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Health costs and economic impact of wind assisted ship propulsion

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Highlights:

- Wind assisted ship propulsion
- Assessment of heath externalities of air pollution
- Application of the Economic Valuation of Air Pollution Model
- A case study on a compliance problem

Abstract

World seaborne transportation is crucial for world trade and global economic growth. Shipping has been increasing since 2009, including oil & gas, dry bulk and container freight, and is very likely to continue this trend in the near future. However, international shipping also produces 2.7% of the world's total CO2 emissions, and globally, air pollutants emitted from international shipping are increasing due to the rise in trade. It is a well-established fact that Greenhouse Gasses (GHGs) cause climate change and that air pollutants trigger a range of health issues for humans. To demonstrate the applicability of the proposed framework, this paper will focus on a general assessment of the health-related externality of air pollution emitted from wind-assisted hybrid ship propulsion within two different emission reduction scenarios. The paper will further analyse the emission impact from both individual scenarios. A Chemical Transport Model (CTM) is used to estimate the realistic concentration of relevant air pollutants, and the Economic Valuation of Air-pollution Model (EVA) is applied to assessing the health-related economic externalities of air pollution.

1 Introduction

World seaborne transportation is crucial for world trade and global economic growth. Shipping has been increasing since 2009 (Clarkson, 2016), including oil & gas, dry bulk and container freight, and is very likely to continue this trend in the near future.

However, international shipping also is the source of air pollutants such as NO_x, SO_2 and Particulate Matter (PM) (Eyring et al., 2010; Richter et al., 2004). Globally, air pollutants emitted from international shipping are increasing due to the rise in trade. Also in Europe, the shipping sector is a relevant contributor to ambient air pollution (Matthias et al., 2016, 2010). In contrast, anthropogenic land-based emissions of air pollutants have been considerably decreased in the past three decades (EMEP, 2015; Smith et al., 2011). It is a well-established fact that air pollutants trigger a range of health issues for humans (Brunekreef and Forsberg, 2005; Brunekreef and Holgate, 2002; Kampa and Castanas, 2008). In addition, coastal ecosystems and urban areas within close vicinity of shipping routes are particularly affected by shipping related air pollutants. Therefore, it is crucial and urgent to invest in low emission shipping in terms of both environmental and public health point of views.

Ezzati et al. (2002) showed that air pollution in the urban environment is estimated to cause 1.4% of all premature deaths and 0.5% of all disability-adjusted loss of life years. Additionally, the emission of PM is responsible for increased mortality and morbidity, causing 3% of adult deaths by cardiovascular and respiratory diseases. Approx. 5% of lung and trachea cancer is also attributed to PM air pollution (Cohen et al., 2004). In Denmark, atmospheric pollution causes approx. 3,500 premature deaths annually (Brandt et al., 2013a). International shipping is, furthermore, a major contributor to air pollution levels in Europe as a whole, causing approx. 50,000 premature deaths per year (Brandt et al., 2013b).

In the coastal regions of Europe, shipping has a relatively higher contribution to air pollution then on the European average, which is why the relative health benefits and subsequent reduction of external health costs by reducing ship emissions were expected to be considerable higher. One measure to reduce these emissions is using wind propulsion devices, such as sails, in addition to conventional propulsion by combustion engines and propeller (Lloyd's Register Marine, 2015; Mofor et al., 2015). This concept is denoted as hybrid wind-assisted propulsion (WASP).

Consequently, the EU, IMO (International Maritime Organization) and WHO (World Health Organization) have adopted directives and guidelines that set out air pollution limit values to minimise the impact on human health (EU 2000, 2008; IMO, 2005; WHO 2006a). Emission control areas (ECAs) came into force with MARPOL Annex VI, which set limits on the emissions of air pollutants such as sulphur oxides in sulphur emission control areas (SECAs). The Baltic Sea and North Sea are declared as SECAs. To comply with the ECA regulations of IMO, low sulphur fuels, emission abatement technologies and LNG as an alternative fuel have already been adopted by the shipping industry. Each option, however, is associated with different advantages and disadvantages.

Due to the stringent environmental regulations, relevant stakeholders of the seaborne transportation industry have started to consider other ways than the mentioned abatement systems and alternative fuels to comply with IMO regulations and become more environmentally friendly. One promising direction is to decrease the fuel consumption of ships by increasing energy efficiency. Additional alternative is to employing renewable energy means on board of ships using innovative technologies and best practice. Once fuel consumption is decreased, externalities and the negative consequences of air pollutants resulting from shipping are reduced.

Energy efficiency improvement has been a well-established area since the 1970s, while renewable or clean energy use on board ships is a relatively new and growing field. When it comes to renewable energy employment, there are mainly two options to consider: wind and solar energy. Commercially sized merchant vessels cannot solely be propelled by wind or solar power. However, these energy sources can contribute to overall energy efficiency through hybrid propulsion systems, combining renewables and traditional fuel.

It should be noted that vessels have, indeed, previously been propelled by wind energy for many centuries. Wind energy has in the recent years regained a new momentum and popularity. Compared to other renewable solutions, wind energy has the advantage of being always available in open sea (Talluri et al. 2016).

Several research projects have studied the potential of fuel savings through the use of wind energy on vessels (Lloyd's Marine Register, 2015; Mofor et al., 2015).

According to Smith et al. (2013), 10 to 50% fuel saving is achievable from wind energy despite the fact that there is a wide spectrum of barriers for the uptake of wind energy in the shipping industry (Rehmatulla et al. 2015). According to Talluri et al. (2016), the ability of the vertical axis wind turbine (VAWT) to adapt to any wind direction may be considered most advantageous when compared to all the other wind-assisted technologies for marine propulsion, and hence, makes it ideal for utilisation in locations with highly variable wind directions.

Impact studies on the use of wind-assisted propulsion systems on ships have until now mainly been limited to the assessment of air pollution and fuel savings. Limited studies have been undertaken on sail-assisted ships (Shukla and Kunal, 2009; Lambrecht et al., 1994) fitted with horizontal-axis wind turbines combined for marine propulsion (Bockmann and Steen, 2011) and (Talluri et al. 2016) or vertical axis wind turbines fitted on the deck of a ship in conjunction with conventional power supply.

The aim of this research, however, is to assess the health-related economic externalities of air pollution (ambient atmospheric concentration) resulting from use of hybrid wind-assisted ship propulsion by considering two different emission reduction scenarios. The model applied for this purpose is the Economic Valuation of Air pollution Model (EVA; Brandt et al., 2011; 2013a; b)).

The paper is structured as follows: chapter 2 presents the methodology chosen and applied (EVA model). This is followed by the case study in chapter 3. Chapter 4 discusses the results and the study is concluded in the last chapter.

2 Materials and Methods

2.1 The integrated health impact assessment model system, EVA model.

In recent years, extensive measures have been adopted by authorities to remove harmful compounds from fuel (e.g. lead, benzene and sulphur from petrol and diesel) as well as to reduce emissions of air pollutants (e.g. fine PM and NO_X) with significant positive impacts on air pollution levels from local sources.

However, remote emissions, such as NO_X, SO_2 and PM from sea transport and industry, can be transported in the atmosphere over long distances contributing to local air pollution. Additionally, harmful compounds, such as sulfuric acid, nitric acid and secondary PM, are formed by chemical reaction during the transport. Therefore, remote emission sources can have even greater impact on human health and the environment than local emissions.

This paper applies the EVA modelling system that offers a detailed analysis of health-related externality costs. In contrast to previous publications, the health assessment module is coupled with the chemistry transport model CMAQ (Community Multiscale Air Quality) (Byun and Schere, 2006). This setup has the advantage over other approaches by describing non-linear processes using a comprehensive and thoroughly tested chemical transport model for calculating how specific changes in emissions affect air pollution levels.

The EVA model allows us to study differentiated scenarios to estimate the external heath cost of emissions from specific sources or sectors (called SNAP categories) within specific geographic regions within a given year. Using the so called "tagging" method, all scenarios are calculated individually assuming non-linear atmospheric chemical transformations and feedback mechanisms (i.e. without adopting the linear extra-/interpolation of standard reductions as used by the RAINS-Regional Air Pollution Information and Simulation, GAINS-Greenhouse Gas and Air Pollution Interactions and Synergies system. Alcamo et al., 1990, Klassen et al., 2004.

This paper specifically applies the integrated EVA modelling system to calculate the health-related economic externalities of air pollution from shipping emissions. The concept of the EVA system (Brandt et al., 2013a; 2013b; Geels et al., 2015) is based on the impact pathway.

The EVA system includes 18 different health outcomes (both morbidity and mortality) with associated economic valuation (see Table 1) related to health impacts from $PM_{2.5}$, O_3, SO_2 and CO. The $PM_{2.5}$ consists of the primary particles (black carbon and mineral dust) as well as the secondary inorganic aerosols (SIA). Impacts from O_3 can be counted as both positive and negative since O_3 can both be produced and removed as a result of non-linear atmospheric chemistry due to NO_x and VOC chemistry. All exposure-response functions used in the system have been reviewed and documented in literature. See Brandt et al. (2013a) for a full description of the model system.

2.2 Wind propulsion devices and expected emission reductions

The use of wind propulsion devices as means to reduce fuel consumption and emissions of ships are in the focus of this publication. The word ‘sails’ will be partly used in the sections below, because it is more compact than ‘wind propulsion device’ and easier to read. However, it has to be emphasized that different types of wind propulsion devices have been developed in the past century, which partly differ considerably from the classical sails. Examples these wind propulsion devices are wing sails, Dyna Rigs (modern square rig), Flettner rotors, and kites. A detailed description on these and further devices is given in Lloyd’s Marine Register (2015), Mander (2017), Mofor et al. (2015), and Schwarz-Röhr et al. (2015).

In the paragraphs below, important aspects on wind propelled ships are summarized first. The summary shows why estimating reductions in fuel consumption and in emissions for a fleet of ships is not trivial. Then a brief literature overview on publicly available research on modern wind propulsion devices is presented. This section is finalized by a summary of published ranges of fuel reductions and emission. The number of peer-reviewed publication on technical aspects of wind assisted propulsion unfortunately is low. Therefore, several conference proceedings and reports are cited.

All types of wind propulsion devices have in common that they gain propulsion power for the vessel from the wind. But, they work differently well under different wind conditions, i.e. apparent wind speed and direction. ‘Apparent’ means relative to the ship at its current speed. Flettner rotors are most efficient when the apparent wind blows from 90° (0° would be oncoming wind), whereas most other devices are more efficient at angles above 90° (e.g. Smith et al., 2013; Traut et al., 2014). Most wind ship designs assume more than one sail rig or rotor is deployed on the ship. A group of sails has different propulsion characteristics than an individual device, i.e. three square rigs shade each other when the wind comes from 180° (behind) and become less effective. Superstructures on deck like the command bridge additionally impact the wind flow and propulsion characteristics.

The wind force acts via the wind propulsion device on the ship. It can split into two components: a forward force and a sideways force (with respect to the direction of movement of the ship). The latter induces a drift of the vessel to the side. The sideways drift should be minimized and forward motion maximized. The wind propulsion device is aligned in its optimal position with respect to the apparent wind to ensure this. Additionally, the ship’s hull has to be shaped in way that it (a) favors forward motion, (b) prohibits sideways motion, and (c) optimally converts sideways force into forward force (e.g. Smith et al., 2013). In contrast, the hull of a propeller-propelled ship has to be optimized for low water resistance. Flettner rotors induce low sideways forces, whereas most mast-based sail-like devices induce considerable sideways forces – variable, depending on the apparent wind. Therefore, the ship hull has to be optimized for the installed wind propulsion device if the optimal propulsion power should be gained from the wind.

Wind ships utilize the apparent wind and not the absolute wind. Most wind propulsion devices favor apparent wind directions between 90° and 180°. The faster a ship moves the more frequent wind directions from the front and the less frequent wind directions from the back become. Hence, WASP is less favorable for ships with a high target/design speed, i.e. 18 knots and above.

WASP ships needs to adjust their engine-based propulsion power to the current wind conditions, which can vary on short time scales. Cargo ships are commonly propelled by diesel-direct (engine directly drives the shaft at which the propeller is mounted) or by diesel-electric engines (engine generates electric energy which drives electric motors). Diesel-direct engines respond slowly to changes in rotation speed of the propeller. Additionally, the engines are optimized for a specific load range. If the engine load falls below the optimized range, the combustion conditions, i.e. temperature, are not optimal and emissions of some air pollutants scale non-linear with respect to the fuel consumption, i.e. NOx and VOCs. Diesel-electric drives are more flexible with this respect: instead of one large engine, two or more small engines generate the electric power. This power is buffered. If less power is needed, individual engines are shut down while some of the others still run on their optimal load. However, diesel-electric engines 'lose' energy because the electric power production has no efficiency of 100%. Additionally, a diesel-electric system is more maintenance intensive. Hence, diesel-direct are favoured when a cargo ship is planned to travel over long distances with full speed. Thus, emission reductions depend on the engine setup and they do not scale linearly with reduced engine power for propulsion and fuel consumption.

In summary, calculating emission reductions of WASP ships is not straightforward. First, one needs to consider not only the type of wind propulsion device but also the shape of the ship's hull. Second, the ship's route and target speed and the wind conditions govern how effective different types of wind propulsion devices are. Third, the reduction of fuel consumption and emissions does not linearly depend on the forward propulsion power gained by the wind. Instead, it needs to be calculated based on the engine setup. Finally, ocean currents and the sea state have a minor impact on power necessary for propelling a ship. Therefore, it is not trivial to derive emission reductions for a fleet of WASP vessels and it is questionable whether it is reasonable to calculate these reductions 'exactly'.

Several recent scientific studies deal with the forces generated by individual wind propulsion devices and by fully equipped WASP ships (Craft et al., 2014; Dadd et al., 2011; Fritz, 2013; Gilje, 2013; Li et al., 2015; Nakashima et al., 2011; Ouchi et al., 2013; Ren et al., 2012; Traut et al., 2014). Lift and drag forces of individual devices, which result in forward and sideways forces, and the forces' dependence on device alignment and wind conditions are considered in detail. Additionally, the efficiency of different devices is compared and design improvements are tested. Bockmann and Steen (2011) and partly Schwarz-Röhr et al. (2015) deal with the reduction of the power consumption by WASP technologies. However, estimations of the reduction of fuel consumption and emissions are rare and limited to non-peer reviewed literature (Clauss et al., 2007; Li and Lu-yu, 2010; Luyu et al., 2010; Pearson, 2014; Schwarz-Röhr et al., 2015; Smith et al., 2013). Published size ranges of fuel savings or emission reductions approximately are:

- Claus et al. (2007): 10% to 45% (depending on target speed)
- Pearson (2014): 25% at 8 knots
- Smith et al. (2013): 10% to 60%
- Schwarz-Röhr et al. (2015): 10% to 40%
- Luyu et al. (2010): 7%
- Li et al. (2010): 6%
- Lloyd's Register Marine (2015): 10% to 40%, event up to 50% in individual cases

A linear relation between fuel consumption and emissions of air pollutants is assumed here. Moreover, ship type, ship size, wind propulsion device, target speed, and the ship's route are not distinguished.

2.3 Case study: hybrid wind-assisted propulsion scenarios

The study cases are based on SAIL, an EU project aimed at developing innovative, effective, efficient and sustainable transnational sailing solutions using less, or even no fossil fuels. With volatile oil markets and the challenges of climate change and air pollution in mind, SAIL contributes to the European-wide transition to sustainable hybrid shipping.

In order to assess the positive impacts on human health by WASP shipping, two WASP scenarios were designed. They differ in regards to the type and size of the vessels equipped with sails. Fuel savings and emission reductions of 35% were assumed for both cases.

- SAIL1: all bulk carriers are equipped
- SAIL2: all transport vessels in a size range of 3,000 < GT < 10,000 are equipped

The reasons for focussing on bulk carriers and on small vessels are described in the following two paragraphs. The final paragraphs deals with the choice of 35% emission reduction.

Based on section 2.2, one can identify ship types, which are better suited for wind propulsion devices than others. Container vessels typically travel at high speeds between 16 and 24 knots. Ferries are subject to a very strict time schedules. Tankers are subject to stricter safety rules than other cargo ship types, which make the installation of permanent wind propulsion devices complicates. Therefore, these cargo ship types are not well suited for WASP devices. Bulk carries seems to be most suitable with respect to design speed (below 15 knots). Additionally, they often transport not high perishable cargo wherefore delays due to bad wind conditions are acceptable.

Cargo ships are expensive to build and have a life expectancy of 25 to 30 years. WASP ships are even more expensive than classical cargo ships (see section 3.4). Hence, retrofitting exiting vessels with wind propulsion devices would be an option to increase the number of sailing vessels faster and for lower expenses. However, the hull shape of these vessels is not optimized for wind propulsion. Therefore, new vessels are expected to utilize the wind more efficient for propulsion. Because of high prizes for new ships and a considerable risk that WASP ships do not work as expected, it can be expect that predominantly small WASP cargo ships will be build.

As described in section 2.2, the exact emission reductions of WASP ships are complex to calculate and depend on several uncertain factors, i.e. type of wind propulsion device, setup of these devices, wind conditions, design of the ship's hull, and engine setup. Additionally, route optimization with respect to current wind conditions would have been reasonable to proper calculate expected emission reductions. In the view of these uncertainties and, in the author's view, in a low gain in knowledge compared to a high programming and calculation effort, it was decided to choose an optimistic average value for the expected emission reduction based on the currently available literature. This is 35%. Because of the low impact on air quality presented in section 3, a sensitivity study for this parameter does not seem to be reasonable.

2.4 Model setup

2.4.1 Chemistry transport model

The chemistry transport simulations were performed by the Community Multiscale Air Quality (CMAQ) modeling system version 5.0.1, which is developed and maintained by the U.S. EPA (Byun and Schere, 2006). Gas phase chemistry was represented by the cb05tucl (Yarwood et al., 2005; Whitten et al., 2010; Tanaka et al., 2003) and aerosol chemistry by AERO5 base on ISORROPIA 1.7 (Nenes et al., 1998, 1999).

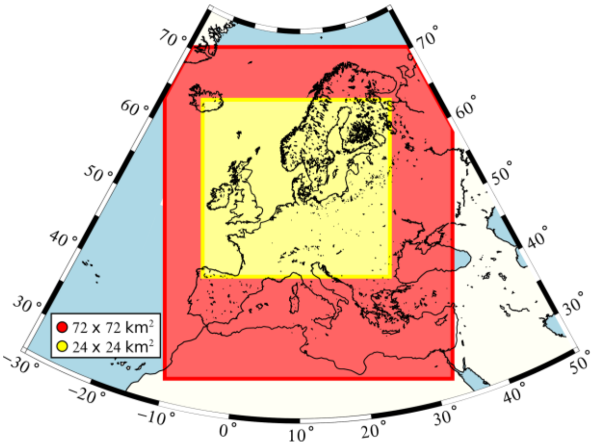

Figure 1: The study region and the extend of the two model domains for the hourly emission data and of the chemistry transport simulations. Results from the inner grid (yellow, 24 x 24 km^2) were provided for health impact estimations.

A coarse 72 x 72 km^2 grid and a one-way nested 24 x 24 km^2 grid cover the study regions (Fig. 1). The outer boundary conditions were taken from global TM5 model runs (Huijnen et al., 2010). The chemistry transport simulations were driven by meteorological data from a regional reanalysis of the coastDatII database (Geyer and Rockel, 2013), which was calculated with COSMO-CLM (Consortium for Small-scale Modeling – Climate Limited-area Modeling) (Rockel et al., 2008). The meteorological data were processed by a modified version of CMAQ's Meteorology-Chemistry Interface Processor (MCIP) (Otte and Pleim, 2010).

Simulations were performed for the year 2013.

2.4.2 Emissions

Air emissions from shipping in the reference case and in the two scenarios were calculated on the base of AIS data (Aulinger et al., 2015). Fuel savings of 35% per vessel equipped with a wind propulsion device were assumed, and the reduction in emissions for the whole fleet was calculated (Table 2). A linear relationship between power production, fuel consumption and emissions was assumed. The SO_2 emissions were calculated according to the SECA sulphur threshold of 1.0% (by mass), which was valid in 2013.

Land based emissions were generated by the emission model SMOKE for Europe (Bieser et al., 2011) and sea salt emissions were calculated within the chemistry transport model (Kelly et al., 2010) with modifications described in Neumann et al. (2016). All emissions have a spatial resolution of 72 x 72 km^2 and 24 x 24 km^2, respectively, and a temporal resolution of 1 h. The emission data fields serve as input for the subsequent chemistry and transport modelling.

It was assumed that small and medium-sized bulk carriers are the most appropriate vessel types for the application of wind-assisted propulsion systems. First of all, their travel speed is between 9 and 12 knots, which is favourable for wind propulsion. At a speed of 20 knots (container vessels), wind propulsion systems become less effective. Secondly, when it comes to other kinds of vessels, such as container vessels, the sail masts may interfere with gantry cranes. Thirdly, small vessels are expected to be among the first to be equipped with wind propulsion devices since the financial risk of adopting the technology is lower than with large vessels. However, the share of small bulk carries (3,000 < gross tonnage (GT) < 10,000) in the North Sea region is very low. Therefore, the positive effect on air quality from equipping small bulkers with wind propulsion devices is estimated to be negligible. Therefore, one 'all bulkers' (SAIL1) and one 'all small vessels' (SAIL2) scenarios were set up.

Both scenarios are compared against a reference case in which no vessels are equipped with wind propulsion. Although the scenarios are conceived for the medium long-term, the base year has been set at 2013 to make the scenarios comparable.

3 Results and Discussion

3.1 Resulting emissions

The calculated emissions of SO_2 and $PM_{2.5}$ in the reference case are shown on the left of Fig. 2. In the centre and right columns, the differences from the reference case to the SAIL1 and SAIL2 scenarios, respectively, is plotted.

Shipping routes are recognisable in the reference SO_2 emission map of Fig. 2. Thus, SO_2 emissions contribute considerably to total SO_2 emissions in this region. In the SAIL1 scenario, emission reductions mainly impact the English Channel and around Denmark. In the SAIL2 scenario in contrast, emission reductions are more spread out.

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 and NO_x in the atmosphere. The atmospheric concentrations of SO_2 and $PM_{2.5}$ predicted by CMAQ are provided as Fig. 3.

The total sulfur emissions were reduced by nearly 4% in the SAIL1 case (Table 2). In contrast, 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) yielded a 90% reduction of sulfur emissions. Thus, with respect to sulfur, the SECAs most probably have a far higher impact on external health costs than the SAIL scenarios could offer.

However, Wind-Assisted Shipping not only reduces SO_2 emissions but also NO_x and PM as well as CO, CO_2 and VOC (volatile organic compounds) emissions. Additionally, it reduces fuel consumption. While NO_x emissions will be limited from 2021 for new build ships, VOCs, CO, and CO2 emissions are not expected to be target of legislative thresholds within the next years. In contrast to the SECAs, the NECAs restrict NO_x emissions only for new build ships. Because of the life expectancy of 25 to 30 years for cargo ships, the North and Baltic Sea NECAs will not considerably impact NO_x emissions before 2030. However, equipping existing ships with WASP devices will yield NO_x emission reductions sooner.

As demonstrated by this, both SAIL scenarios offer benefits in terms of reducing SO_2 emission by around 20,000 metric tons per year. In this regard, wind-assisted propulsion constitutes a proactive technology in reducing air emissions to achieve the goals of the SECA and NECA areas.

3.2 Impact of air pollution on health

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

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

3.3 Total related health cost externalities

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

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

Tables 7 and 8 feature health externality costs for Denmark. Air pollution accounts for costs of about 6.8 million euro. The reduction of these costs in the SAIL scenarios is in the order of 0.01 million euro.

The shipping sector does not dominantly contribute to the emission of air pollutants, which is indicated by Figures 2 and 3. In the reference case, the simulation using the EVA model shows an external health cost for central Europe totalling 437,550 million euros. The maximum reduction in external health costs amounts to 150 million euros (SAIL1), which equals 0.03% of the total external health cost from air pollution. Whilst 150 mio euros are a large amount of money, a relative reduction by 0.03% is nearly negligible.

In contrast for Denmark, the maximum reduction in external health costs amounts 0.15% (Table 8). Although this figure is very low too, it is five times as high as the European average. Denmark is considerably more impacted by shipping related air pollution because a major shipping route passes through the Skagerrak and the Kattegat. This emphasizes that the health impacts are considerably higher in the vicinity of areas with high shipping activity, i.e. the English Channel, the Dutch coast, and the Kattegat. Therefore, it is important in future studies to focus on regions of particular shipping impact.

Moreover, it has to be noted that all air pollution sources are considered for the presented evaluation. Therefore, emission reduction measures in individual emission sectors, such as shipping, energy generation, or road transport, will have a low effect on the total external health costs.

3.4 Investment cost comparison

The health benefits from reduced air pollution by WASP shipping need to be compared to the additional investment costs for wind propulsion devices. Table 9 shows the calculation of the four analysed SAIL project scenarios provided by Bonduelle et al. (2015, p.53). The scenarios compare the impact on economic performance of a bulk vessel when either using fuel (IFO or MDO) or wind-assisted hybrid propulsion (delta wing sail). For the purpose of calculation it is assumed that fuel consumption for the vessel while sailing at a speed of 11 knots.

The four scenarios by Bonduelle et al. (2015) are described as follow:

1. Marine Diesel Oil scenario (MDO). In this scenario, all calculations are made assuming that MDO is used.
2. Marine Diesel Oil and wind-assisted scenario (MDO wind). In this scenario all calculations are made assuming that the vessel uses MDO but is also equipped with a delta wing sail
3. Intermediate Fuel Oil scenario (IFO). In this scenario, all calculations are made assuming that the vessel operates using IFO and is equipped with an open-loop seawater scrubber.
4. Intermediate Fuel Oil and wind-assisted scenario (IFO wind). In this scenario all calculations are made assuming that the vessel uses IFO and is equipped with an open-loop seawater scrubber and a delta wing sail.

The investment costs for a WASP approximately amount €1 million: from €5.8 mio to €6.8 mio in the MDO case and from €5.9 mio to €6.9 mio in the IFO case. Thus, the health benefits of equipping all North and Baltic Sea bulk carriers with WASP refinances WASP devices on approximately 116 (SAIL2) to 154 (SAIL1) of these bulk carriers. In comparison, total 194 small bulk carriers (3,000 < GT < 10,000) were considered to be equipped with WASP devices in the SAIL1 and SAIL2 cases. However, the payback periods do not differ between the non-WASP and WASP case for each fuel type. For MDO the payback period of the investment even decreases by more than one year. Calculated for the life expectancy of a cargo ship (25 to 30 years), one can even expect an increased revenue by installing WASP technology.

By comparing scenario MDO with scenario IFO wind (see Table 2), we can identify that hybrid solutions that run on fuel and wind reduces the payback time period by 6 years. The net present value of future savings due to the adoption of wind-assisted technology in the IFO wind scenario is approx. €3 million more than the MDO scenario.

4 Conclusions

Wind-Assisted Shipping (WAS) solutions will, according to this study, enhance the shipping industry's compliance with the current SO_x, NO_x and PM Emission Control Areas (ECAs) in the Baltic, North and North American Seas. Although solely WAS will not make ECAs obsolete, it is a valuable measure to reduce not only regulated air pollutants, i.e. sulfur and NO_x, but also currently unregulated pollutants such as VOCs.

In central Europe, the contribution of air pollution emissions from shipping is not dominant. The external health cost for central Europe totalling 437,550 mio euros were reduced by up to 150 mio euros (0.03%, SAIL1). In Denmark, the relative reduction of external health costs was five times higher (0.15%). Thus, regions in the vicinity of major shipping routes are stronger economically impacted by the shipping sector and will benefit more from WAS.

It would therefore be advisable to offer incentives for ship-owners to use WAS technology similar to those offered by the incentive scheme for the Clean Shipping Index. This would allow the ship-owners to gain some direct benefits by using the system, such as reduced or discounted port fees and perhaps lower insurance premiums and lower interest rates, etc. However, the potential cost of installing wind propulsion on all vessels, according the two scenario (SAIL 1 and SAIL 2), could limit the health cost saving due to the high cost of WAS installation. Thus, the monetary health benefits do not outweigh the initial investment costs. However, the investment costs for additional WASP devices will be paid back during the operational time of a bulk carry as presented in section 3.4. Moreover, the comparison indicates that investors might expect an increased revenue over the lifetime of a WASP ship even without governmental incentives.

It can be concluded that looking into health costs and economic impact of wind assisted ship propulsion is the first novelty of the research. Furthermore, the know-how gained about the health cost externalities of Wind-Assisted shipping through this project can also be used to help relevant stakeholders to develop their regional and national policies and roadmaps.

5 Future Research

Recent sustainability developments in the shipping industry in relation to climate change, in particular with the coming into force of MARPOL Annex VI, has boosted research development to improve the different clean-tech and make wind-assisted propulsion a reality.

Expanding on these research directions, we believe that future research within wind-assisted technology (WAS) should mainly focus on identifying the capital cost of different scenarios offering comparative analyses of different abatement solutions and alternative fuels in addition to contextual and organisational drivers and barriers related to WAS. The following sections further introduce these research directions.

Moreover, more detailed emission saving estimations based on route optimization and multi-year evaluations are necessary. These are important to estimate the long term emission reductions by WASP ships because seasonal and short term meteorological effects might have a high impact power savings by wind propulsion. In addition, coastal regions with high shipping activity should be considered in detail. Particularly in these regions, the health benefits by WASP technologies are expected to be higher.

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Table 1: Health outcomes, exposure-response functions and economic valuation in the EVA model system.

Health effects (species)	Exposure-response coefficient	Valuation, Euros (2006 prizes)
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)	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 admissions		
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
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

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).

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

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

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

Table 5: The total external costs in millions 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	18.770	-0.010	-0.010
Restricted Activity Days	47.460	-0.020	-0.020
Respiratory Hospital Admissions	0.160	0.000	0.000
Cerebrovascular Hospital Admissions	0.457	0.000	0.000
Congestive Heart Failure	0.458	0.000	0.000
Lung Cancer	1.148	-0.001	-0.001
Bronchodilator Use	1.838	-0.001	0.000
Cough	6.367	-0.002	-0.002
Lower Respiratory Symptoms	0.638	0.000	0.000
Acute premature deaths	47.180	-0.010	-0.010
Chronic YOLL*	311.900	-0.100	-0.100
Infant mortality	1.260	-0.001	-0.001

Table 6: The total external costs in millions of euros for 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	0.074	0.000	0.000
SO_2	12.335	-0.009	-0.008
SO_4^{2-}	75.750	-0.062	-0.059
Total sulphur	88.084	-0.072	-0.067
O_3	34.857	0.003	0.003
NO_3^-	73.841	-0.047	-0.031
Total nitrogen	108.697	-0.044	-0.028
$PM_{2.5}$	240.769	-0.038	-0.021
Total	438.000	-0.154	-0.116

Table 7: The total external health costs in millions 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
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 millions 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 [mio EUR]**		
	Reference	**SAIL1 - Ref**	**SAIL2 - Ref**
CO	**1.254**	**0.000**	**0.000**
SO_2	198.589	-0.294	-0.287
SO_4	1 186.150	-1.737	-1.623
Total Sulphur	**1 384.739**	**-2.031**	**-1.910**
O_3	504.944	-0.219	0.036
NO_3	1 392.027	-2.599	-2.080
Total Nitrogen	**1 896.972**	**-2.819**	**-2.044**
$PM_{2.5}$	3 519.487	-5.573	-5.075
Total	**6 801.198**	**-10.423**	**-9.029**

Table 9: Investment costs and payback period of a bulk carrier (11 knots). Four design cases are considered: two conventional bulkers using MDO or IFO fuel and two wind-assisted propelled bulkers (delta sail) using MDO or IFO. The data are no own work but taken from Bonduelle et al. (2015).

	Unit	**MDO**	**MDO wind**	**IFO**	**IFO Wind**
Total investment	Million €	5.79	6.76	5.95	6.92
Payback period	Years	16.71	15.32	9.46	10.49
ROI	%	9	10	14	13
Average freight earned	€/ton of cargo	103	103	103	103

Source: Bonduelle et al., Roadmap for Sail Transport, Interreg IVB-SAIL Project, November 2015.

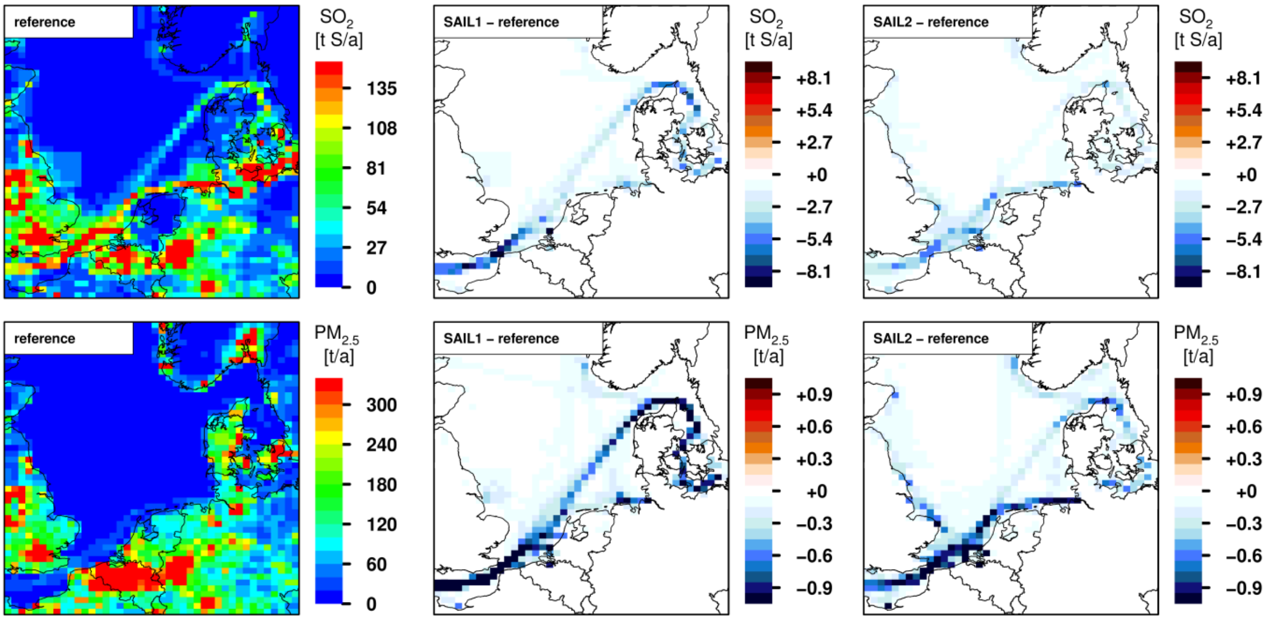

Figure 2: Emissions of SO_2 in t S/a (top) and of $PM_{2.5}$ in t/a (bottom) for the year 2013. The unit t S/a means "tonnes sulphur per year" which is the half of t SO_2/a. left: total emissions in the reference case; centre: difference between SAIL1 scenario and reference case; right: difference between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

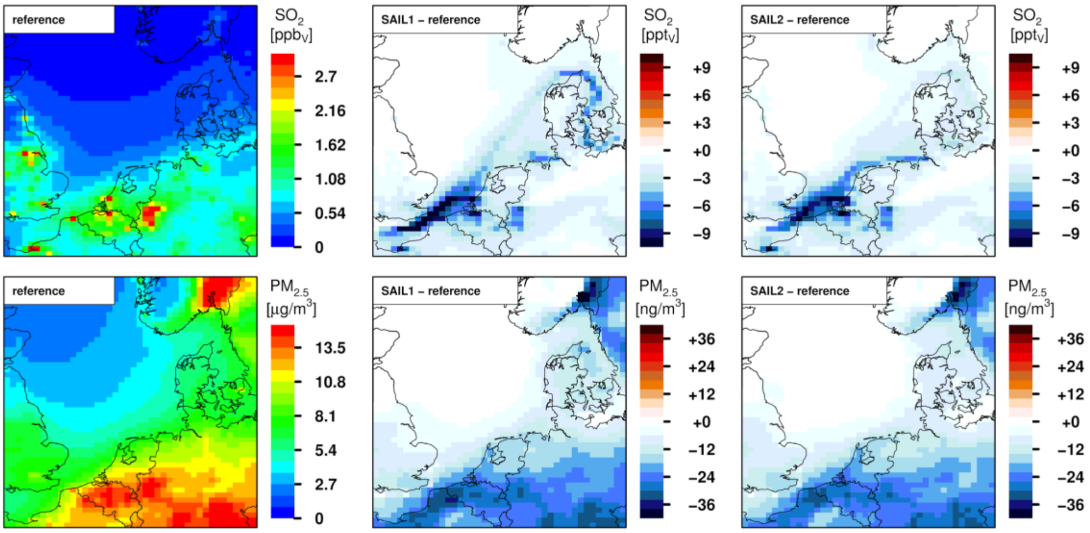

Figure 3. Atmospheric concentrations of SO_2 in ppb(V) and ppt(V) and of $PM_{2.5}$ in µg/m^3 and ng/m^3 for the year 2013. left: average concentration in the reference case; centre: difference between SAIL1 scenario and reference case; right: difference between SAIL2 scenario and reference case.