



**Sail into a
sustainable future**

Roadmap

Air pollution, health and economic assessment report

European Union



The European Regional
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The Interreg IVB
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Introduction

Air pollution is high on the international agenda. Consequently, the EU and WHO (World Health Organization) provide directives and guidelines regarding limit values to minimise the impact on human health (EU 2008⁽¹⁾; WHO 2006a).

Urban outdoor air pollution is globally responsible for an estimated 1.4% of premature deaths⁽²⁾ and 0.5% of disability-adjusted life years lost (Ezzati et al., 2002⁽³⁾). Studies furthermore indicate that PM is responsible for increased mortality and morbidity. Approx. 3% of adult deaths caused by cardiovascular and respiratory diseases and approx. 5% of lung and trachea cancers are attributable to PM pollution (Cohen et al., 2004, Schlesinger et al., 2006). In Denmark, approx. 3,500 people die prematurely annually due to atmospheric pollution (Brandt et al., 2013a). International ship traffic is one of the main contributors to health impacts from air pollution causing approximately 50000 premature deaths in Europe per year (Brandt et al., 2013b).

Globally, total NO_x, SO₂ and PM emissions from shipping are increasing due to increased global ship traffic. In coastal regions, shipping emissions are a mounting challenge because of the vicinity to coastal ecosystems and urban areas. Investments into low emission shipping are urgent from both an environmental and public health point of view. Global sulphur emission thresholds and regional emission control areas based on MARPOL Annex VI are instruments for reducing air pollution caused by ships. Emissions reductions are achieved via low sulphur fuels and via technical facilities such as scrubbers. Hybrid wind shipping is a feasible alternative or addition to these measures.

Among the tools used when seeking to optimise regulation strategies and create effective policies addressing air pollution are economic valuation models. Simulations of specific scenarios can be used to assess the cost-benefit of a hypothetical reduction in emissions, for instance. Generally, such valuations study emission concentrations assuming a standardised linear source-receptor relationship between emission changes and subsequent changes in air pollution levels. These model-based valuations are therefore rough approximations in relation to the real effect of emission reductions.

The aim of this report is to make a general assessment of the health-related externalities of air pollution (ambient atmospheric concentration) related to the use of wind-assisted hybrid ship propulsion in two different emission reduction scenarios. Moreover, the report also aims at being a supporting roadmap for decision-making within various fields.

This report of health cost externalities of emissions from sea transport adopts an alternative approach, which calculates the emission impacts from every individual scenario without assuming linearity of the – in reality – highly non-linear atmospheric chemistry. A Chemical Transport Model (CTM), which calculates reactions and transport (advection and diffusion) of chemical compounds, is employed in order to estimate realistic concentrations of relevant air pollutants and realistic concentration responses from emission reduction scenarios. The CTM simulations are forced by the emission scenarios.

The modelled concentrations are supplied for another model for assessing health-related economic externalities of air pollution. The model applied for the latter purpose is the Economic Valuation of Air

¹EU, 2008: Directive 2008/50/EC of the European Parliament on ambient air quality and cleaner air for Europe, 21 May 2008.

² According the WHO reports that in 2012 around 3.7 million people died - one in eight of total global deaths – as a result of air pollution exposure.

³(Ezzati, et al., 360:1347–1360, 2002.

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pollution Model (EVA; Brandt et al., 2011; 2013a; b)). This report will also address the benefit of using the wind-assisted hybrid ship propulsion in terms of health cost saving for the society.

1. Assumptions and model setup

Hybrid shipping offers a feasible solution for emission reduction of many air pollutants. Such measures of emission reduction would be a welcome positive turn in an issue of growing concern.

In sea areas with favourable wind conditions, a hybrid ship has the potential of considerable fuel and emission reductions, depending on actual weather conditions, engine type, ship characteristics and speed (see "Estimating the power of the wind" factsheet). For evaluating the impact of hybrid wind shipping of air quality and human health, it was assumed that certain freight ship types of various sizes are equipped with wind propulsion devices.

1.1 Wind hybrid propulsion scenarios

We assume that small and medium size bulk carriers are the most appropriate vessel type for applying wind propulsion systems. First, their travel speed is between 9 and 12 knots which is favourable for wind propulsion. At 20 knots speed (container vessels) wind propulsion systems become less effective (Sail, Work Package 3). Second, masts may interfere with cranes during the unloading procedure of other vessel types such as container vessels. Finally, we expect small vessels to be equipped with wind propulsion devices first because the financial risk is lower than equipping large vessels. However, the number of small bulk carriers ($3,000 < \text{gross tonnage (GT)} < 10,000$) is very low in the North Sea region. Therefore, the positive effect on air quality by equipping small bulkers with wind propulsion devices was estimated to be negligible.

Therefore, two hybrid wind propulsion scenarios were assumed which include more vessels but a less realistic to be fully implemented within the next decade. They differ in the type and size of ships equipped with sails:

- SAIL1: all bulk carriers are equipped
- SAIL2: all transport vessels in a size range of $3000 < \text{GT} < 10000$ are equipped

Both scenarios will be compared against a reference case in which no vessels are equipped with sail concept. Even though the considered scenarios are situated in the far future, the year 2013 is used as base year in order to make the scenarios comparable.

1.2 Emissions

The emissions of air pollutants and other relevant chemicals were calculated by the emission model SMOKE for Europe (land based emissions) (Bieser et al., 2011), on the base of AIS data (shipping emissions) (Aulinger et al., 2015) and within the chemistry transport model (sea salt) (Kelly et al., 2010). As a result, emission maps for Europe and central Europe have been constructed with a spatial resolution of $72 \times 72 \text{ km}^2$ and $24 \times 24 \text{ km}^2$, respectively, and a temporal resolution of 1 h. These emission data fields serve as input for the subsequent chemistry and transport modelling described below. Figure 1 shows the model domains.

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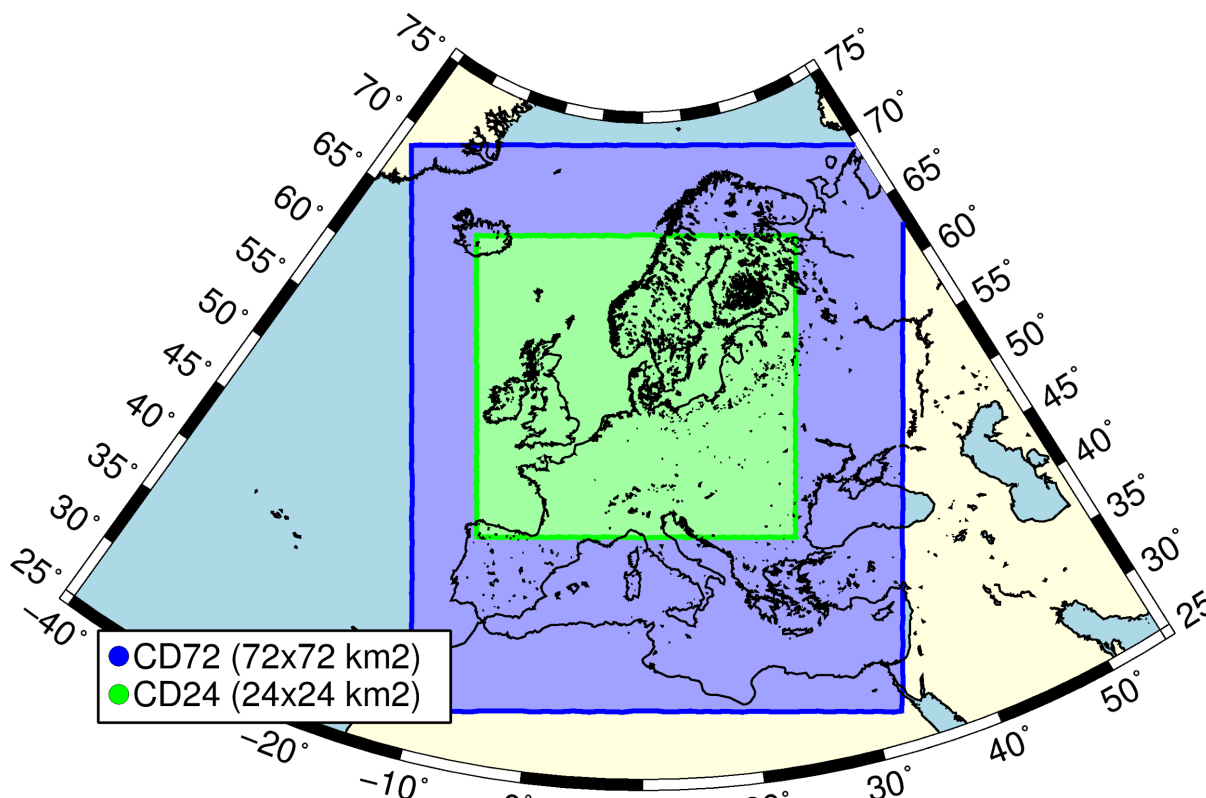


Figure 1: Domains for hourly emission data and chemistry transport simulations. Results from the inner grid (green, CD24) were provided for health impact estimations.

1.1.1 Land emissions inventory

The emission model SMOKE is the official emission model of the United States Environmental Protection Agency (US EPA) and is one of the most used emission models worldwide. It is the official emission model of the Models-3 Community Modelling and Analysis System (CMAS) and creates emission data suitable for the Community Multiscale Air Quality (CMAQ) (section 1.2). Anthropogenic emissions are calculated using the “Top-Down” methodology while biogenic emissions are calculated by the Bottom-Up model BEIS3 (see references in Bieser et al., 2011). In the United States, standardised emission inventories on state and county level are employed for the top-down approach. In contrast to the US, European emission inventories and datasets are quite heterogeneous. Most countries use different methodologies to assess their national emissions. Bieser et al. (2011) created SMOKE for Europe which is an adaptation of SMOKE to European emission inventories. For SMOKE for Europe it was decided to aim for overall consistency by using Pan-European datasets when available. The produced emissions are primarily based on data from the European Monitoring and Evaluating Programme (EMEP)⁴ and from the European Pollutants Emission Register (EPER)⁵.

⁴ Initiated by the Convention on Long-range Transboundary Air Pollution (LRTAP), signed in 1979, the European Monitoring and Evaluation Programme (EMEP) was implemented. National annual emission estimates are reported by the parties under the LRTAP convention, using the standardized methods defined by the CORINAIR (CORE Inventory of AIR emissions) guidebooks. The officially submitted data is published together with a corrected version that was reviewed by national experts.

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1.1.2 Ship emission inventory

The basis for the ship fleet and the ship movements on the North Sea is a data set with AIS positions of ships for the entire year 2011. This allowed for tracking the movements and manoeuvres of single ships including their actual speed. With a ship characteristics data base that contains the engine specifications of all ships given in the AIS data set the engine load, and hence, the energy demand of the ships could be derived from their actual speed.

Based on these data, fuel use as well as NO_x, SO₂, CO, Hydrocarbon (HC), and Particulate Matter (PM) emissions are calculated with load-dependent emission factors in µg/kWh for the different species. For the first time, load dependent emission factors resulting from test bed measurements of about 250 different ship engines were used to calculate a ship emission inventory. For the details, the reader is referred to the paper by Aulinger et al. (2015).

1.1.3 Emission reduction through wind propulsion

It was assumed that a vessel which is equipped with a wind propulsion device uses on average 35% less power and, thus, saves 35% fuels and emits 35% less pollutants.

According to the report of Sail work package 3, 35% seems to be a good average value for the power reduction. The constant saving of 35% and the assumed linearity between power saving and emission reductions is quite rough: Firstly, the weather conditions vary which leads to variable power savings – such as stronger wind and possibly higher power savings in winter time. Secondly, power savings are route dependent because they depend on the relative direction of the wind. Thirdly, the relationship between power usage and fuel consumption is not linear as assumed here: the relative fuel consumption per produced watt of power commonly increases with decreasing engine loading. Finally, the emission composition changes with engine loading which is caused by different combustion temperatures and oxygen availability. However, since the 35% average power saving is already a rough estimation, the added error by assuming linearity between power saving and emission reduction is not relevant for the second guess estimations performed here.

1.2 Chemistry Transport Model

The chemistry transport simulations were performed with the Community Multiscale Air Quality (CMAQ) model of the US EPA (Byun and Ching 1999; Byun and Schere, 2006; Binkowski and Roselle, 2003). The CMAQ model was used in its version 5.0.1 with the CB05tump chemistry mechanism (carbon bond version 5) and the AERO6 aerosol chemistry mechanism. Compared to its previous version, the model update includes several new features (Foley et al., 2010), among them are gas phase chlorine chemistry, improved secondary organic aerosol (SOA) formation (Edney et al., 2007) and an updated representation of sea salt that considers reactions with nitric acid and the formation of coarse mode nitrate (Kelly et al., 2010; Fountoukis and Nenes, 2007). The model was run for the entire year 2013 with a spinup time of 2 weeks. Standard profiles for the most important atmospheric pollutants were used as initial conditions. However, their effect on the simulated atmospheric concentrations is negligible after the spin up.

The model was setup on a 72 x 72 km² grid for entire Europe and on a nested 24 x 24 km² grid for central Europe (Figure 1). The vertical model extent contains 30 layers up to 100 hPa in a sigma hybrid pressure coordinate system. 20 of these layers are below approx. 2 km, the lowest layer extends to about 36 m above ground. For this study, only the simulation results of the 24 x 24 km² domain were evaluated

Using a comprehensive CTM to calculate the effects under specific emission scenarios has the key advantage of accounting for non-linear chemical transformations and feedback mechanisms

⁵ EPER is the European Pollutant Emission Register, the first Europe-wide register of industrial emissions into air and water, which was established by the European Commission in July 2000.

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influencing air pollutants. Non-linearity in the source-receptor relationship is particularly evident for certain atmospheric components, such as NO_x, VOC, ozone, PM, and NH₃, in addition to SO₂. Exemplary, fine sulphate particles form in the atmosphere from SO₂ via sulphuric acid. Therefore, PM (particulate matter) emissions from ships might be low compared to other sources but resulting atmospheric PM concentrations might be high due to SO₂ emissions from ships.

1.3 The external economic valuation of air pollution model

To calculate the external health costs caused by SO₂, NO_x, PM, and CO exhaust emissions of wind assisted hybrid propulsion, this study applies the EVA (Economic Valuation of Air pollution; Brandt et al., 2013a) modelling system developed by Aarhus University.

The Economic Valuation of Air pollution model (EVA) is based on an impact-pathway chain (e.g. Friedrich and Bickel, 2001) and consists of a three-dimensional Eulerian model for regional-scale air pollutant transport and chemical transformation, the Danish Eulerian Hemispheric Model (DEHM⁽⁶⁾) and a Gaussian Plume Model for local-scale air pollutant transport. In order to obtain estimates of location-specific impacts and costs, the EVA model has been specifically developed to couple the results from air pollution models with detailed population data⁽⁷⁾ for Denmark derived from different sources, including from literature and from costs functions adapted to Danish and European conditions. Other components of the EVA model are economic valuations of individual impacts and exposure response functions adapted partly from Watkiss et al. (2005)⁽⁸⁾, which are based on assessments from EU and WHO health experts.. The derived exposure-response coefficients and economic valuation factors are given in Table 1.

However, in this study, EVA is only employed for the final step: the estimation of health impacts and its economical valuation. Emissions are calculated as defined in section 1.2 and concentrations are calculated by CMAQ (section 1.3). An example application of the whole EVA modelling system can be found in Brandt et al. (2011; 2013b) where it is applied on a similar example. The contribution of shipping to air pollution and the effect of different sulphur emission thresholds is presented and discussed there.

⁶The Danish Eulerian Hemispheric Model (DEHM) developed by Aarhus University, is a three-dimensional, offline, large-scale, Eulerian, atmospheric chemistry transport (CTM) (Christensen, 1997; Christensen et al., 2004; Frohn 2004; Brandt et al., 2012;) developed to study long-range transport of air pollution in the Northern Hemisphere and Europe. The model domain covers the Northern Hemisphere, discretised in a 150 × 150 horizontal grid using a polar stereographic projection and with multiple two-way nesting capabilities over Europe.

⁷Denmark has a central registry detailing the addresses, gender and age of every resident in Denmark (the Central Person Register, CPR). For the European scale data was obtained from EUROSTAT 2000.

⁸Watkiss, et al., 2005.

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Table 1. Shows the health effects and economic valuation applicable for Danish/European conditions currently included in the EVA model system (Brandt et al., (2013a).

Health effects (compounds)	Exposure-response coefficient (α)	Valuation, Euros (2006-prices)
Morbidity		
Chronic Bronchitis (PM)	8.2E-5 cases/ μgm^{-3} (adults)	52,962 per case
Restricted activity days (PM)	= 8.4E-4 days/ μgm^{-3} (adults) -3.46E-5 days/ μgm^{-3} (adults) -2.47E-4 days/ μgm^{-3} (adults>65) -8.42E-5 days/ μgm^{-3} (adults)	131 per day
Congestive heart failure (PM)	3.09E-5 cases/ μgm^{-3}	16,409 per case
Congestive heart failure (CO)	5.64E-7 cases/ μgm^{-3}	
Lung cancer (PM)	1.26E-5 cases/ μgm^{-3}	21,152 per case
Hospital admission		
Respiratory (PM)	3.46E-6 cases/ μgm^{-3}	7,931 per case
Respiratory (SO ₂)	2.04E-6 cases/ μgm^{-3}	
Cerebrovascular (PM)	8.42E-6 cases/ μgm^{-3}	10,047 per case
Asthma children (7.6 % < 16 years)		
Bronchodilator use (PM)	1.29E-1 cases/ μgm^{-3}	23 per case
Cough (PM)	4.46E-1 days/ μgm^{-3}	59 per day
Lower respiratory symptoms (PM)	1.72E-1 days/ μgm^{-3}	16 per day
Asthma adults (5.9 % > 15 years)		
Bronchodilator use (PM)	2.72E-1 cases/ μgm^{-3}	23 per case
Cough (PM)	2.8E-1 days/ μgm^{-3}	59 per day
Lower respiratory symptoms (PM)	1.01E-1 days/ μgm^{-3}	16 per day
Loss of IQ		
Lead (Pb) (<1 year)*	1.3 points/ μgm^{-3}	24,967 per point
Mercury (Hg) (fosters)*	0.33 points/ μgm^{-3}	24,967 per point
Mortality		
Acute mortality (SO ₂)	7.85E-6 cases/ μgm^{-3}	2,111,888 per case
Acute mortality (O ₃)	3.27E-6*SOMO35 cases/ μgm^{-3}	
Chronic mortality (PM)	1.138E-3 YOLL / μgm^{-3} (>30 years)	77,199 per YOLL
Infant mortality (PM)	6.68E-6 cases/ μgm^{-3} (> 9 months)	3,167,832 per case

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2. Presentation of study case

2.1 Resulting emissions

Shipping emissions for the base case and the two scenarios were calculated according to sections 1.1 and 1.2. Fuel savings and emission reductions of 35% per vessel equipped with a wind propulsion device were assumed and savings for the whole fleet were calculated (Table 4). The realistic case was described in section 1.1 but it is not considered further due to its low impact. The SO₂ emissions were calculated according to the SECA sulphur threshold of 1.0% (by mass) which was valid in 2013. Since 1st Jan 2015 this threshold is at 0.1%, which is not considered here.

Table 2: Shipping emissions in the reference case and emission reduction potential [ton/yr] in three different wind hybrid propulsion scenarios. 35% fuel savings per hybrid freight sailing vessel are assumed. The scenarios by name and type of equipped ship are: realistic (Bulk Carriers; 3,000 < GT < 10,000), SAIL1 (all bulk carriers), SAIL2 (all freight vessels; 3,000 < GT < 10,000).

Values in ton/yr	Reference case ship emissions	Emission reduction compared to reference		
		Realistic	SAIL1	SAIL2
Fuel	7,326,094	7,334	287,078	256,353
NO _x	539,021	545	21,507	19,121
SO ₂	123,358	118	4,906	4,395
CO ₂	23,205,570	23,229	908,170	811,617

Figure 2 shows the emissions of SO₂ and PM_{2.5} in the reference case on the left. In the centre column the difference between SAIL1 and reference emissions is plotted and on the right hand side the difference between SAIL2 and reference emissions. When the full emissions and no differences were plotted one would not recognise any differences (see different scaling of the colour bar).

Shipping tracks are recognisable in the reference SO₂ emission map of Figure 2. Thus, SO₂ emissions considerably contribute to total SO₂ emissions in this region. In the SAIL1 scenario, emission reductions take mainly place in the English Channel and around Denmark. In the SAIL2 scenario in contrast, emission reductions are more spread in space. This is due to the fact that small cargo vessels of various types have more different routes and target ports than Bulk carriers of various sizes.

The contribution of primary PM_{2.5} from shipping to total PM_{2.5} emissions is quite low. However, this does not necessarily mean that shipping does not contribute significantly to PM loading. Secondary particles may form from gaseous emissions such as SO₂ in the atmosphere.

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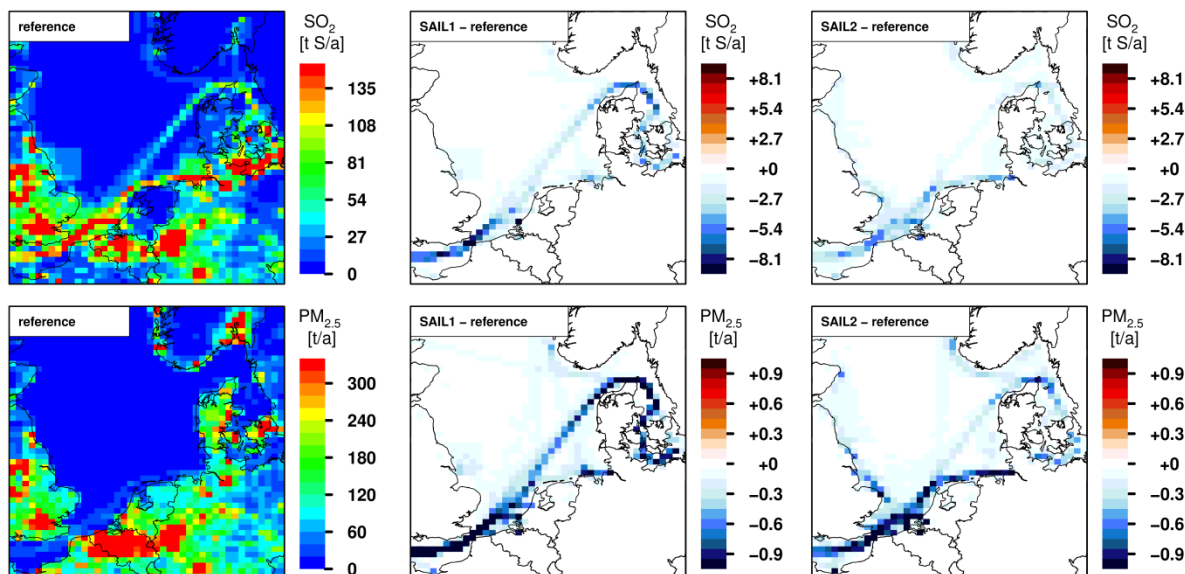


Figure 2: Emissions of SO₂ in t S/a (top) and of PM_{2.5} in t/a (bottom) for the year 2013. The unit t S/a means “tonnes sulphur per year” which is the half of t SO₂/a. left: total emissions in the reference case; centre: difference between SAIL1 scenario and reference case; right: difference between SAIL2 scenario and reference case.

2.1 Resulting Concentrations

Figure 3 shows modelled atmospheric ground level concentrations of SO₂ and PM_{2.5}. The arrangement is the same as in Figure 2 for the emissions. Please note that the units between the left column and the other column vary. The values on the left are by the factor 1000 higher.

The spatial pattern of atmospheric pollution by SO₂ is well correlated with the emission pattern. SO₂ is also blown from the Channel eastward towards Belgium, the Netherlands and central Germany.

The PM_{2.5} pollution pattern does not correlate with its emission pattern. Ship emitted NO_x and SO₂ react to nitric and sulphuric acid. These substances are blown eastward towards the land where ammonia is emitted from fields and barns. Nitric acid and sulphuric acid react with ammonia to ammonium nitrate and ammonium sulphate particles, respectively. Therefore, ship-caused particles formation takes place above inland regions of Belgium, the Netherlands, Germany and Sweden and increases the air pollution, there.

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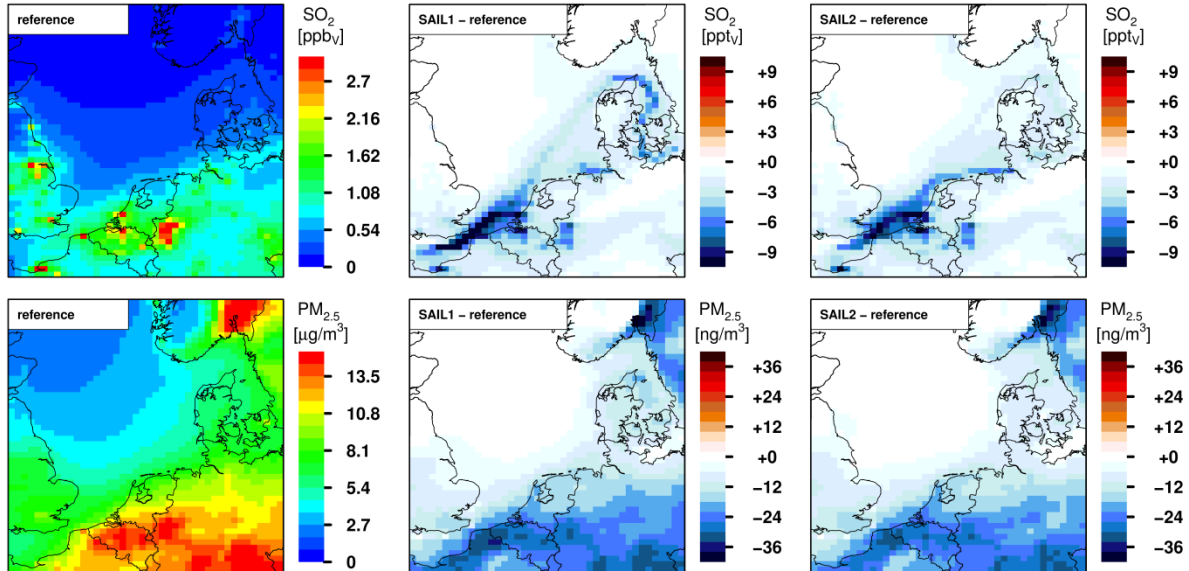


Figure 3: Annual average concentrations of SO₂ in ppb(V) and ppt(V) (top, 1 ppb = 1000 ppt) and of PM_{2.5} in µg/m³ and ng/m³ (bottom, 1 µg/m³ = 1000 ng/m³) for the year 2013. Left: total atmospheric concentrations in the reference case in ppb(V) and µg/m³; centre: difference between SAIL1 scenario and reference case in ppt(V) and ng/m³; right: difference between SAIL2 scenario and reference case.

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3. Health and economic impact

3.1 Impact of air pollution on health

This section describes the assessment related to health impact of using wind assisted hybrid ship propulsion in the two scenarios (SAIL1 and SAIL2).

Table 3 shows the number of cases of health impacts in central Europe (Figure 1, green domain), which are caused by air pollution. Total numbers and no differences are given. The relative reduction in the number of cases through emission reductions in the SAIL1 and SAIL2 scenarios is below 1% per health impact. Table 4 shows the same data but for Denmark, only.

Table 3: Number of cases of different health impacts caused by air pollution in central Europe. The numbers do not refer to shipping-related air pollution, only, but to total air pollution. The column “reference” shows total numbers and the columns “SAIL1 - Ref” and “SAIL2 - Ref” show reductions of the SAIL scenarios compared to the reference scenario.

Mortality/Morbidity	Number of cases in central Europe		
	reference	SAIL1 - Ref.	SAIL2 - Ref.
Chronic Bronchitis	354,329	-135	-102
Restricted Activity Days	362,270,720	-137,984	-103,680
Respiratory Hospital Admissions	20,199	-8	-6
Cerebrovascular Hospital Admissions	45,447	-17	-13
Congestive Heart Failure	27,916	-8	-6
Lung Cancer	54,264	-21	-15
Bronchodilator Use Children	10,573,780	-4,002	-3,017
Bronchodilator Use Adults	69,344,704	-26,248	-19,792
Cough Children	36,532,816	-13,804	-10,416
Cough Adults	71,384,272	-27,088	-20,384
Lower Respiratory Symptoms Children	14,098,386	-5,340	-4,024
Lower Respiratory Symptoms Adults	25,749,330	-9,766	-7,370
Acute premature deaths	22,340	-3	-2
Chronic YOLL*	4,040,264	-1,532	-1,153
Infant mortality	398	0	0

*:YOLL is Year Of Life Lost related to particles. No. of premature death=YOLL/10.6

As Figure 3 indicates, air pollution levels around Denmark are more reduced in the SAIL1 scenario than in the SAIL2 scenario. This is also reflected by the number of cases in table 4: slightly higher improvement in SAIL1 compared to SAIL2.

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Table 4: Number of cases of different health impacts caused by air pollution in Denmark. The numbers do not refer to shipping-related air pollution, only, but to total air pollution. The column “reference” shows total numbers and the columns “SAIL1 - Ref” and “SAIL2 - Ref” show reductions of the SAIL scenarios compared to the reference scenario.

Mortality/Morbidity	Number of cases in Denmark		
	Reference	SAIL1 - Ref	SAIL2 - Ref
Chronic Bronchitis	5,832	-10	-8
Restricted Activity Days	5,962,830	-9,696	-8,588
Respiratory Hospital Admissions	326	-1	-1
Cerebrovascular Hospital Admissions	734	-1	-1
Congestive Heart Failure	475	-1	-1
Lung Cancer	893	-2	-1
Bronchodilator Use Children	157,125	-256	-227
Bronchodilator Use Adults	1,141,408	-1,856	-1,644
Cough Children	542,873	-886	-785
Cough Adults	1,174,978	-1,911	-1,692
Lower Respiratory Symptoms Children	285,897	-486	-419
Lower Respiratory Symptoms Adults	423,831	-689	-610
Acute premature deaths	333	0	0
Chronic YOLL*	62,279	-101	-90
Infant mortality	7	0	0

*:YOLL is Year Of Life Lost related to particles. No. of premature death=YOLL/10.6

3.2 Total cost health related cost externalities

In this section, the external costs are given for the two scenarios (SAIL1 and SAIL2).

The results in Table 5 show the costs related to the impact on human health due air pollution in central Europe. Table 6 shows the same data but related to air pollution species. The costs are in the order of several 10bn EUR. However, the difference between SAIL scenarios and reference scenario are in the order of 100 to 150 million EUR.

Table 5: The total external costs in billions of euros for central Europe split by impact. The numbers do not refer to shipping-related air pollution, only, but to total air pollution. The column “reference” shows total costs and the columns “SAIL1 - Ref” and “SAIL2 - Ref” show reductions of the SAIL scenarios compared to the reference scenario.

Mortality/Morbidity	External costs in central Europe [bn EUR]		
	Reference	SAIL1 – Ref	SAIL2 - Ref
Chronic Bronchitis	18.77	-0.01	-0.01
Restricted Activity Days	47.46	-0.02	-0.02

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Respiratory Hospital Admissions	0.16	0.00	0.00
Cerebrovascular Hospital Admissions	0.46	0.00	0.00
Congestive Heart Failure	0.46	0.00	0.00
Lung Cancer	1.15	0.00	0.00
Bronchodilator Use	1.84	0.00	0.00
Cough	6.37	0.00	0.00
Lower Respiratory Symptoms	0.64	0.00	0.00
Acute premature deaths	47.18	-0.01	-0.01
Chronic YOLL*	311.90	-0.10	-0.10
Infant mortality	1.26	0.00	0.00

Table 6: The total external costs in billions of euros for the central Europe split by air pollutant. The numbers do not refer to shipping-related air pollution, only, but to total air pollution. The column “reference” shows total costs and the columns “SAIL1 - Ref” and “SAIL2 - Ref” show reductions of the SAIL scenarios compared to the reference scenario.

Species	Total external costs in central Europe [bn EUR]		
	Reference	SAIL1 – Ref	SAIL2 - Ref
CO	0.07	0.00	0.00
SO ₂	12.33	-0.01	-0.01
SO ₄ ²⁻	75.75	-0.06	-0.06
Total sulphur	88.08	-0.07	-0.07
O ₃	34.86	0.00	0.00
NO ₃ ⁻	73.84	-0.05	-0.03
Total nitrogen	108.70	-0.04	-0.03
PM _{2.5}	240.77	-0.04	-0.02
Total	437.55	-0.15	-0.12

Tables 7 and 8 contain costs for Denmark. Air pollution accounts for costs of about 6.8bn EUR. The reduction of these costs in the SAIL scenarios is in the order of 0.01bn EUR.

Table 7: The total external costs in billions of euros for Denmark split by impact. The numbers do not refer to shipping-related air pollution, only, but to total air pollution. The column “reference” shows total costs and the columns “SAIL1 - Ref” and “SAIL2 - Ref” show reductions of the SAIL scenarios compared to the reference scenario.

Mortality/Morbidity	Total external costs in Denmark [bn EUR]		
	Reference	SAIL1 - Ref	SAIL2 - Ref
Chronic Bronchitis	0.309	-0.001	-0.001
Restricted Activity Days	0.781	-0.001	-0.001
Respiratory Hospital Admissions	0.003	0.000	0.000

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Mortality/Morbidity	Total external costs in Denmark [bn EUR]		
	Reference	SAIL1 - Ref	SAIL2 - Ref
Cerebrovascular Hospital Admissions	0.007	0.000	0.000
Congestive Heart Failure	0.008	0.000	0.000
Lung Cancer	0.019	0.000	0.000
Bronchodilator Use	0.030	0.000	0.000
Cough	0.101	0.000	0.000
Lower Respiratory Symptoms	0.010	0.000	0.000
Acute premature deaths	0.703	-0.001	0.000
Chronic YOLL*	4.808	-0.008	-0.007
Infant mortality	0.023	0.000	0.000

Table 8: The total external costs in billions of euros for Denmark split by air pollutant. The numbers do not refer to shipping-related air pollution, only, but to total air pollution. The column “reference” shows total costs and the columns “SAIL1 - Ref” and “SAIL2 - Ref” show reductions of the SAIL scenarios compared to the reference scenario.

Species	Total external costs in Denmark [bn EUR]		
	Reference	SAIL1 - Ref	SAIL2 - Ref
CO	0.001	0.000	0.000
SO ₂	0.199	0.000	0.000
SO ₄	1.186	-0.002	-0.002
Total sulphur	1.385	-0.002	-0.002
O ₃	0.505	0.000	0.000
NO ₃	1.392	-0.003	-0.002
Total nitrogen	1.897	-0.003	-0.002
PM _{2.5}	3.519	-0.006	-0.005
Total	6.801	-0.010	-0.009

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4. Overall conclusion

The overall EVA model result for human health impact for central Europe shows that the total health-related external costs are 437.55bn EUR in the reference case, 437.40bn EUR in the SAIL1 scenario and 437.44bn euros in the SAIL2 scenario. The maximum reduction of external health costs is 150m EUR (SAIL1), which amounts to about 0.03% of the total external health costs.

From this result we conclude that the impact of the two SAIL wind hybrid propulsion scenarios on air pollution and thus the related health externality costs in central Europe is low. In this region, the contribution of emissions from shipping to air pollution is present but not dominant as indicated by Figure 2 and Figure 3.

In coastal regions, the relative contribution from shipping to air pollution is higher. Therefore, the relative health benefits and reductions of external costs through wind hybrid propulsion are expected to be considerable higher in these regions.

Additionally, this report and Brandt et al. (2011) have highlighted that air pollution still constitutes a serious problem for human health and that the external health costs of air pollution from shipping are considerable.

The maritime sector is subject to numerous IMO conventions and EU Directives. Notably, the MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI sets the limits for fuel sulphur content (max 0.1%) used in the Emission Control Areas (ECA) such as the North Sea and the Baltic Sea, which came into force in 2015. In 2016, this region will become a Nitrogen Oxide Emissions Control Area (NECA) under the IMO, which will target NO_x emissions in the region, although the effect will be decidedly incremental since the NECA regulatory measures deal with engine design. The European Commission regulated emissions for ships with the Council Directive 2005/33/EC(9), which amended Council Directive 1999/32/EC.

As demonstrated in our study cases, both SAIL scenarios will definitely offer benefits in terms of reducing SO₂ emission by around 20,000 metric tons per year. In this regard, the sail concept will constitute a good proactive technology in reducing air pollution emissions to achieve the goals of the SECA and NECA areas.

Wind Assisted Shipping (WAS) solutions will thus enhance compliance with the current SO_x, NO_x and PM Emission Control Areas (SECA's) in the Baltic, North and North American Seas. To incentivize ship-owners to use WAS technology it would be therefore advisable to introduce an incentive scheme similar to the Clean Shipping Index. This will allow to the ship-owner to have some benefit such as reduction port fees, – discounts on port dues; lower insurance premiums; lower interest rates from banks, etc.

As table 2 indicates, the sulphur emission reduction resulting from the stricter SECA thresholds for sulphur content in marine fuel (from 1.0% sulphur since 2010 to 0.1% sulphur since 2015) will no doubt have a far higher impact than the SAIL scenarios could potentially have. However, WAS reduces not only SO₂ emissions but also NO_x and PM as well as CO, CO₂ and VOC (volatile organic compounds) emissions. Additionally, it reduces the fuel consumption.

⁽⁹⁾DIRECTIVE 2005/33/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 July 2005 amending Directive 1999/32/EC.

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