P. Howard, 2014)).

If our results are used as policy advice, the following considerations need to be remembered.

1. The climate change effect of Nordic SLCF emissions is still in need of more verification with respect to magnitude of the impact,
2. The SLCF scenarios used are not perfectly aligned with current national emission projections for SLCF emissions,
3. The underlying values used to calculate climate, health, and environmental damage costs are similar but not fully aligned with the costs proposed by national agencies.

In addition, climate scientists recognize that the choice of climate metric for our type of analysis largely depends on the purpose of the analysis (Tanaka, Peters, and Fuglestvedt 2014; B. Aamaas, Peters, and Fuglestvedt, 2013). Which purpose that matches which metric or time horizon, has not been suggested to our knowledge.

Since $GWP_{100}$ is the metric most commonly used in climate policy instruments (such as in the UNFCCC Nationally Determined Contributions and the EU Emission Trading System), we have chosen this metric and time horizon. Most other metrics and time horizons that we know of as common in the literature, would have rendered a higher climate damage cost of SLCF emissions than we have presented in this report.

## 5.2. Conclusions

Based on our data, method, results, uncertainties, and discussion, the following conclusions can be suggested:

1. The SLCF emission damage costs currently utilised for air pollution decision support in the Nordic region are under-estimating the social damage costs of these pollutants,
2. Including SLCF climate damage costs would increase the socio-economic value of reducing emission. In our calculations that use conservative climate metrics, the increase would lie around 10–20%,
3. If the Nordic countries would be as effective at reducing $CO_2$ emissions as is projected nationally, Nordic SLCF emissions might become a problem as important, when assessed in monetary terms, as $CO_2$ emissions sometime around 2050,
4. More research, on especially the climate impact of Nordic SLCF emissions, would improve the robustness of the analysis of economic damage costs.

## 5.3. Recommendations

For the Nordic Council of Ministers group on air and climate we have the following recommendations:

a. Suggest to national governments that they complement their guideline values for socio-economic damage costs of SLCF emissions with estimates of their climate damage costs,
b. Improve the scientific underpinning of the climate impact of Nordic SLCF emissions,
c. Complement the global average social cost of carbon and social cost of methane estimates with values better adjusted for intra-Nordic circumstances and settings (inter alia by correcting so that VSL and VOLY values used for valuation of air pollution is the same as the ones used to value $CO_2$ emissions),
d. Consider promoting an increase in national/Nordic emission abatement ambition levels since the socio-economic benefits likely are larger than previously known, especially for the SLCFs that are 'warming'.

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# Appendix I: Comparison of $CH_4$, $NH_3$, NMVOC, and $NO_x$ emissions in the latest national projections (Inv.) and in the (CIAM and TFIAM 2024) BSL scenario

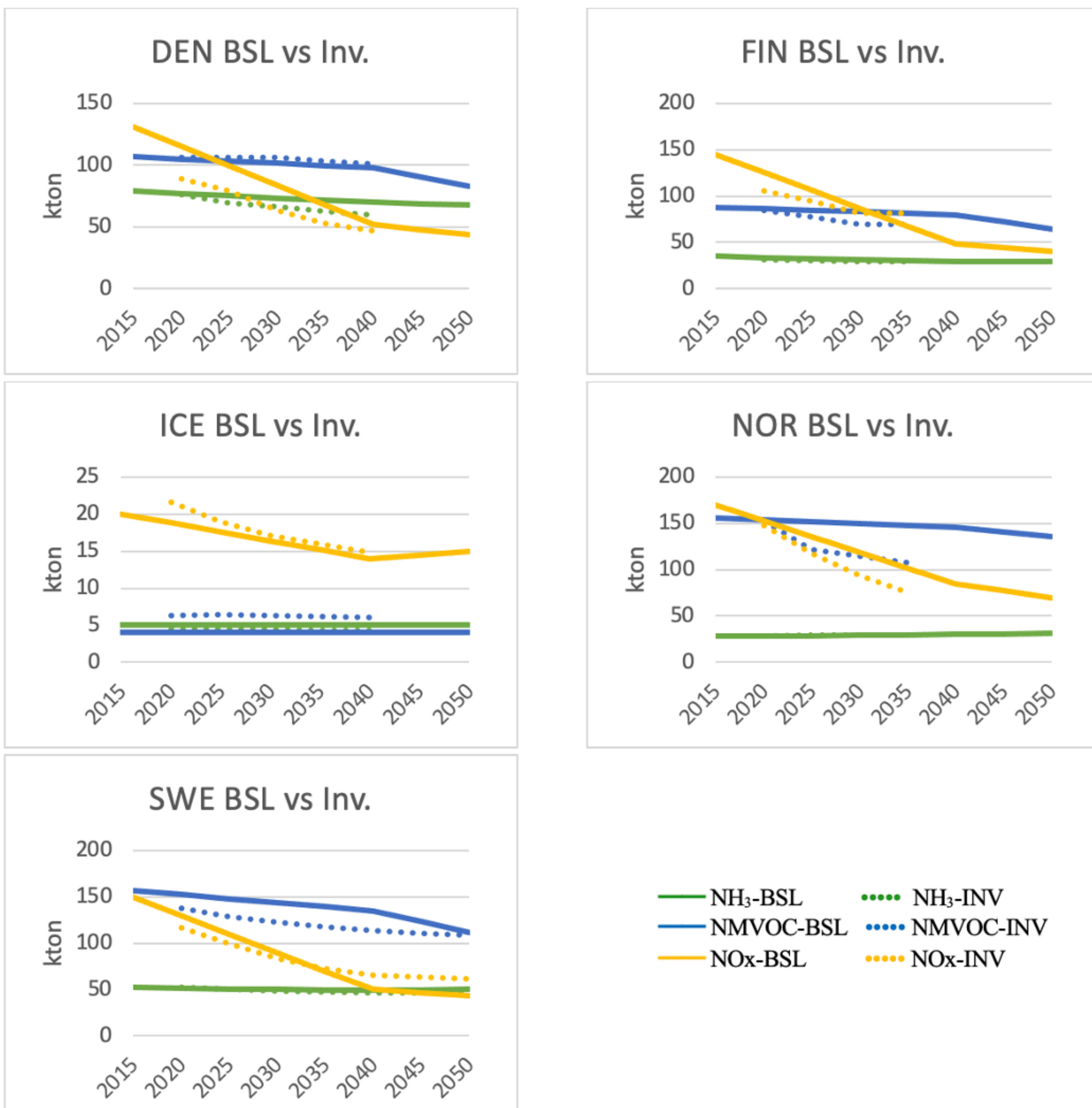


**Figure A 1** Comparison of $CH_4$, $NH_3$, NMVOC, and $NO_x$ emissions in the latest national projections and in the (CIAM and TFIAM 2024) BSL scenario.

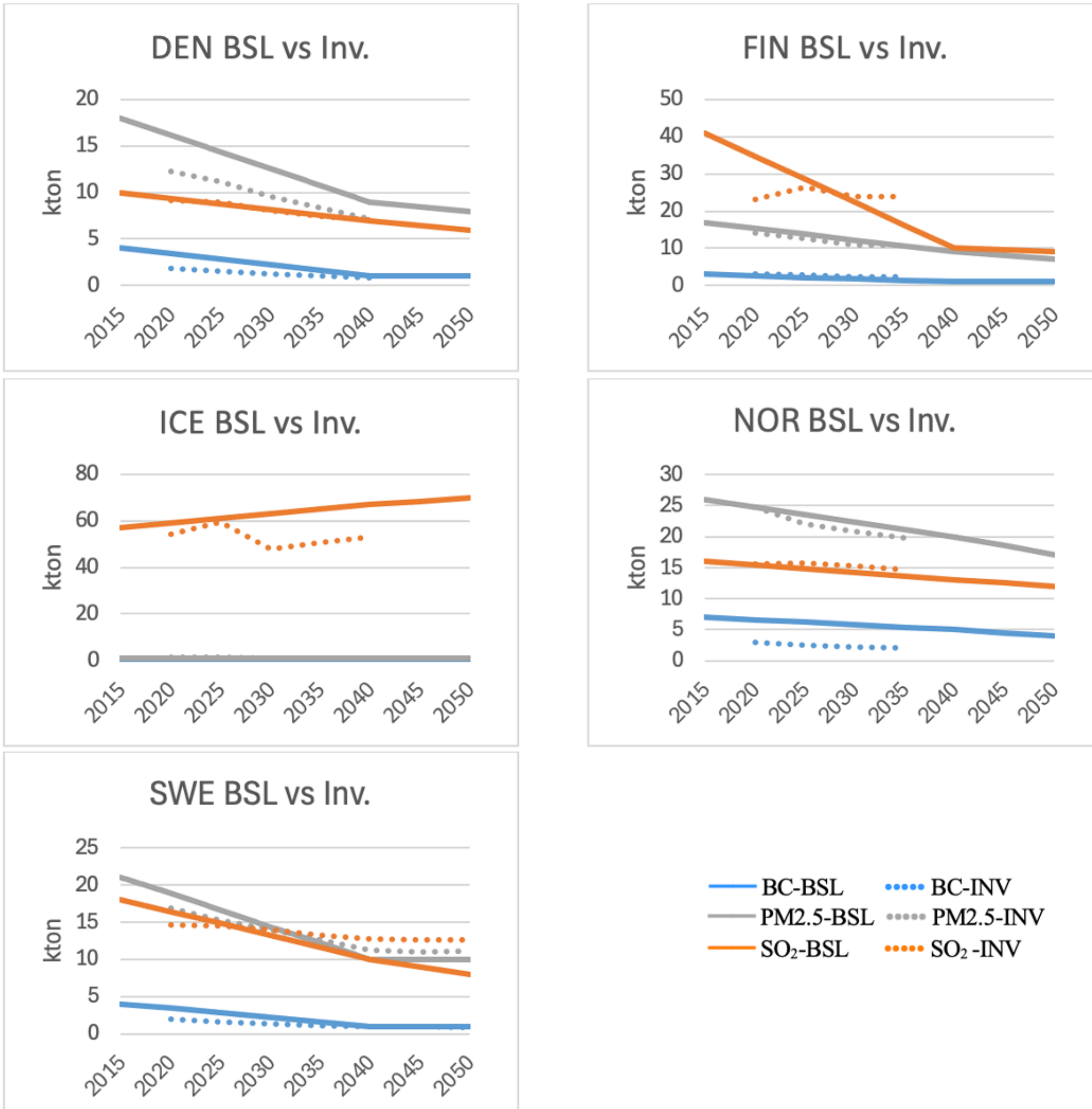


**Figure A 2** Comparison of BC, PM2.5 and $SO_2$ emissions in the latest national projections and in the (CIAM and TFIAM 2024) BSL scenario.

# Appendix II: Sensitivity analyses


**Figure A 3:** Climate damage costs of SLCF emissions if assuming low climate effect, low social cost of methane, and high discount rate.

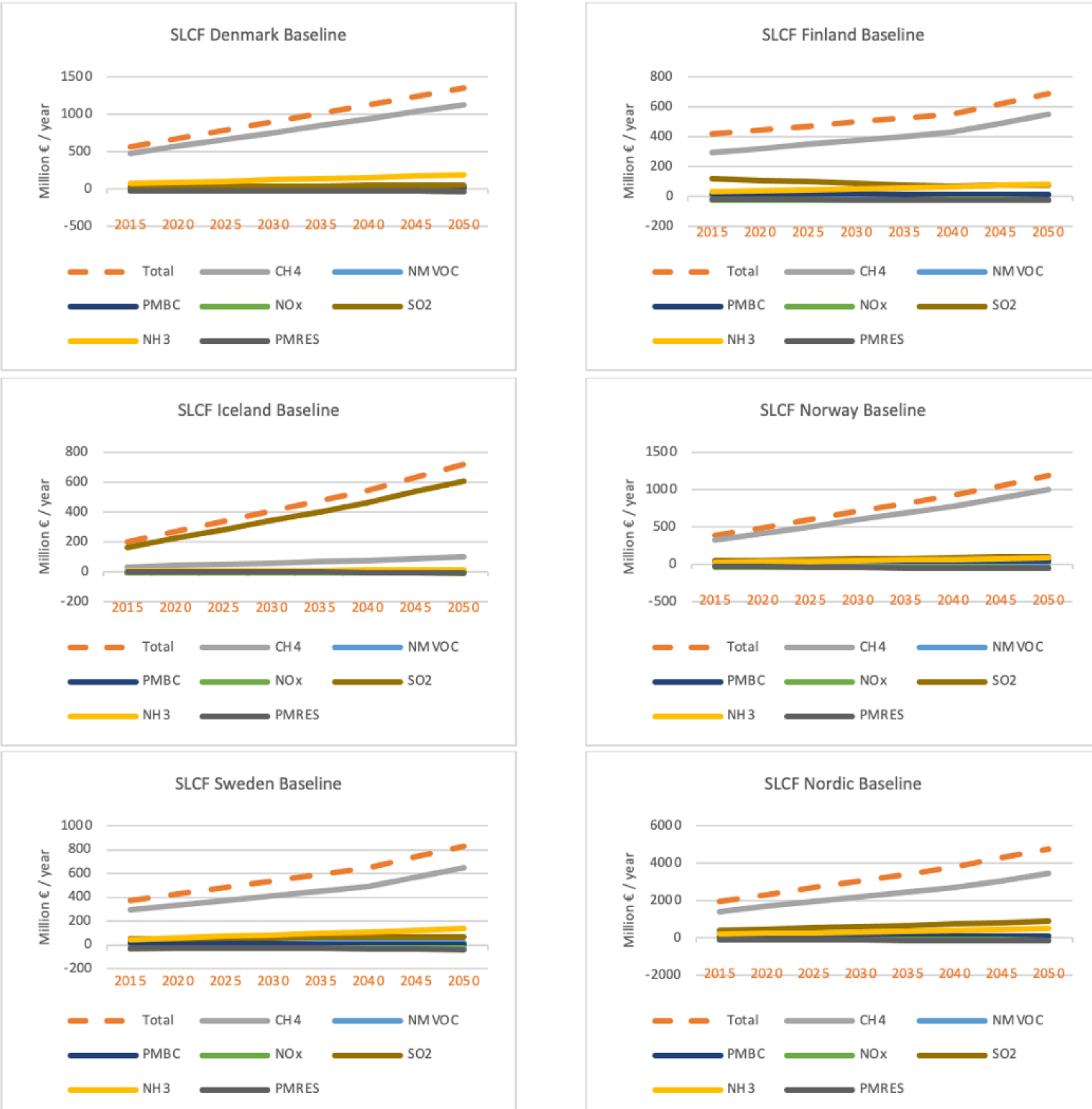


**Figure A 4** Climate damage costs of SLCF emissions if assuming high climate effect and low discount rate.

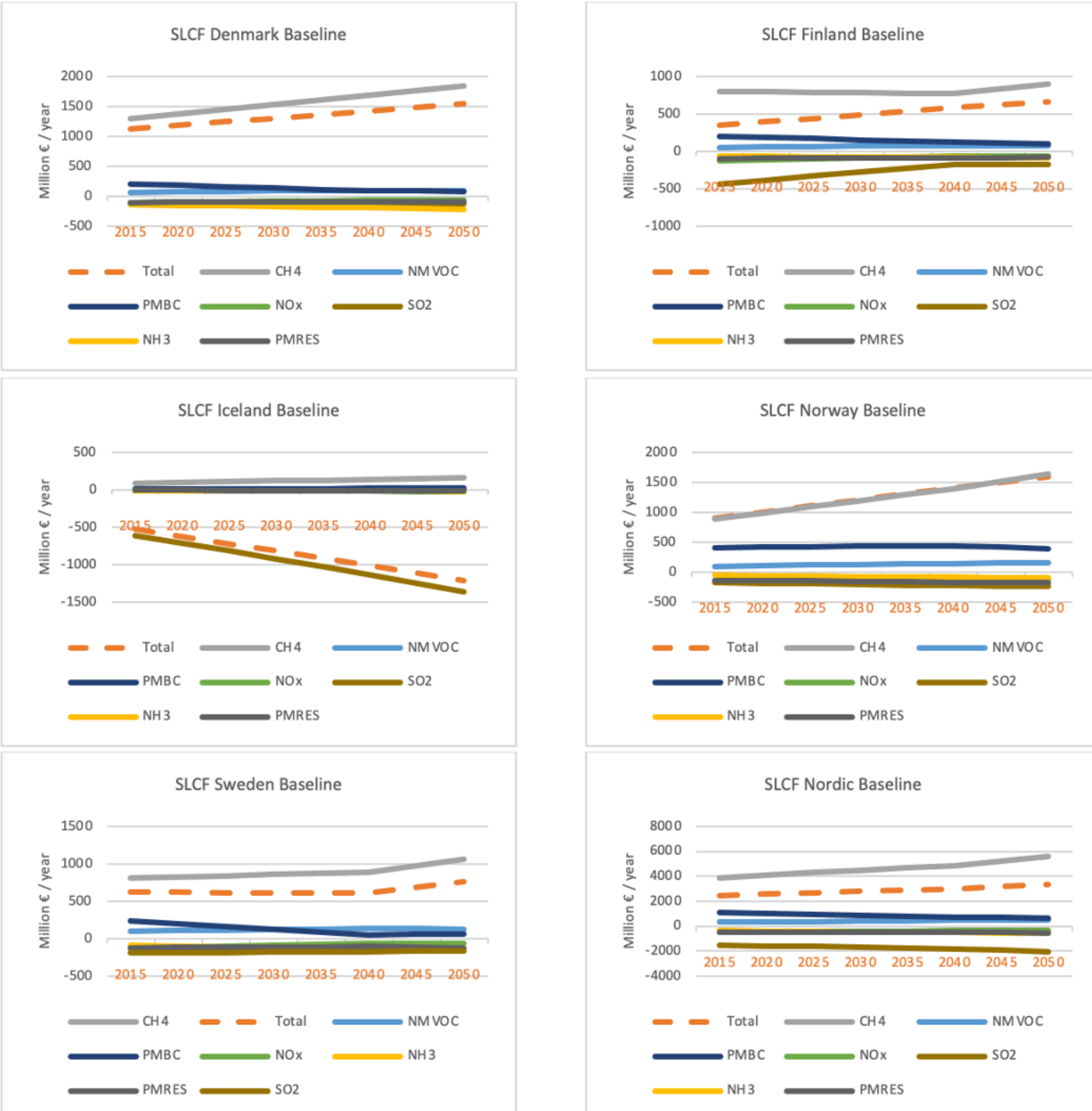


**Figure A 5** Climate damage costs of SLCF emissions if using the climate metric $GWP_{100}$ as $CO_2$ equivalents instead of $CH_4$-equivalents and the mid social costs of carbon instead of social cost of methane as presented in Table 2.


**Figure A 6** Climate damage costs of SLCF emissions if using the climate metric $GWP_{100}$ as $CO_2$ equivalents instead of $CH_4$-equivalents and the low social costs of carbon instead of social cost of methane as presented in Table 2.

# Appendix III: Socio-economic benefits per sector from MTFR emission reductions

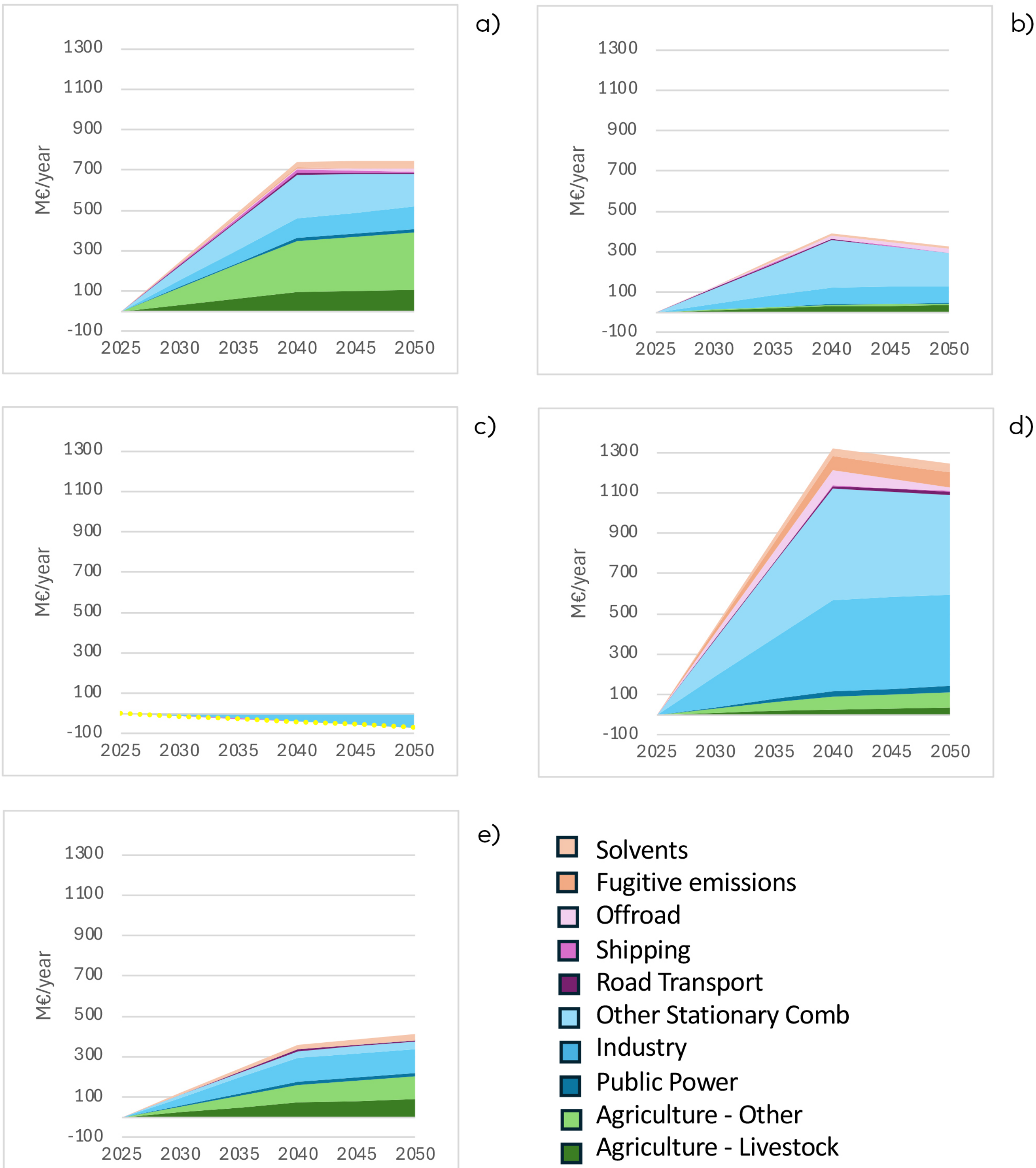


**Figure A 7** Effect on SLCF damage costs when reducing emissions from BSL emission levels into MTFR emission levels – results per sector. a) Denmark, b) Finland, c) Iceland, d) Norway, e) Sweden.

# About this publication

## Damage Costs of Nordic emissions of Short-Lived Climate Pollutants and $CO_2$

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