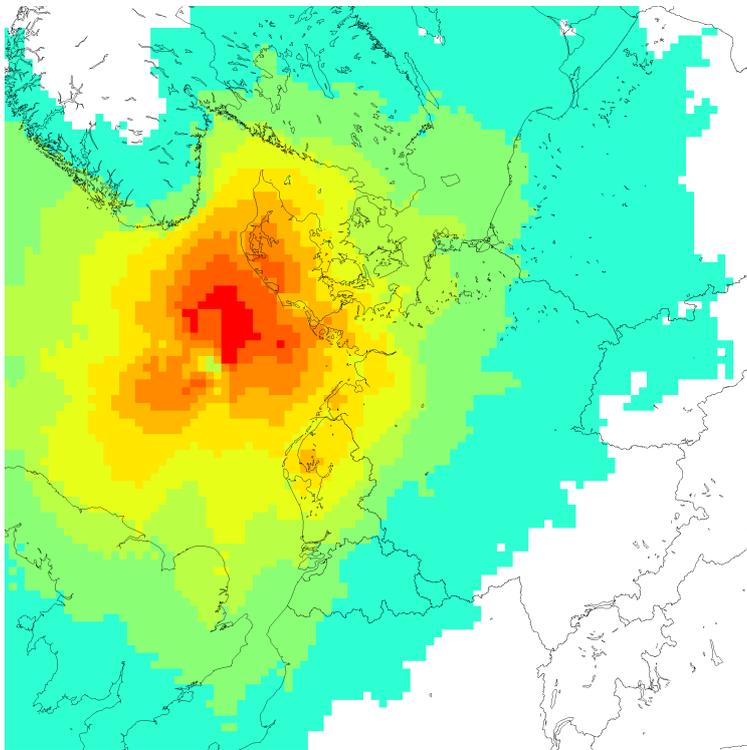


Unit damage costs for emissions from the Danish gas- and oil platforms in the North Sea

Scientific note from DCE – Danish Centre for Environment and Energy

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Data sheet

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1 Introduction

The purpose of this scientific note is to calculate and present health-related welfare economic unit damage costs associated with emissions from the power turbines and flaring on the Danish oil and gas platforms in the North Sea. This work was commissioned by TotalEnergies EP Danmark A/S, the primary operator in the Danish sector of the North Sea.

The most recent official set of health-related welfare economic unit damage costs for Danish emissions is presented in the Danish publication “Miljøøkonomiske beregningspriser for emissioner 4.0” (Welfare economic damage costs for emissions 4.0) (Brandt et al., 2023). This publication provides unit damage costs for the ten overall emission sectors and covers the major chemical species: nitrogen oxides (NO_x), sulfur oxides (SO_x), and primary particulate matter ($\text{PPM}_{2.5}$; primary emitted particles with diameter less than $2.5 \mu\text{m}$). The latter includes primary emissions of dust/ash, Elemental Carbon (EC), and Primary Organic Aerosols (POA). Emissions from power turbines on offshore platforms were included in the unit damage costs calculations for SNAP 1 (Selected Nomenclature for Air Pollution) in Brandt et al. (2023), together with the land-based electricity and heat production in one single category. The SNAP 1 sector includes emissions from combustion in the energy and transformation industries that include public electricity and heat production, petroleum refining and manufacture of solid fuels and other energy industries.

In this study, we calculate unit damage costs for total emissions of nitrogen oxides (NO_x) from all Danish gas and oil platforms operating in the North Sea. Additionally, we assess the feasibility of calculating unit damage costs for emissions of sulfur oxides (SO_x) and primary particulate matter ($\text{PPM}_{2.5}$), depending on whether these pollutants are emitted in significant quantities. Since Brandt et al. (2023), the emissions are now reported in GNFR sectors (Gridded Nomenclature For Reporting), where the emissions from the Danish gas and oil platforms are divided into power production (GNFR B) and flaring (GNFR D1). Emissions from both subsectors are included in this study. However, emissions from flaring (GNFR D1) represent only a very small fraction of the total emissions in the results.

The calculations are performed using a combination of the DEHM air pollution model, which estimates the contribution of emissions from the North Sea to air pollution concentrations in Denmark and across Europe, and the EVA model system, which quantifies the associated health impacts and external costs of air pollution in the same areas. The methodology follows the approach and valuation used in Brandt et al. (2023), ensuring comparability of results.

2 The EVA model system

Health impacts and associated welfare economic costs from air pollution are calculated using the integrated model system EVA_{v8.0} (Andersen et al., 2004; 2006; Brandt et al., 2013a; 2013b; Geels et al., 2015; 2021; Im et al., 2018; 2019; 2023). EVA (Economic Valuation of Air pollution) is based on the impact-pathway approach (Friedrich and Bickel, 2001) and has been developed to estimate health outcomes resulting from air pollution exposure, including both mortality and morbidity, as well as to quantify the associated welfare-economic or external costs.

The EVA model system has been applied to calculate health-related external costs from major emission sectors in Europe and international shipping (Brandt et al., 2013a, 2013b; Geels et al., 2021; Nordstrøm et al., 2024), across Europe and the United States (Im et al., 2018), in the Nordic countries (Geels et al., 2025; 2021; Im et al., 2019), and in future global assessments (Im et al., 2023). In Denmark, EVA has been used in numerous projects to support the development of emission reduction strategies for major cities (see e.g. Jensen et al., 2024, and references herein) and at the national level, as part of the Danish air quality monitoring programme NOVANA (see e.g. Ellermann et al., 2020; Nordstrøm et al., 2024). The EVA system has also been compared to other health impact assessment models, including those presented in Anenberg et al. (2015) and Lehtomäki et al. (2020).

The EVA model system has previously been used to calculate unit damage costs of emissions, defined as the external cost associated with emitting one kilogram of a given chemical species. The most recent unit damage cost estimates for the ten overall emission sectors are published in Brandt et al. (2023). The results presented in this study are based on a model setup and input data comparable to those reported in Brandt et al. (2023). However, the results previously reported in Brandt et al. (2023) were based on emissions for the year 2021 and meteorology for the year 2022 where the results presented here are based on emissions for the year 2023 and the meteorological years 2022-2024.

The data flow within the model system is illustrated in Figure 2.1. The impact-pathway approach begins with emissions, which serve as input to air pollution modeling. This modeling produces spatio-temporally resolved concentrations of health-relevant chemical species. Using these concentration fields in combination with gridded population data, human exposure is calculated for each grid cell. Based on exposure-response functions, derived from epidemiological studies, the statistical health outcomes – both mortality and morbidity – are subsequently estimated. Each health outcome is assigned an economic value, and by summing the costs across all cases, the total external (welfare-economic) cost is derived. With deterministic air pollution models, the contribution of specific sources or emission sectors to health impacts and associated costs can be identified. By dividing these resulting costs by the corresponding emissions, unit damage costs per kilogram of emitted substance can be estimated.

The EVA model system applies the best available data and models at each stage of the impact-pathway approach.

- 1) Gridded emission data for Danish sources are calculated using the SPREAD model (Plejdrup et al., 2021), which provides data for all relevant chemical species at a spatial resolution of 1 km × 1 km. The dataset covers the entirety of Denmark and is disaggregated into both overall emission sectors and detailed sub-sectors.
- 2) The Danish Eulerian Hemispheric Model (DEHM) (Christensen, 1997; Frohn et al., 2002; Brandt et al., 2012; Colette et al., 2025) is applied at the regional scale. DEHM is a state-of-the-art, fully deterministic chemistry-transport model (CTM) that simulates transport and dispersion driven by wind, chemical transformation, and surface deposition for 89 chemical species. The model is configured with a mother domain covering the Northern Hemisphere, featuring the intercontinental transport of air pollution, and three nested domains with increasing spatial resolution, covering Europe, Northern Europe, and Denmark. DEHM is defined on a polar stereographic projection, true at 60° north, and includes 29 vertical layers. DEHM is routinely used and evaluated against observations in the Danish air quality monitoring programme NOVANA and in the European Copernicus Atmospheric Monitoring Service (CAMS) (Colette et al., 2025). Meteorological input data used as input to the DEHM model, are calculated using the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008).
- 3) Gridded population data are used to estimate human exposure. For Denmark, data are based on the Central Population Register (CPR), while for other regions, the Gridded World Population (GWP) dataset is applied.
- 4) Exposure-response functions (ERFs) are used to estimate health impacts in terms of both morbidity and mortality. These functions are mostly based on recommendations from World Health Organization experts (WHO, 2013; 2021). EVA calculates premature deaths due to both short-term (acute) and long-term (chronic) exposure to air pollution, where the chronic exposure is most significant. WHO (2021) identifies a relative risk increase of 8% for chronic mortality associated with air pollution exposure of particles with diameter less than 2.5 µm (PM_{2.5}) that is applied in the EVA system.
- 5) Economic valuations of health impacts from air pollution are based on the methodology presented in Brandt et al. (2023). In this study, all costs are expressed in 2022 price levels.

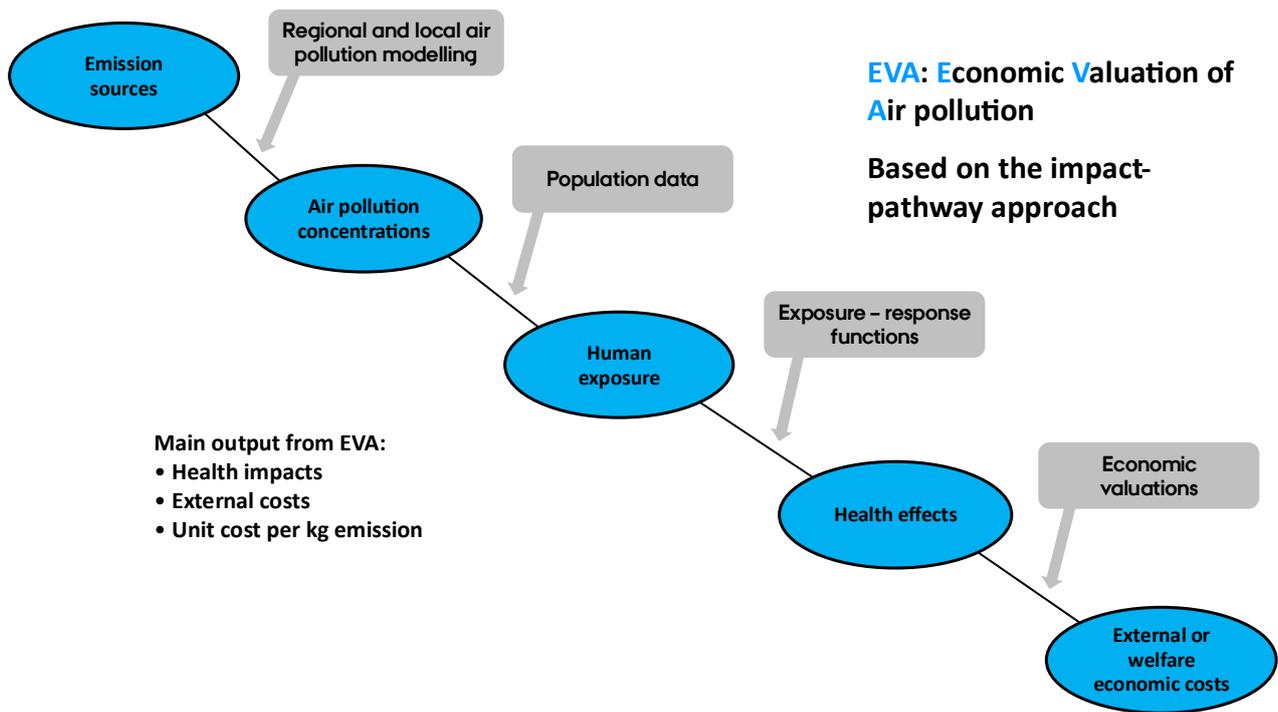


Figure 2.1. Illustration of the impact-pathway approach used in the EVA model system.

3 Results

The regional-scale air pollution model DEHM, together with the EVA model system, was run for the three consecutive years 2022–2024, using 2023 emission data as input for all years. Mean values over the three-year period were calculated to reduce the potential influence of meteorological variability and extreme weather events on the results.

DEHM is run twice: once for a baseline scenario in which all emissions are included, and once for a scenario where all emissions are included except those of specific interest. The difference between the two model runs represents the contribution from the targeted emission sources. In this study, the emissions of interest are those originating from power turbines and flaring on the Danish gas and oil platforms in the North Sea. These emissions formally belong to the GNFR B and GNFR D1 sectors, respectively. The emissions from the power turbines on the platforms were previously included in the SNAP 1 sector, as assessed in Brandt et al. (2023).

Emissions from the Danish emission inventories, provided at a 1 km × 1 km spatial resolution, are included in the DEHM model. The emissions from the power turbines and flaring on Danish gas and oil platforms in the North Sea (sector GNFR B and D1) for the year 2023 is presented in Table 3.1. Emissions of sulfur oxides (SO_x), represented as the sum of SO₂ and SO₄, are reported in full mass as kg-SO₂. Similarly, nitrogen oxides (NO_x), comprising NO and NO₂, are reported as kg-NO₂. Primary emitted particles with diameters less than 2.5 μm (PPM_{2.5}) are categorized into dust/ash, Elemental Carbon (EC), and Primary Organic Aerosols (POA), and are reported in full mass.

Among these pollutants, NO_x is the only chemical species with a significant emission level, amounting to 3,047,706 kg (approximately 3.05 kilotonnes) in 2023, which is the most recent year for which Danish emission data are available. Of these, only 38,130 kg originates from flaring on the platforms, corresponding to around 1.3 % in 2023.

Table 3.1. Emissions from the power turbines and flaring on the Danish gas- and oil platforms in the North Sea in kg for the year 2023.

Emission species	SO _x	NO _x	PPM _{2.5} -dust	PPM _{2.5} -EC	PPM _{2.5} -POA	Sum PPM _{2.5}
Units	kg-SO ₂	kg-NO ₂	kg	kg	kg	kg
GNFR B & D1, North Sea	4,908	3,047,706	1,360	837	4,648	6,846

The DEHM model was run as described above, and the impacts of the emissions, listed in Table 3.1, on air pollution concentration fields were assessed. Emissions of SO_x and PPM_{2.5} were found to be very low, and upon examining their contributions to ambient concentrations, it was concluded that the signal-to-noise ratio in the DEHM model for these species is too low to yield reliable results. For primary particles, a small but detectable contribution was observed in the vicinity of the platforms in the North Sea; however, due to the very low population in this area, the resulting health-related external costs are negligible. Consequently, the focus of the assessment is placed on NO_x emissions, for which a significant and reliable signal is observed.

NO_x emissions contribute to the formation of ozone (O₃) and nitrogen dioxide (NO₂), as well as to secondary inorganic particles containing nitrate (NO₃⁻) in the atmosphere. Nitrate is part of PM_{2.5} that causes mortality and morbidity. Among these, the contribution to health impacts from nitrate is by far the most significant. The chemical transformation of NO_x into nitrate can take from several hours to days, during which time the pollutants are transported over long distances by atmospheric winds. This process is illustrated in Figure 3.1, which shows the contribution of NO_x emissions from Danish gas and oil platforms to the geographical distribution of the total nitrate concentrations, as calculated by the DEHM model. The results are presented for the model domain three, which covers Northern Europe. Contributions outside this domain are also included in the overall calculations.

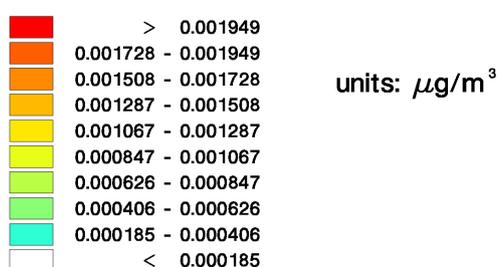
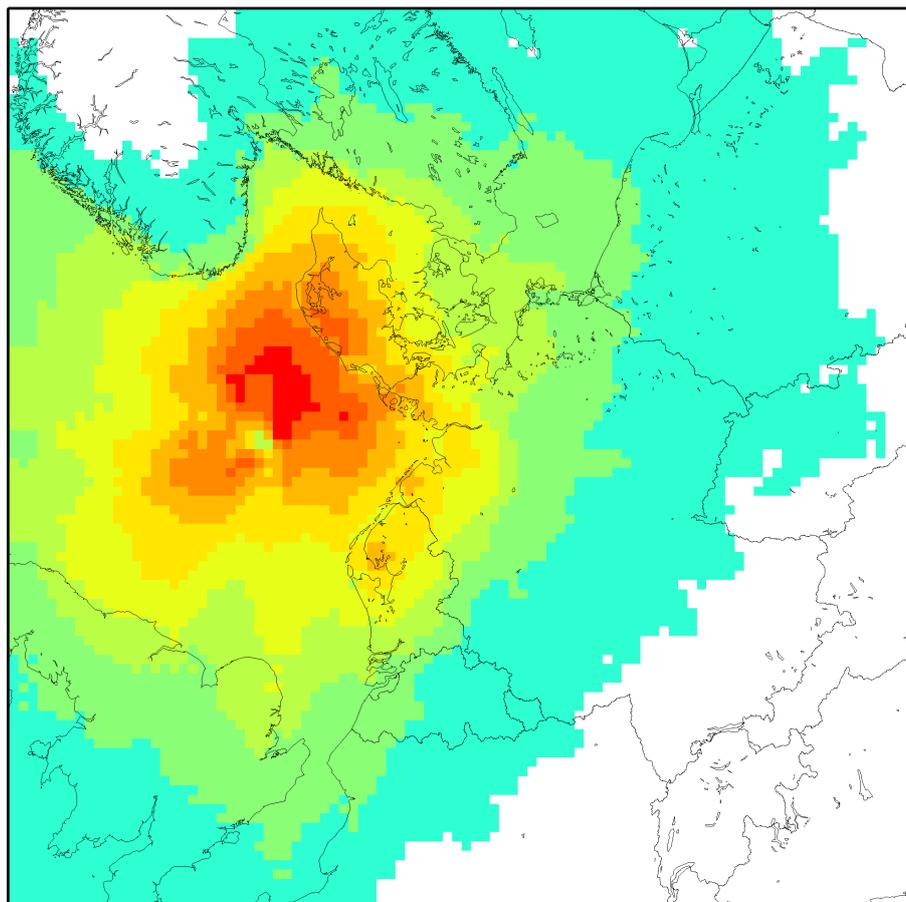


Figure 3.1. Contribution to the total nitrate (NO₃⁻) concentrations, from emissions on the Danish gas- and oil platforms, as calculated by the DEHM model for model domain three, as annual mean values over the years 2022-2024.

Figure 3.2 shows the total PM_{2.5} concentrations over Europe, as calculated by the DEHM model and presented as a mean over the years 2022 to 2024. The chemical species included in PM_{2.5} are the primary emitted particles mineral dust/ash, elemental carbon (EC), primary organic carbon (POA), sea salt, secondary inorganic aerosols (SIA including sulfate, nitrate, and ammonium) and secondary organic aerosols (SOA). Due to the hygroscopic behaviour of sea salt and SIA, water is also a part of PM_{2.5}.

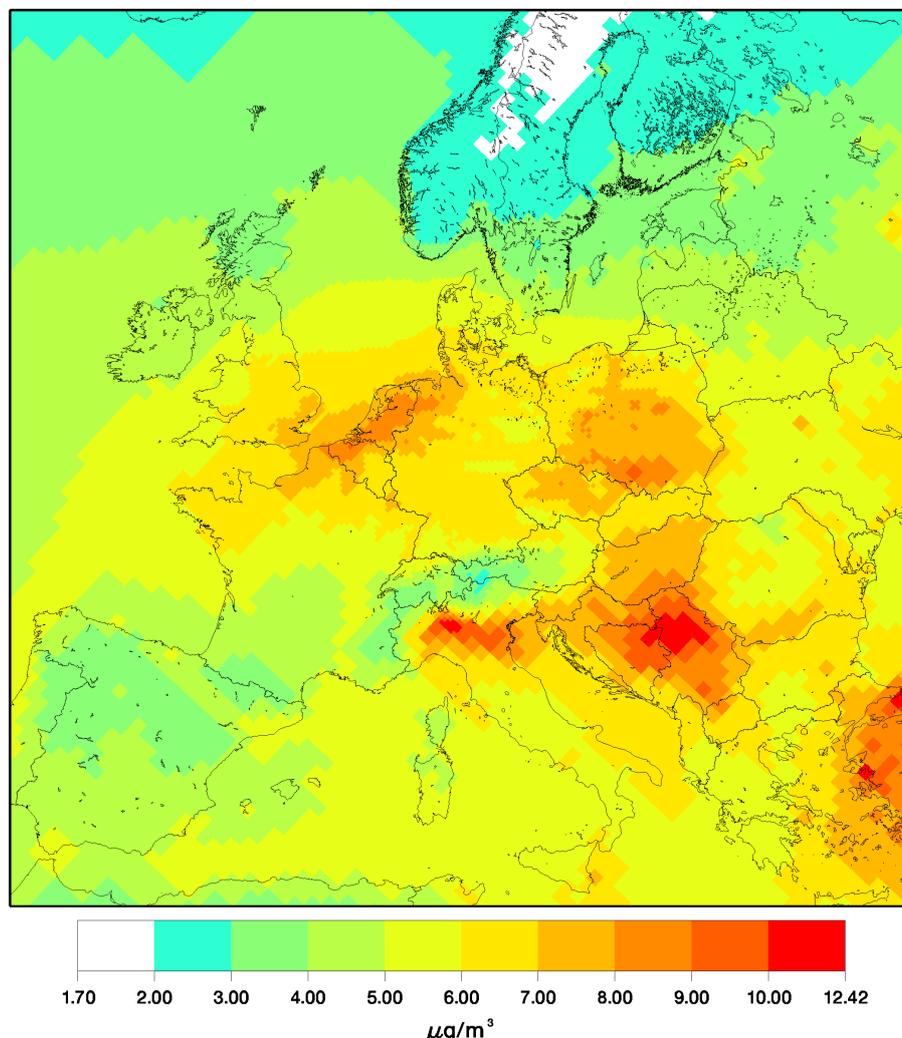


Figure 3.2. Total PM_{2.5} concentrations over Europe as annual mean values over the years 2022-2024. Concentrations are calculated by the DEHM model, and presented using results from all four model domains, taking the highest resolution model results in each location.

Table 3.2 presents the total number of health impact cases as calculated by the EVA model system. These cases are linked to emissions from power turbines and flaring on the Danish gas and oil platforms in the North Sea (see Table 3.1). The results cover the entire European domain and are shown for each individual year from 2022 to 2024, along with their mean values.

The emissions are estimated to contribute to approximately 40 premature deaths (due to both short- and long-term exposure) across Europe. They are also linked to around 1,590 work loss days and approximately 21,600 restricted activity days along with other health outcomes listed in the table. A larger variability is seen between the years for minor restricted activity days. The reason is that this health outcome is based on ozone concentrations and not PM_{2.5}.

Table 3.2. Total number of cases for different health outcomes, associated with the power turbines and flaring, on the Danish gas- and oil platforms in the North Sea for the years 2022-2024, and as a mean over the three years.

	2022	2023	2024	Mean (2022-2024)
Premature deaths (short-term exposure)	5	8	5	6
Premature deaths (long-term exposure)	36	34	31	34
Premature deaths (total)	41	42	36	40
Respiratory hospital admissions	22	26	22	23
Cerebrovascular hospital admissions	18	31	19	23
Cough (children)	4	4	3	4
Chronic bronchitis (adults)	29	28	25	27
Chronic bronchitis (children)	93	89	80	87
Work loss days	1,720	1,600	1,440	1,590
Restricted activity days	23,100	21,900	19,700	21,600
Minor restricted activity days	6,690	18,100	8,290	11,000
Lung cancer	5	4	4	4

Table 3.3 presents the total health-related external costs associated with NO_x emissions from power turbines and flaring on the Danish gas and oil platforms in the North Sea for the years 2022–2024, as well as the mean value across the three-year period. The average cost per year is estimated at €75.6 million, with some variation between the individual years.

The EVA model system can provide results at both national and regional levels. In addition to calculating impacts for the whole of Europe, we have specifically assessed the contribution to Denmark. The results show that approximately 4 % of the total health impacts and associated external costs from NO_x emissions from the North Sea platforms occur within Denmark. In contrast, the NO_x emissions from the entire SNAP 1 sector, which also includes land-based electricity and heat production, have a domestic health cost share of 13 % for the year 2022 (Brandt et al., 2023).

Table 3.3. Total external costs in million Euros, related to health impacts from the power turbines and flaring, on the Danish gas- and oil platforms in the North Sea, for the years 2022-2024 and as a mean over the three years.

Species, emissions	NO _x
Species, health	O ₃ /NO ₂ /NO ₃
Unit	Million Euros
GNFR B and D1, North Sea, 2022	72.3
GNFR B and D1, North Sea, 2023	87.2
GNFR B and D1, North Sea, 2024	67.3
Mean value (2022-2024)	75.6

Conventionally, as the emissions stem from Denmark’s territory, the full external cost (domestic and abroad) should be included in a socio-economic assessment (cf. Møller et al., 2000). The more so as Denmark is a party to international agreements on air pollution, having recognized the damages inflicted on other countries from emissions (OECD, 2006).

By relating the external cost directly to the emissions, the unit costs are estimated. Table 3.4 presents the unit damage costs of emitting one kilogram of NO_x from power turbines and flaring on Danish gas and oil platforms in

the North Sea for the years 2022–2024, as well as the mean value across the three-year period. The average unit damage cost is estimated at €25 per kg-NO₂, corresponding to DKK 187 per kg-NO₂.

Table 3.4. Unit damage costs in Euros for NO_x emissions, related to health impacts from the NO_x emissions from power turbines and flaring, on the Danish gas- and oil platforms in the North Sea, for the years 2022-2024 and as a mean over the three years.

Species, emissions	NO _x
Species, health	O ₃ /NO ₂ /NO ₃
Unit	Euro/kg-NO ₂
GNFR B & D1, North Sea, 2022	24
GNFR B & D1, North Sea, 2023	29
GNFR B & D1, North Sea, 2024	22
Mean value (2022-2024)	25

For comparison, Brandt et al. (2023) reported a unit damage costs of DKK 166 per kg-NO₂ (€22) for the entire electricity and heat production sector in Denmark, including also the power turbines on the platforms (SNAP 1).

The difference can be due to two main factors that influence the unit damage costs. One obvious factor is the different location of the sources with respect to the distribution of the population. This is most important for the primary emitted species, like the primary particles, while it is less important for the secondary formed species, since these are formed over hours to days and therefore a regional phenomenon. The second factor is complex non-linear atmospheric chemistry, which is important for the formation of secondary aerosols and ozone. The present calculations are run with 2023 emissions, where NO_x emissions are lower in Denmark compared to earlier. This means that there is less NO_x available to form ammonium nitrate (NH₄NO₃) from the land-based emissions which again means that there is more ammonia available (NH₃) in the atmosphere. At the same time, the NO_x emissions from the gas and oil platforms in the North Sea increased in 2023 compared to the years before, and together with the excessive ammonia, this can increase the formation of ammonium nitrate and therefore also the unit damage costs.

4 Discussion and conclusion

In this study, we estimate a mean unit damage costs of €25 per kg-NO₂ (equivalent to DKK 187 per kg-NO₂) for NO_x emissions from power turbines and flaring on the Danish gas and oil platforms in the North Sea, averaged over the years 2022–2024. For comparison, Brandt et al. (2023) reported a unit damage costs of DKK 166 (€22) per kg-NO₂ for the electricity and heat production sector in Denmark (SNAP 1), which also included the emissions in the North Sea.

As an initial assumption, lower unit damage costs for emissions in the North Sea would be expected compared to land-based electricity and heat production, due to the greater distance from population centers. This is particularly relevant for emissions of primary particles (PPM_{2.5}), whose exposure impacts are typically concentrated closer to the emission source, compared to secondary formed particles in the atmosphere. In this study, it was not possible to calculate a unit damage cost for primary emitted particles from the platforms in the North Sea, as the emission levels were too low to produce a sufficiently strong signal-to-noise ratio in the models. Moreover, the low magnitude of PPM_{2.5} emissions reduces their relevance in this context.

The unit damage costs for NO_x emissions are comparable (13 % higher) to that previously estimated for the total electricity and heat production. This similarity arises because both ozone and nitrate—secondary pollutants formed from NO_x emissions—are regional rather than local phenomena. The chemical transformation of NO_x into nitrate in the atmosphere typically takes several hours to days, during which time the reactive species can be transported over long distances by wind. As a result, the area affected by nitrate formed from NO_x emissions in the North Sea is extensive, leading to a similar valuation of unit damage costs (see Figure 3.1). However, unit damage costs are not only dependent on location of the sources and the chemical species of interest, but also on complex non-linear atmospheric chemistry, which influence the formation of secondary species like O₃ and NO₃⁻. Differences in the emissions alone can lead to differences in the unit damage costs due to the chemistry.

The EVA model system is undergoing continuous development. In this study, a relative risk of 8% for chronic mortality due to long-term exposure is applied, based on WHO (2021). However, a more recent meta-analysis based on the results from many new studies, suggests a higher relative risk of 9.5% (Orellano et al., 2024). Additionally, the list of morbidity-related health outcomes has been expanded in accordance with new recommendations presented by Forastiere et al. (2024). As these updates to the EVA model are still in the research phase, they could not be incorporated into the present analysis. Nevertheless, all else being equal, the integration of this new evidence into the EVA system would likely result in higher unit damage costs.

A detailed discussion of uncertainties in the model calculations is provided in Danish in Nordstrøm et al. (2024). It should also be noted that the current study does not account for the impacts of emissions in the North Sea on climate and natural ecosystems. Incorporating these effects would be expected to increase the estimated unit damage costs.

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