sail

Sail into a sustainable future

Roadmap

Air pollution, health and economic assessment report

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1 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; WHO, 2006).

Urban outdoor air pollution is globally responsible for an estimated 1.4% of premature deaths([1])and 0.5% of disability-adjusted life years lost (Ezzati et al., 2002). 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, SO_2 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 (IMO, 2000) 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 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.

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[1] 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.

2 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 (Schwarz-Röhr et al., 2015). 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.

2.1 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 (Schwarz-Röhr et al., 2015). 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. Thus, we introduced an emission scenario which assumes that all small bulkers (3,000 < gross tonnage (GT) < 10,000) are equipped and denoted it as “realistic”. However, the number of small bulk carries is very low in the North Sea region as well as resulting emission reductions (Table 2). Therefore, the positive effect on air quality by equipping small bulkers with wind propulsion devices was estimated to be negligible and the scenario was rejected.

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 < 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.

2.2 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 employed chemistry transport model (sea salt) (Kelly et al., 2010) which is described in section 2.3. As a result, emission maps for Europe and central Europe have been constructed with a spatial resolution of 72 x 72 km^2 and 24 x 24 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.

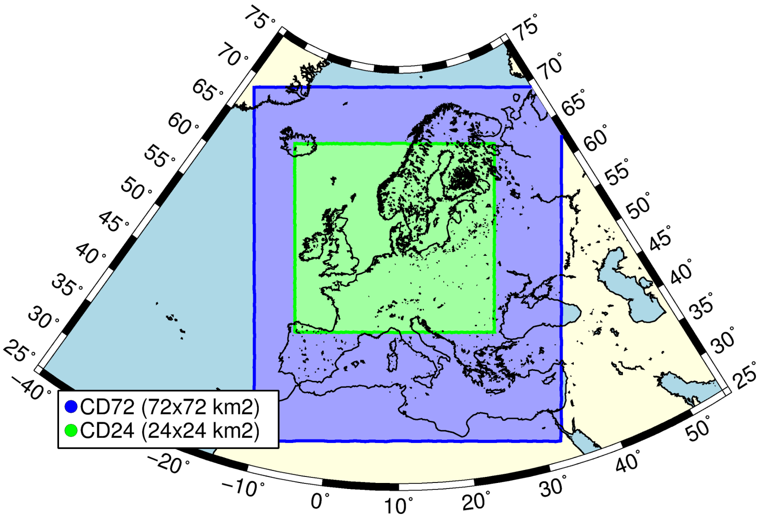

Figure 1: Domains for hourly emission data and chemistry transport simulations. Results from the inner grid (green, CD24) were provided for health impact estimations.

2.2.1 Land emissions inventory

The emission model SMOKE is the official emission model of the Unites 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 2.3). 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 adaption 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)[2] and from the European Pollutants Emission Register (EPER)[3].

2.2.2 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 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.

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[2] 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.

[3] 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.

Based on these data, fuel use as well as NO_X, SO_2, 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).

2.2.3 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 (Schwarz-Röhr et al., 2015), 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.

2.3 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 km^2 grid for entire Europe and on a nested 24 x 24 km^2 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 km^2 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 influencing air pollutants. Non-linearity in the source-receptor relationship is particularly evident for certain atmospheric components, such as NOx, VOC, ozone, PM, and NH_3, in addition to SO_2. Exemplary, fine sulphate particles form in the atmosphere from SO_2. PM emissions from ships might be low compared to other sources but resulting atmospheric PM concentrations might be high due to

SO_2 emissions from ships.

2.4 The external economic valuation of air pollution model

To calculate the external health costs caused by SO_2, NOx, PM, and CO exhaust emissions of wind assisted hybrid propulsion, this study applies the Economic Valuation of Air pollution (EVA; Brandt et al., 2013a) modelling system developed by Aarhus University.

The EVA model 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([4])) 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([5]) for Denmark. It is based on data derived from different sources, including from literature and from costs functions adapted to Danish and European conditions (Brandt et al., 2011; 2013a; b). Other components of the EVA model are economic valuations of individual impacts and exposure response functions adapted partly from Watkiss et al. (2005), 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 2.2 and concentrations are calculated by CMAQ (section 2.3). 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.

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[4] The 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.

[5] Denmark 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.

Table 1: 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)	Valutation, 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

3 Presentation of study case

3.1 Resulting emissions

Shipping emissions for the base case and the three scenarios – realistic, SAIL1, and SAIL2 – were calculated according to sections 2.1 and 2.2. 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 2). The realistic case was described in section 2.1 but it is not considered further due to its low impact. The SO_2 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 fright 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).

Fuel/Species	**Reference case [tons/yr]**	**Reduction compared to reference [tons/yr]**		
		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

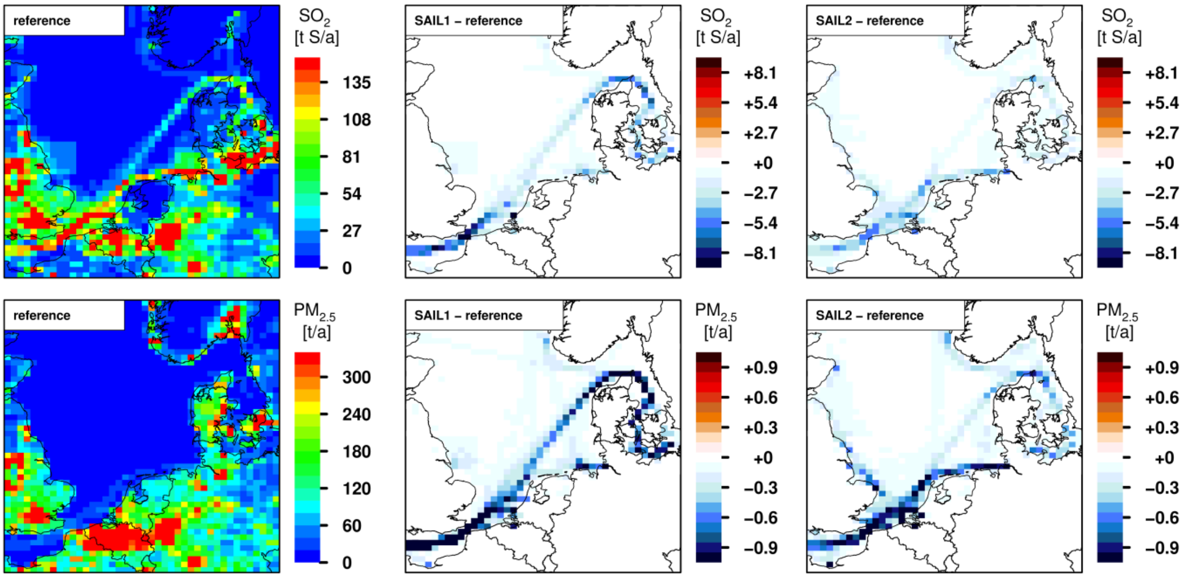

Figure 2: Annual average emissions of SO_2 in t S/a (top) and of $PM_{2.5}$ in t/a (bottom) for the year 2013. The unit t S/a means "tonnes sulphur per year" which is the half of t SO_2/a. left: total emissions in the reference case; centre and right: difference between SAIL1 and reference case and between SAIL2 and reference case.

Figure 2 shows the emissions of SO_2 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. If the full emissions and no differences were plotted one would not recognise any differences (see different scaling of the colour bars).

Shipping tracks are recognisable in the reference SO_2 emission map of Figure 2. Thus, SO_2 emissions considerably contribute to total SO_2 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 Bulkers 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 SO_2 in the atmosphere.

3.2 Resulting Concentrations

Figure 3 shows modelled atmospheric ground level concentrations of SO_2 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 SO_2 is well correlated with the emission pattern. SO_2 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 SO_2 react to nitric and sulphuric acid. These substances are blown eastward towards the land were 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.

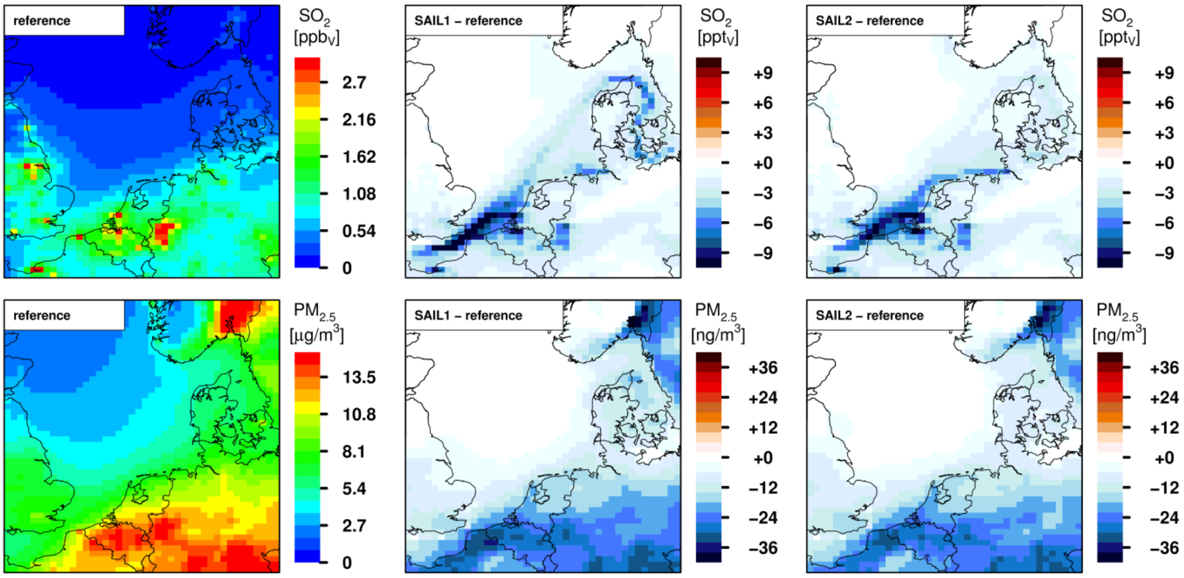

Figure 3: Annual average concentrations of SO_2 in ppb(V) and ppt(V) (top, 1 ppb = 1000 ppt) and of $PM_{2.5}$ in µg/m^3 and ng/m^3 (bottom, 1 µg/m^3 = 1000 ng/m^3) for the year 2013. left: total atmospheric concentrations in the reference case; centre and right: difference between SAIL1 and reference case and between SAIL2 and reference case.

4 Health and economic impact

4.1 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) and in Denmark, which are caused by air pollution. The two columns "Ref" show total numbers and the other four show differences. With respect to Europe, the relative reduction in the number of cases through emission reductions in the SAIL1 and SAIL2 scenarios is below 1% per health impact.

Table 3: Number of cases of different health impacts caused by air pollution in central Europe (columns 2 to 4) and in Denmark (columns 5 to 7). The numbers in the "Ref" columns refer to the cases related to the overall air pollution – not only by shipping. The columns "SAIL1 - Ref" and "SAIL2 - Ref" show reductions by the SAIL scenarios compared to the reference scenario.

Mortality/Morbidity	**Number of cases: central Europe**			**Number of cases: Denmark**		
	Ref	**SAIL1 – Ref**	**SAIL2 – Ref**	**Ref**	**SAIL1 – Ref**	**SAIL2 – Ref**
Chronic Bronchitis	354,329	-135	-102	5,832	-10	-8
Restricted Activity Days	362,270,720	-137,984	-103,680	5,962,830	-9,696	-8,588
Respiratory Hospital Admissions	20,199	-8	-6	326	-1	-1
Cerebrovascular Hospital Admissions	45,447	-17	-13	734	-1	-1
Congestive Heart Failure	27,916	-8	-6	475	-1	-1
Lung Cancer	54,264	-21	-15	893	-2	-1
Bronchodilator Use Children	10,573,780	-4,002	-3,017	157,125	-256	-227
Bronchodilator Use Adults	69,344,704	-26,248	-19,792	1,141,408	-1,856	-1,644
Cough Children	36,532,816	-13,804	-10,416	542,873	-886	-785
Cough Adults	71,384,272	-27,088	-20,384	1,174,978	-1,911	-1,692
Lower Respiratory Symptoms Children	14,098,386	-5,340	-4,024	285,897	-486	-419
Lower Respiratory Symptoms Adults	25,749,330	-9,766	-7,370	423,831	-689	-610
Acute premature deaths	22,340	-3	-2	333	0	0
Chronic YOLL*	4,040,264	-1,532	-1,153	62,279	-101	-90
Infant mortality	398	0	0	7	0	0

*:YOLL is Year Of Life Lost related to particles. Number 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 3: slightly higher improvement in SAIL1 compared to SAIL2 for Denmark is shown.

4.2 Total cost health related cost externalities

In this section, the external costs are given for the two scenarios with respect to the reference case.

The results in Table 4 show the costs related to the impact on human health due air pollution in central Europe (left) and Denmark (right). Table 5 shows the same data but related to air pollution species. With respect to Europe, the costs are in the order of nearly 438bn EUR. However, the differences between SAIL scenarios and reference scenario are only in the order of 120 to 150 million EUR which is less than 0.1% reduction. In 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 which is approximately 0.15% reduction.

Table 4: The total external costs in billions of EUR for central Europe (columns 2 to 4) and Denmark (columns 5 to 7) split by impact. The cost in the “Ref” columns refer to the overall air pollution – not only to shipping-related air pollution. The columns “SAIL1 - Ref” and “SAIL2 - Ref” show reductions of health costs by the SAIL scenarios compared to the reference scenario.

	External costs [bn EUR]: central Europe			**External costs [bn EUR]: Denmark**		
Mortality/Morbidity	**Ref**	**SAIL1 – Ref**	**SAIL2 – Ref**	**Ref**	**SAIL1 – Ref**	**SAIL2 – Ref**
Chronic Bronchitis	18.77	-0.01	-0.01	0.309	-0.001	-0.001
Restricted Activity Days	47.46	-0.02	-0.02	0.781	-0.001	-0.001
Respiratory Hospital Admissions	0.16	0.00	0.00	0.003	0.000	0.000
Cerebrovascular Hospital Admissions	0.46	0.00	0.00	0.007	0.000	0.000
Congestive Heart Failure	0.46	0.00	0.00	0.008	0.000	0.000
Lung Cancer	1.15	0.00	0.00	0.019	0.000	0.000
Bronchodilator Use	1.84	0.00	0.00	0.030	0.000	0.000
Cough	6.37	0.00	0.00	0.101	0.000	0.000
Lower Respiratory Symptoms	0.64	0.00	0.00	0.010	0.000	0.000
Acute premature deaths	47.18	-0.01	-0.01	0.703	-0.001	0.000
Chronic YOLL*	311.90	-0.10	-0.10	4.808	-0.008	-0.007
Infant mortality	1.26	0.00	0.00	0.023	0.000	0.000

*:YOLL is Year Of Life Lost related to particles. Number of premature death=YOLL/10.6

With respect to central Europe, approximately 50% of external cost reductions by the SAIL scenarios is caused by a reduction of SO_X. In Denmark, SO_X has the lowest contribution to cost reductions. Instead, cost reductions by $PM_{2.5}$ dominate. However, nitrate (NO_3^-) and sulphate (SO_4^{2-}) represent secondary particles – particles which are formed in the atmosphere and not emitted as particles. Therefore, the health cost improvements caused by the SAIL scenarios – in Denmark as well as in central Europe – are mainly due to the reduction of primary and secondary particulate matter.

Table 5: Similar to Table 4 but health costs are split by air pollutant. Concentrations of O_3 and NO_3^- depend on NO and NO_2 (NO_X) concentrations. Therefore, these two species are summerized by “Total NO_X”. $PM_{2.5}$ does not include secondary sulphate and nitrate particles.

Species	**External costs [bn EUR]: central Europe**			**External costs [bn EUR]: Denmark**		
	Ref	**SAIL1 – Ref**	**SAIL2 – Ref**	**Ref**	**SAIL1 – Ref**	**SAIL2 – Ref**
CO	0.07	0.00	0.00	0.001	0.000	0.000
SO_2	12.33	-0.01	-0.01	0.199	0.000	0.000
SO_4^{2-}	75.75	-0.06	-0.06	1.186	-0.002	-0.002
Total SO_X	**88.08**	**-0.07**	**-0.07**	**1.385**	**-0.002**	**-0.002**
O_3	34.86	0.00	0.00	0.505	0.000	0.000
NO_3^-	73.84	-0.05	-0.03	1.392	-0.003	-0.002
Total NO_X	**108.70**	**-0.04**	**-0.03**	**1.897**	**-0.003**	**-0.002**
$PM_{2.5}$	240.77	-0.04	-0.02	3.519	-0.006	-0.005
Total	**437.55**	**-0.15**	**-0.12**	**6.801**	**-0.010**	**-0.009**

5 Overall conclusion

The overall EVA model result for human heath 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 Figures 2 and 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 (EU, 2005), which amended Council Directive 1999/32/EC (EU, 1999).

As demonstrated in our study cases, both SAIL scenarios will definitely offer benefits in terms of reducing SO_2 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 us 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 SO_2 emissions but also NO_X and PM as well as CO, CO_2 and VOC (volatile organic compounds) emissions. Additionally, it reduces the fuel consumption which is a positive effect in a world with limited resources.

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