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Estimating the health and economic burden of shipping related air pollution in the Iberian Peninsula

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ABSTRACT

Air pollution is the leading cause of the global burden of disease from the environment, entailing substantial economic consequences. International shipping is a significant source of NO_x, SO_2, CO and PM, which can cause known negative health impacts. Thus, this study aimed to estimate the health impacts and the associated external costs of ship-related air pollution in the Iberian Peninsula for 2015. Moreover, the impact of CAP2020 regulations on 2015 emissions was studied. Log-linear functions based on WHO-HRAPIE relative risks for $PM_{2.5}$ and NO_2 all-cause mortality and morbidity health end-points, and integrated exposure–response functions for $PM_{2.5}$ cause-specific mortality, were used to calculate the excess burden of disease. The number of deaths and years of life lost (YLL) due to NO_2 ship-related emissions was similar to those of $PM_{2.5}$ ship-related emissions. Estimated all-cause premature deaths attributable to $PM_{2.5}$ ship-related emissions represented an average increase of 7.7% for the Iberian Peninsula when compared to the scenario without shipping contribution. Costs of around 9 100 million € yr-1 (for value of statistical life approach - VSL) and 1 825 million € yr^{-1} (for value of life year approach - VOLY) were estimated for PM and NO_2 all-cause burden of disease. For $PM_{2.5}$ cause-specific mortality, a cost of around 3 475 million € yr^{-1} (for VSL approach) and 851 million € yr^{-1} (for VOLY approach) were estimated. Costs due to PM and NO_2 all-cause burden represented around 0.72% and 0.15% of the Iberian Peninsula gross domestic product in 2015, respectively for VSL and VOLY approaches. For $PM_{2.5}$ cause-specific mortality, costs represented around 0.28% and 0.06%, respectively, for VSL and VOLY approaches. If CAP2020 regulations had been applied in 2015, around 50% and 30% respectively of $PM_{2.5}$ and NO_2 ship-related mortality would been avoided. These results show that air pollution from ships has a considerable impact on health and associated costs affecting the Iberian Peninsula.

1. Introduction

Air pollution is the leading cause of the global burden of disease (BOD) from the environment, causing substantial economic consequences. Around 91% of the world's population lives in places where air quality levels exceed WHO guidelines (Brandt et al., 2013; WHO, 2021, 2016a; WHO Regional Office for Europe and OECD, 2015). According to WHO, air pollution accounted for around 7 million deaths globally per year, of which about 500 000 for European Region (WHO, 2021). Ambient particulate matter (PM) is the major contributor to ambient air pollution and responsible for the biggest quantifiable share of the BOD from air pollution (WHO Regional Office for Europe and OECD, 2015). Epidemiological studies have established associations between the reduction of life expectancy, premature mortality and morbidity from cardiovascular, cerebrovascular and respiratory diseases caused by the long-term exposure to $PM_{2.5}$ (Apte et al., 2015; Arden et al., 2011, 2009;

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Faridi et al., 2018; Ginsberg et al., 2016; Burnett et al., 2014). Health risks associated with PM (PM_{10} and $PM_{2.5}$) are especially well documented, being the most widely used indicator to estimate health impacts from exposure to ambient air pollution (Apte et al., 2015; Corbett et al., 2007; Sofiev et al., 2018; WHO, 2021). In the Global Burden of Disease study for 2015, long-term exposure to ambient $PM_{2.5}$ was pointed out as the fifth largest risk factor for overall mortality, representing 7.6% of total global deaths and 4.2% of overall disability adjusted life years (DALYs) (Cohen et al., 2017). In the last years, several new health impact assessments of air pollution for many sectors and subject areas have been conducted to inform policymakers, public health officials and scientists, as a result of a major review on the effects of air pollution on health made by WHO in 2013 (DEFRA, 2017; WHO, 2013, 2005). International shipping is a significant source of air pollutants, mainly NO_x, SO_2 and PM (Bencs et al., 2020; Monteiro et al., 2018; Russo et al., 2018), that cause negative health impacts (Brandt et al., 2013; Corbett et al., 2007; Jonson et al., 2015; Sofiev et al., 2018; Viana et al., 2020). Shipping remains one of the less regulated anthropogenic emissions sources (Antturi et al., 2016; EEA, 2013; Nunes et al., 2017). Studies on shipping emissions impact on human health have been increasing in recent years. Along the years, the studies have been using different better developed methods, as well as detail on input data for the shipping activity, thus improving the estimations of the health impacts. Consequently, comparisons between recent and older studies should be made carefully and sometimes results are even not comparable. As far as known, the first attempt to study the health effects of shipping emissions was made by Corbett et al. (2007). The authors estimated global and regional mortalities (applying cardiopulmonary and lung cancer concentration-risk functions) due to the increase of ambient PM caused by shipping emissions. This study indicated that shipping emissions were responsible for around 60 000 premature deaths annually, mainly in the coastal areas of Europe, East Asia and South Asia. From 2013, researchers' interest in the study of the health burden from shipping emissions and associated costs has been intensified. Brandt et al. (2013) studied the health impacts of international ship traffic in Europe and their external costs. The authors estimated that 7% and 12% of the total relative external costs in Europe due to air pollution in 2000 and 2020, respectively, were related to international ship traffic. Moreover, a decrease of 36% on the total relative external costs between 2000 and 2020 resulting from regulatory efforts for reducing ship-related sulphur emissions was estimated for the Baltic and North Seas. Jonson et al. (2015) assessed the effects of ship emissions in and around the Baltic Sea and the North Sea using EMEP air pollution model. To quantify the impact on human health, the authors calculated the number of years of life lost (YLL) with and without ship emissions. The results showed an additional 0.1 to 0.2 years of life lost per person in areas close to the major ship tracks. Antturi et al. (2016) provided a cost-benefit analysis of the sulphur reduction policy in the Baltic Sea SECA. Authors calculated the costs of the abatement of emissions based on the ship-owners choice between the use of fuel with low content of sulphur and a scrubber. They modelled the profits considering the formation and dispersion of the emissions (with SILAM model), and the positive health impacts resulting from the decrease of ambient $PM_{2.5}$ concentrations. The results indicated for the Baltic Sea a non-cost effective sulphur regulation with an estimated annual cost of 465 M€ and a benefit of 2 200 saved Disability Adjusted Life-Years (DALYs) or monetised 105 M€. Liu et al. (2016) studied the health and climate impacts of ocean-going ships in East Asia and reported that this region contributed by 16% for the global CO_2 in 2013. The authors highlighted that the contribution from 2002 to 2005 was only 4–7%. Moreover, the authors examined the impact of ship emission-derived $PM_{2.5}$ and ozone on human health via respiratory and cardiovascular diseases, as well as lung cancer, estimating 14 500 to 37 500 premature deaths per year. Additionally, Sofiev et al. (2018) estimated public health and climate impacts of low-sulphur fuels in global shipping for 2020 and reported reductions of 34% and 54% in mortality and morbidity, respectively. More recently, Tang et al. (2020) studied the impact of shipping emissions on air quality and human health in the Gothenburg area. Authors estimated a mean loss of the life expectancy of 0.015 years per person associated with shipping related $PM_{2.5}$ exposure and 2.6 premature deaths/year associated with shipping related NO_2 exposure. Viana et al. (2020) estimated health impacts from maritime transport in 8 coastal cities of the Mediterranean region and the health benefits from cleaner fuels (2020 global sulphur cap, from now one referred as CAP2020). As main results, authors estimated a total of 430 (95% CI: 220–650) premature deaths/year of which Barcelona and Athens registered more than 100 and a reduction of 15% in the number of $PM_{2.5}$-attributable premature deaths resulting of the CAP2020.

The impacts on air quality of ship emissions have been studied for Europe, including the Iberian Peninsula domain (Bencs et al., 2020; EEA, 2013; Fabregat et al., 2021; Monteiro et al., 2018; Russo et al., 2018). Health impacts studies from exposure to air pollution have been performed for cities in the Iberian Peninsula (Boldo et al., 2011; Izquierdo et al., 2020). Nevertheless, it is not possible to draw conclusions regarding shipping emissions impacts. Studies on the impact of shipping emissions on human health considering the Iberian Peninsula domain are still scarce (Corbett et al., 2007; Sofiev et al., 2018; Viana et al., 2020), and none has been performed exclusively for this region. As the Iberian Peninsula is the most western point of the European continent and the only natural opening by sea between the Mediterranean Sea and the Atlantic ocean, a study specifically for this region fills an existent gap in the literature. Moreover, to support regulatory actions, it is necessary understanding the magnitude of different health end-points (morbidity and mortality), as well as, estimating the related external costs. Moreover, quantifying the impacts of the most recent regulation on sulphur fuel content, established by MARPOL Annex VI (CAP2020) gives perspective on what could have happened if it was applied sooner. Thus, this study aims to assess the contribution of the international ship traffic to health-related impacts and associated costs in the Iberian Peninsula during 2015, using two key indicators: i) particulate matter ($PM_{2.5}$ and PM_{10}), because it is linked with many adverse health outcomes, from acute respiratory symptoms to premature deaths; and ii) NO_2 one of the more emitted air pollutants from ships, with enough available data to enable a reliable quantification of the health effects. Moreover, the impact of the application of the CAP2020 in 2015 shipping emission data was quantified.

2. Methodology

2.1. PM and NO_2 concentrations

To estimate the health and economic burden of shipping emissions in the Iberian Peninsula, modelled air pollutant annual average concentrations considering and not considering shipping emissions from a previous study performed by Nunes et al. (2020) were used. This study used shipping emissions for the Iberian Peninsula area for 2015 obtained with the Ship Traffic Emission Assessment Model (STEAM3), that is considered one of the most reliable models to estimate shipping emissions (Alver et al., 2018; Milazzo et al., 2017; Nunes et al., 2017) and the EMEP/MSC-W chemistry transport model to evaluate the contributions of ship emissions for the air quality (Norwegian Meteorological Institute, 2017). To evaluate the potential impact of implementing the CAP2020 regulation a simulation using the shipping emissions data from 2015 considering the CAP2020 regulations was performed. For the 2015 shipping emissions data, it was considered a global sulphur content of 3.5%. In addition, it was considered a 0.1% maximum sulphur content for fuels used by ships that berth for more than two hours in European Union ports and a maximum of 1.5% for passenger ships operating to or from any European Union port. For the implementation of the CAP2020 regulation the global sulphur content was changed to 0.5% outside the European Union port areas and all the other regulations mentioned above were kept. Modelled concentrations in each grid cell were used to obtain the annual average of $PM_{2.5}$, PM_{10} and NO_2 concentrations. More detailed information about the model and scenarios can be found in Simpson et al. (2012) and Nunes et al. (2020). The quality assurance of this model to estimate concentrations due to shipping emissions was reported in previous studies (Jonson et al., 2015; Norwegian Meteorological Institute, 2018).

2.2. Health impact assessment

The shipping related health impacts were calculated based on three scenarios: (i) a shipping scenario (S-SCN) considering other anthropogenic emissions and shipping emissions, (ii) a shipping scenario considering other anthropogenic emissions and the shipping emissions with the CAP2020 regulations (CAP2020-SCN); and (iii) a baseline scenario (B-SCN) not considering shipping emissions. Detailed information on S-SCN and B-SCN scenarios can be found in Nunes et al. (2020). The influence of the shipping emissions on health was calculated comparing the differences between the shipping scenarios (S-SCN and CAP2020-SCN) and the baseline scenario.

2.2.1. Health end-points associated with long-term exposure

To assess the excess health burden (respiratory disease mortality and morbidity) attributable to long-term exposure to particulate matter ($PM_{2.5}$ and PM_{10}) and NO_2 from shipping, log-linear functions based on WHO-HRAPIE relative risks were used. For each health end-point, derived from available epidemiological studies, relative risks (RR) were estimated as recommended by WHO (2019) and other authors (Anenberg et al., 2016; Cárdaba Arranz et al., 2014; Li et al., 2016; Natalie et al., 2017; Yorifuji et al., 2015). Furthermore, as described by Apte et al. (2015; Song et al. (2017); Xie et al. (2016) and WHO (2019), to assess the cause-specific mortality attributable to $PM_{2.5}$, the following concepts were used: i) exposure for five end-points in adults (stroke, ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD) and lung cancer (LC)) considering twelve age classes (particularly for IHD and stroke) and children under five years old (acute respiratory lung infection (ALRI); and ii) integrated exposure–response functions (IERs) developed by Burnett et al. (2014) building on Arden et al. (2011, 2009). The IERs established by Burnett et al. (2014) have been developed for the Global Burden of Disease (GBD) studies based on cohort studies in the US, Canada, and western Europe, thus including the Iberian Peninsula (Cohen et al., 2017). These IERs were chosen for this study because, as far as known and to date, they represent the best understanding in terms of the epidemiological evidence on the mortality impacts of $PM_{2.5}$, being enhanced with regular GBD updates (Ostro et al., 2018).

Relative risks (RR) for log-linear functions to estimate morbidity as well as PM_{10} post-neonatal mortality, and $PM_{2.5}$ and NO_2 all-cause mortality, and IERs to estimate $PM_{2.5}$ cause-specific mortality, were assessed using the following expressions, respectively:

$$RR_{log-linear} = e^{\beta(C-C_0)} \quad (1)$$

$$RR_{IER} = 1 + \alpha\{1 - exp[-\gamma(C - C_0)^{\delta}]\} \quad (2)$$

where C is the annual $PM_{2.5}$, PM_{10} or NO_2 concentrations and C_0 is the endpoint-specific theoretical minimum-risk concentration, i.e. the concentration below which there are no additional health risks. No theoretical minimum-risk concentration was considered for $PM_{2.5}$ all-cause mortality and PM_{10} post-neonatal mortality. A theoretical minimum-risk concentration of 20 $\mu g\ m^{-3}$ was assumed for NO_2 all-cause mortality estimations of the $RR_{log-linear}$ (Héroux et al., 2015; Holland, 2014a). For the estimation of RR_{IER} a value of 5.8 $\mu g\ m^{-3}$ was considered according to Burnett et al. (2014), Héroux et al. (2015), Krewski et al. (2009) and Lim et al. (2012). All the theoretical minimum-risk concentrations were used to consider the most restrictive values. β-coefficient relates the change in the RR to a unit change in air pollutant concentration. α, γ, δ are estimated parameters that determine the shape of the IERs as the result of a stochastic fitting process. For very large concentrations RR_{IER} approximates $1 + \alpha$. δ is a power of $PM_{2.5}$ to predict risk over a very large range of concentrations. RR_{IER} $(C_0 + 1)$ approximates $1 + \alpha\gamma$. $\gamma = [RR_{IER}(C_0 + 1) - 1]/[RR_{IER}(\infty) - 1]$ is a ratio of the RR at low-to-high exposures. For each endpoint, Burnett et al. (2014) provided a distribution of 1000 point estimates of C_0, α, γ, and δ. To calculate the mean RR for the IER functions, a lookup table was used for each health end-point containing the mean RR sampling distribution for $PM_{2.5}$ concentrations in the range of 0–410 $\mu g\ m^{-3}$ with 0.1 $\mu g\ m^{-3}$ increment steps (Apte et al., 2015).

After RR calculations, the attributable fractions (AF) were calculated following the attributable risk or excess risk expression as:

$$AF = (RR - 1)/RR \quad (3)$$

To estimate the excess burden (mortality and morbidity) of disease (EBD), the increment in the number of deaths and additional cases due to shipping particulate air pollution over 2015 was estimated, using the following equation:

$$\Delta EBDs = BI \times AF \times Pop \quad (4)$$

where *BI* is the baseline incidence of the selected health end-point for a given population and *Pop* is the population within the age group of interest.

Also, the life expectancy reduction i.e., the increment of YLL was determined. For all-cause and post-neonatal mortality, YLL were calculated using the WHO life-tables methodology, where a hypothetical life expectancy is compared with the life expectancy affected by air pollution. Then the number of YLL was assumed to equal to life expectancy at the age of death (Faridi et al., 2018; WHO, 2019b). For the cause-specific mortality, YLL for each health end-point and age range of interest were calculated with the same expression of Eq. (4), in which *BI* was replaced by the baseline ratios of the YLL from the Global Burden of Disease Study (GBD) results tool (IHME, 2019; Lelieveld et al., 2018).

2.2.2. Population data and baseline incidences

Population data by age (one year intervals) for Portugal and Spain at local administrative level (LAU) 2 level (municipality level to Spain and civil parish to Portugal) were obtained from the Eurostat 2011 Census database hub (ESS, 2018).

Mortality and morbidity health end-points were chosen from the scientific evidence available in recent studies of impact assessments. Therefore, all-cause (excluding accidental causes), post-neonatal and cause-specific mortality (IHD, stroke, COPD, LC and ALRI) were included. Morbidity end-points included in the present study were mainly chosen following the Health risks of air pollution in Europe (HRAPIE) project recommendations for European Air Pollution (Holland, 2014a, 2014b) comprising hospital admissions for cardiovascular and respiratory diseases, bronchitis, asthma and days with restricted activities.

All-cause mortality rates were calculated for the different age groups from the WHO life-tables. The post-neonatal mortality baseline rates were obtained from the National Statistical Systems of Portugal and Spain (Instituto Nacional de Estadística INE, 2018, Instituto Nacional de Estatística INE, 2018). Regarding the cause-specific mortality, BI (deaths and YLL) were obtained from the Institute for Health Metrics and Evaluation (IHME) Global Burden of Disease Study (GBD) results tool. Data on the prevalence of bronchitis in children, incidences of asthma symptoms in asthmatic children, chronic bronchitis in adults and restricted activity days (RADs) were taken from the report of HRAPIE, based on United Nations mid estimates for the population (Holland, 2014a). It is important to emphasise that the work loss days (WLDs), asthma symptom days and the days spent in hospital from respiratory and circulatory episodes were subtracted from RADs. Data on hospital admissions for respiratory and cardiovascular causes and work lost days were taken or derived from the OECD Status database (OECD, 2018). The work lost days were calculated, combining data on absenteeism from work due to illness and the employment rates of each country. Health input metrics used to assess health impacts from long-term exposure to shipping related $PM_{2.5}$, PM_{10} and NO_2 concentrations are listed in Table S1 (Supplementary Material). It is important to emphasise that health end-points for several subgroups of the population were considered to include the different age groups' specificities. Adult populations (≥30 yr) were considered for all-cause mortality estimations. Also, mortality was calculated for children (post-neonatal mortality and ALRI mortality) and the elderly (IHD and stroke), who are considered vulnerable subgroups with a higher risk of presenting adverse health impacts when exposed to atmospheric contaminants. For morbidity, specific health endpoints for children and people in working age were also considered.

2.3. Assessment of external socio-economic costs of the burden of disease

External socio-economic costs of the burden of disease were calculated with the results of the estimated health impacts for the two scenarios: (i) a shipping scenario (S-SCN) considering other anthropogenic emissions and shipping emissions, and (ii) a baseline scenario (B-SCN) not considering shipping emissions.

Unit health costs (cost per case of illness) were used to estimate the economic value of the burden of disease (labour productivity loss cost, medical and healthcare-related expenses and welfare losses attributed to pain and suffering).

The exposure cost for a particular health end-point was calculated as the product of the exposure–response function (ERF) and its unit health cost value according to Eq. (5) (SCU, 2018).

$$Exposurecost = (ERF) \times (Costpercaseofillnessordeath) \quad (5)$$

Deaths were valued using the value of statistical life (VSL) (how much society is willing to pay to avoid an anonymous death) and YLL were valued using the value of a life year (VOLY). Lung cancer deaths were valued exclusively using the VSL and treatment costs while alive were included. ALRI deaths were also valued using VSL multiplied by a child mortality premium, as parents tend to value the life of a child more than that of an adult (OECD, 2011).

The specific VSL for Portugal and Spain in 2015 were taken from the Health Economic Assessment Tools (HEAT), following the benefit transfer approach that takes into account differences in income levels between two places using the formula recommended in OECD (2014) based on an extensive *meta*-study performed by OECD (2012). This estimation involves two significant adjustments: i) differences in per capita Gross Domestic Product (GDP) and income elasticity to derive the value for any country for 2005; and ii) income growth and price inflation to derive values for that country for years following 2005 according to Eq. (6):

$$VSLC2015 = VSLEU2005 \times \left(\frac{YC}{YEU}\right)^{\beta} \times (1 + \Delta P + \Delta Y)^{\beta} \quad (6)$$

where $VSLEU2005$is the average VSL of the EU27 (European Union considering 27 member states) (USD 3.6 million in 2005), YC is the GDP per capita at the purchasing power parity (PPP) in 2015, YEU is the average GDP per capita of the EU27 at PPP in 2015, β is the income elasticity of VSL which measures the percentage increase in VSL for a percentage increase in income (the income elasticity of 0.8 was used as established by the OECD), PPP is the purchasing power parity adjusted exchange rate in 2005, ΔP is the percentage increase in consumer price from the year 2005 to 2015 (measured by consumer price index (CPI) that reflects the inflation or changes in the cost to the average consumer for acquiring a basket of goods and services), and ΔY is the percentage change in real GDP per capita growth from the reference year to 2015 (which was derived from real GDP per capita annual growth).

The VOLY for economic valuation of air pollution mortality in Europe was adopted according to the research made by Desaigues et al. (2011) that surveyed in 9 European countries. The unit values for morbidity health end-points were adopted according to the Cost-benefit Analysis of Final Policy Scenarios for the EU Clean Air Package (Holland, 2014b). Lung cancer deaths were valued exclusively using the VSL, and the treatment costs during life (cancer morbidity) were included according to Nedellec and Rabl (2016). ALRI deaths were also valued exclusively using the VSL but multiplied by a child mortality premium adopted according to the Public health impacts in Urban environments of Greenhouse Gas Emissions reduction strategies Project (PURGE, 2014). For total costs estimation, HRAPIE project recommendations proposed by WHO regarding which health end-points can be added were followed to minimize the double count of costs (Héroux et al., 2015; Holland, 2014a). Following these recommendations and considering that baseline incidences rates for mortality and morbidity are diagnostically independent, all the morbidity health-endpoints adopted in this study could be added to the PM and NO_2 all-cause mortality estimations. According to that, a total cost estimation was established considering the $PM_{2.5}$ cause-specific mortality, PM_{10} post-neonatal mortality, NO_2 all-cause mortality and all morbidity health-endpoints.

All the values were also adjusted according to Eq. (6). Values and their sources for Portugal and Spain can be found in Table S2 (Supplementary Material).

3. Results

3.1. Mortality and related economic burden

Table 1 shows the mortality as the number of deaths and YLL (when applicable). The mortality related costs are presented in Table 2.

Concerning the effects of the long-term exposure to $PM_{2.5}$ on all-cause mortality, it was estimated that shipping emissions caused 1 944 deaths (95% CI 1 294–2 528) corresponding to 4 637 million € (95% CI 3 085–6 030), and 14 460 (95% CI 8 620–18 808) YLL corresponding to 553 (95% CI 368–720) million € for the Iberian Peninsula. Results were based on the sum of the values obtained for Portugal and Spain presented in Table 1. Estimated all-cause premature deaths attributable to $PM_{2.5}$ ship-related emissions represented an increase of 6.9% for Portugal and 8.5% for Spain (7.7% for the Iberian Peninsula) when compared to the scenario without the contribution of shipping emissions. Concerning YLL, for Portugal, the increase was the same as the premature deaths, while in Spain the increment was 8.8%. As can be seen from Table 1, results for the health effects of the exposure to long-term NO_2 ship-related emissions were almost similar to $PM_{2.5}$. Overall, 1 536 (95% CI 1 907–2 132) deaths corresponding to 3 622 (95% CI 2 140–5 025) million € and 10 939 (95% CI 6 454–15 194) YLL corresponding to 415 (95% CI 245–577) million € due to all (natural) cause mortality attributable to long-term exposure to NO_2 ship-related emissions were estimated.

Considering the five health end-points (IHD, stroke, COPD, LC and ALRI), ship-related $PM_{2.5}$ emissions caused a total of 1 439 deaths corresponding to a cost of 3 477 million € and 22 038 YLL, corresponding to a value of 851 million € in the Iberian Peninsula for 2015. Relative contributions of COPD, LC, IHD and stroke to the total number of premature deaths and YLL can be found in Figure S1 (Supplementary Material). Among deaths attributable to $PM_{2.5}$ ship-related emissions, 96 and 656 were caused by IHD (accounting for 50% and 53% of all deaths), 63 and 209 by stroke (accounting for 33% and 17% of all deaths), 18 and 197 by COPD (accounting for 9 and 16% of all deaths), 16 and 184 by LC (accounting for 8 and 15% of all deaths) and less than 1 by ALRI (accounting for less than 1% of all deaths), for Portugal and Spain, respectively. Similarly, for both Portugal and Spain, the contribution of IHD to YLL was the highest, however, followed by LC, stroke, COPD and ALRI. Although the number of premature deaths as a result of LC was smaller than for stroke and COPD, for LC people died younger,

Table 1
Mortality health impacts as deaths and Years of Lost Life (YLL) due to ship-related air pollution for Portugal and Spain in 2015.

			Deaths (95% CI)		YLL (95% CI)	
Air Pollutant	Health end-points	Risk group	Portugal	Spain	Portugal	Spain
$PM_{2.5}$	All-cause Mortality	Adults (age ≥ 30 yr)	349 (233–454)	1595 (1061–2074)	2645 (1760–3439)	11,815 (7860–15369)
	Mortality, IHD	Adults (age ≥ 25 yr)	96	656	1517	10,517
	Mortality, Stroke	Adults (age ≥ 25 yr)	63	209	893	2878
	Mortality, COPD	Adults (age ≥ 25 yr)	18	197	186	1968
	Mortality, LC	Adults (age ≥ 25 yr)	16	184	336	3722
	Mortality, ALRI	Children (age ≤ 5 yr)	–	–	5	17
	Cause-specific Total	–	193	1246	2937	19,102
PM_{10}	Post-neonatal Mortality	1 month to 1 year	6 (3–10)	37 (20–62)	378 (196–624)	2446 (1273–4035)
NO_2	All-cause Mortality	Adults (age ≥ 30 yr)	336 (197–471)	1200 (710–1661)	2384 (1393–3345)	8555 (5061–11849)

Table 2
Mortality costs of shipping related air pollution for Portugal and Spain in 2015.

			Costs (M[a] €)		YLL (M€)	
Air Pollutant	Health end-points	Risk group	Portugal	Spain	Portugal	Spain
$PM_{2.5}$	All-cause Mortality	Adults (age ≥ 30 yr)	639 (425–830)	3 998 (2 660–5 200)	86 (57–112)	467 (311–608)
	Mortality, IHD	Adults (age ≥ 25 yr)	176	1 643	49	416
	Mortality, Stroke	Adults (age ≥ 25 yr)	116	525€	29	114
	Mortality, COPD	Adults (age ≥ 25 yr)	32	494	6	78
	Mortality, LC	Adults (age ≥ 25 yr)	29	460	11	147
	Mortality, ALRI	Children (age ≤ 5 yr)	–	–	–	1
	Cause-specific Total	–	353	3 122	95	756
PM_{10}	Post-neonatal Mortality	1 month to 1 year	16 (8–27)	139 (75–233)	18 (10–31)	145 (81–239)
NO_2	All-cause Mortality	Adults (age ≥ 30 yr)	614 (360–861)	3 009 (1 780–4 164)	78 (45–109)	338 (200–468)

[a] M€ - Million.

which was reflected in more years of life lost.

The mortality due to IHD and stroke was evaluated for different age groups. The relative contributions of IHD and stroke, to the number of premature deaths and YLL for age-specific groups, can be found, respectively, in Figures S2 and S3 (Supplementary Material). For both diseases and both Portugal and Spain, the majority of deaths (more than 70%), occurred for the population aged 70 years or older, while the youngest (<45 years old) contributed only for 2–4% of the total. For YLL, the elderlies (>70 years old) also accounted for the highest proportion of the total and the youngest (<45 years old) contributed more significantly, 6–10% of the total.

Fig. 1 shows the spatial distribution of the number of deaths at municipality (LAU2) level in the Iberian Peninsula: a) all-cause (central value) mortality deaths caused by $PM_{2.5}$; b) cause-specific mortality (sum of the five health-endpoints) deaths caused by $PM_{2.5}$; c) all-cause mortality deaths caused by NO_2 shipping contribution.

The spatial distribution of the YLL for the same health end-points can be found in Figure S4 (Supplementary Material). As can be seen, in general, the most severely affected areas were the coastal ones (close to major ports), mainly along the south coast of Spain. More locally, regarding the all-cause mortality due to exposure to $PM_{2.5}$, the most affected areas were Barcelona, with the highest number of deaths and YLL, followed by Valencia, Algeciras and Madrid. In Portugal, the most affected areas were Lisbon, Setúbal and Portimão in the south, and some parishes of Porto city in the north, cities that are located close to major port areas of Portugal. The shape of the spatial distribution of the cause-specific mortality due to $PM_{2.5}$ was similar to those of the all-cause mortality. In terms of mortality due to exposure to NO_2, the most affected areas were the same as for $PM_{2.5}$. However, in this case, and as can be seen from Fig. 1 c) and Figure S4 c), it was almost exclusively in these areas that shipping emissions contributed to the increase the burden of disease. Regarding the number of deaths/100 000 inhabitants, the highest contributions were found for all-cause mortality NO_2 ship-related air pollution with contributions of 36.5 deaths/100 000 inhabitants, 48.8 deaths/100 000 inhabitants and 57.5 deaths/100 000 inhabitants in Barcelona, Valencia and Algeciras, respectively. For all-cause mortality $PM_{2.5}$ ship-related air pollution, contributions of 12.5 deaths/100 000 inhabitants, 20.4 deaths/100 000 inhabitants, and 24.1 deaths/100 000 inhabitants were found for Barcelona, Valencia and Algeciras, respectively.

3.2. Morbidity and related economic burden

In addition to mortality, morbidity associated with ship-related air pollution on young children and adults and their related costs were also estimated. Table 3 shows the morbidity as the additional number of cases, as well as, the corresponding uncertainties (when appropriate) for each health end-point and group risk, attributed to ship-related $PM_{2.5}$, PM_{10} and NO_2 emissions for Portugal and Spain. The morbidity related costs are presented in Table 4.

As can be seen in Table 3, for the Iberian Peninsula PM_{10} shipping-related emissions were responsible for 67 (95% CI 0–1336) respiratory hospital admissions, 460 (95% CI 87–829) cardiovascular hospital admissions, 4.26 (95% CI 3.96–56.9) million RADs, 1.60 (95% CI 1.33–1.77) million WLDs and 1 689 (95% CI 667–2 408) new incidences of chronic bronchitis were attributed to PM_{10} ship-related emissions for adults. Additionally, for children, it was estimated 5 954 (95% CI 0–11 620) episodes of acute bronchitis and 79 275 (95% CI 17 764–137 969) asthma symptoms days. Regarding the costs of morbidity, a total of 692 million € was attributed to ship-related emissions.

3.3. Total all-cause economic burden of disease related with shipping air pollution

Fig. 2 shows the total costs of all-cause economic burden of disease related with shipping air pollution for the Iberian Peninsula in 2015.

Giving the pollutants and health end-points considered in this study, and following HRAPIE recommendations to avoid double-counting, a total exposure cost of around 9 100 million € yr^{-1} (for VSL approach) and 1 825 million € yr^{-1} (for VOLY approach) were estimated for all-cause mortality and morbidity. In the present study, morbidity costs represented around 7.6% of total costs, considering the VSL approach.

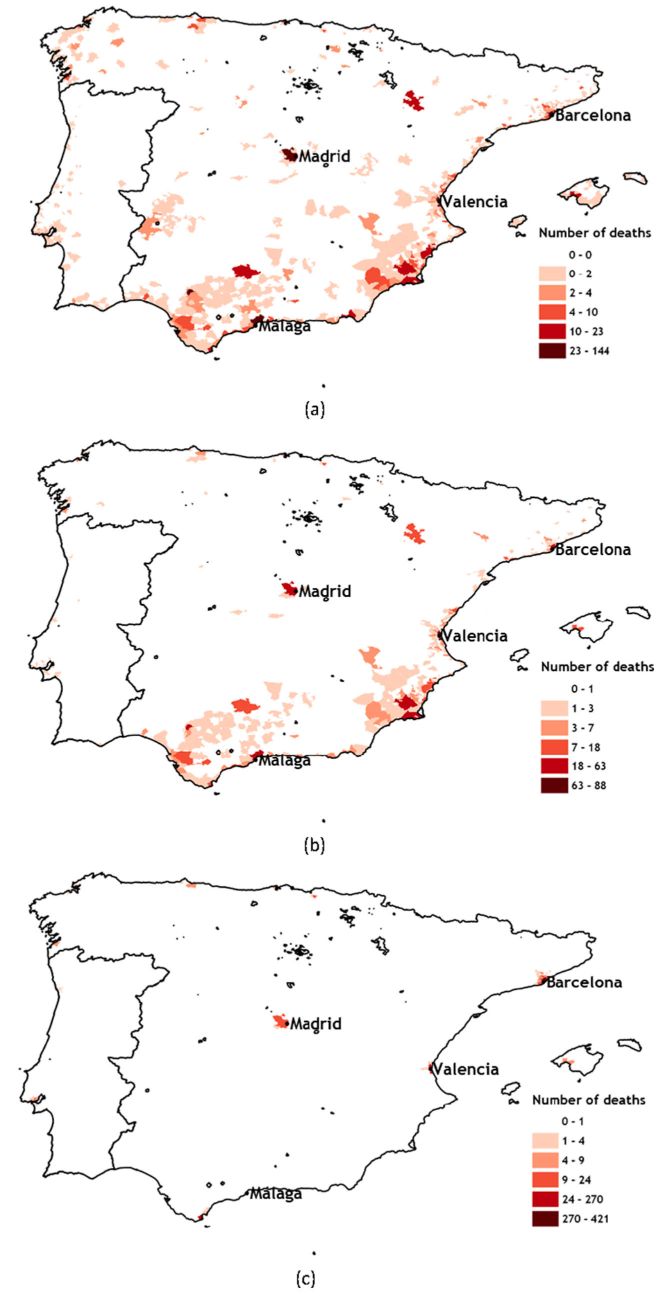

Fig. 1. Spatial distribution at municipality (LAU2) level of a) all-cause mortality deaths caused by $PM_{2.5}$ shipping contribution; b) cause-specific mortality deaths caused by $PM_{2.5}$ shipping contribution; c) all-cause mortality deaths caused by NO_2 shipping contribution.

3.4. Effects of CAP2020 on mortality and morbidity

Table 5 shows the percentage of reduction in the burden of disease due to the CAP2020 implementation (applied to the 2015 data) on the Iberian Peninsula.

As can be seen, for the long-term exposure to $PM_{2.5}$ on all-cause and cause-specific mortality as well as, cardiovascular and respiratory hospital admissions, reductions of 46–47% were estimated. For PM_{10} ship-related health endpoints reductions of 10% were estimated. For the

Table 4
Morbidity costs of shipping related air pollution for Portugal and Spain in 2015.

Air Pollutant	Health end-points	Risk group	Costs (M[a] €) Portugal	Spain
$PM_{2.5}$	Respiratory hospital admissions	All ages	21 K[a] € (0–40 K€)	218 K€ (0–4 M[b] €)
	Cardiovascular hospital admissions	All ages	190 K€ (36 K€-340 K€)	1 M€ (273 K€-3 M€)
	Work loss days (absenteeism)	Working-age (15–64 yr)	75 M€ (64 M€-86 M€)	122 M€ (104 M€-139 M€)
	Restricted activity days	All ages	190 M€ (173 M€-292 M€)	185 M€ (175 M€-201 M€)
PM_{10}	Recurring bronchitis (additional cases)	Children (6–12 yr)	489 K€ (0–961 K€)	3 M€ (0–7 M€)
	Asthma symptom days	Children (5–19 yr)	436 K€ (97 K€-760 K€)	3 M€ (664 K€-5 M€)
	Chronic bronchitis (new cases)	Adults (age ≥ 27 yr)	14 M€ (6 M€-20 M€)	98 M€ (39 M€-139 M€)

[a] K€ - Thousand €;
[b] M€ - Million€.

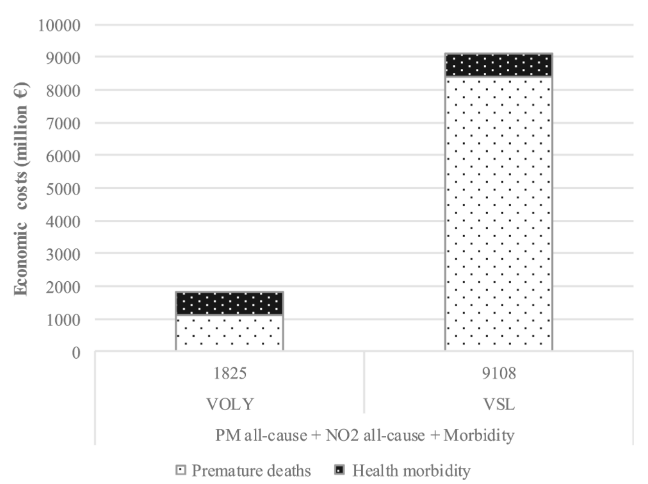

Fig. 2. Total costs of all-cause economic burden of disease related with shipping air pollution for the Iberian Peninsula in 2015.

Table 3
Morbidity as additional cases due to ship-related air pollution for Portugal and Spain in 2015.

Air Pollutant	Health end-points	Risk group	Additional Cases (95% CI) Portugal	Spain
$PM_{2.5}$	Respiratory hospital admissions	All ages	7 (0–130)	60 (0–1206)
	Cardiovascular hospital admissions	All ages	62 (12–111)	398 (75–718)
	Work loss days (absenteeism)	Working age (15–64 yr)	654,387 (558938–748435)	895,555 (766795–1021785)
	Restricted activity days	All ages	2,341,833 (2140738–2601518)	1,924,621 (1817073–2088504)
PM_{10}	Recurring bronchitis (aditional cases)	Children (6–12 yr)	870 (0–1711)	5084 (0–9909)
	Asthma symptom days	Children (5–19 yr)	11,787 (2635–20559)	67,488 (15129–117410)
	Chronic bronchitis (new cases)	Adults (age ≥ 27 yr)	250 (98–357)	1439 (569–2051)

Table 5
Percentage of reduction on the burden of disease due to the CAP2020 implementation (applied to the 2015 data) on the Iberian Peninsula.

Air Pollutant	Health end-points	Risk group	Reduction due to CAP2020 (%)[a]
$PM_{2.5}$	All-cause Mortality	Adults (age ≥ 30 yr)	46
	Cause-specific Total	–	47
	Respiratory hospital admissions	All ages	46
	Cardiovascular hospital admissions	All ages	46
	Work loss days (absenteeism)	Working age (15–64 yr)	30
	Restricted activity days	All ages	26
PM_{10}	Post-neonatal Mortality	1 month to 1 year	10
	Recurring bronchitis (additional cases)	Children (6–12 yr)	10
	Asthma symptom days	Children (5–19 yr)	10
	Chronic bronchitis (new cases)	Adults (age ≥ 27 yr)	11

[a] Results for number of deaths and cases. For YLLs and respective external costs the reductions were the same.

work loss days and for the restricted activity days, reductions of around 30% were found. Regarding the NO_2 ship-related mortality, no reductions were found. The estimated absolute values can be found in Table S3 (Supplementary Material).

4. Discussion

The findings of this study represent the first attempt to estimate the health impacts from shipping and their associated costs, specifically for the Iberian Peninsula. Based on the number of premature deaths calculated from the BOD WHO life-tables (for all causes), it was estimated that $PM_{2.5}$ ship-related emissions could contribute to 0.34% (95% CI: 0.22–0.44%) and 0.39% (95% CI: 0.26–0.51%) of the total premature deaths due to all (natural) causes in Portugal and Spain, respectively. Although the results in terms of the number of premature deaths and YLL attributed to NO_2 exposure from ship emissions have been similar to those of $PM_{2.5}$, compared to the scenario without shipping emissions, the contribution of the NO_2 emissions from ships for deaths and YLL was considerably higher (around 70% for Portugal and 30% for Spain). These results highlight the relevance of shipping emissions to the increase of ambient air NO_2 concentrations and their respective effects on human health, which has already been reported by other authors (Tang et al., 2020). A consideration that is important to discuss is the 2020 global sulphur cap. Viana et al. (2020) reported that the implementation of the CAP2020 could reduce $PM_{2.5}$ ship-related premature deaths by 15% (average for 8 Mediterranean cities), being 45% in Melilla and 7% in Barcelona (Spanish cities analysed), which is considerably lower than what was found in the present study, may be due the different methodologies used. Viana et al. (2020) used results from studies with source apportionment data for shipping. Moreover, to estimate the impact of CAP2020 on the health effects, authors used concentrations estimated by Sofiev et al. (2018). Jonson et al. (2020) that studied the effects of global ship emissions on European air pollution levels evaluated the impact of the CAP2020 requirements and found reductions of around 50% in the $PM_{2.5}$ ship-related concentrations for the Iberian Peninsula. Similar results were found in the present study regarding $PM_{2.5}$ mortality (number of deaths and YLLs) and cardiovascular and respiratory hospital admissions, with 46–47% reductions for the Iberian Peninsula. This result seems to be related with the decrease in the amount of sulphur in the fuel that affects the amount of SO_4 in the primary particles, as well as later in the formation of secondary particles. Sofiev et al. (2018) found less avoided premature mortality for the entire globe (~34%) due to the CAP2020 regulations. Nevertheless, although comparing with the 2015 ship emissions, their study considered applying the CAP2020 to the forecasted emissions for 2020. Thus the results were necessarily different from those of the present study. Regarding NO_2 ship-related mortality no reductions were observed, which is consistent with what was reported by Contini and Merico (2021) and Sofiev et al. (2018). Nevertheless, some authors have reported expected reductions in NO2 concentrations in the future due to the decrease in the consumption of high sulphur content fuels (Sui et al., 2020) and the use of scrubbers to meet the CAP2020 restrictions (Ibrahim, 2016). Consequently, it could be important to improve the discussion of a possible implementation of NOx Emission Control Areas in the Atlantic Ocean and the Mediterranean Sea. Studies have been reported on the implementation of an ECA (SECA + NECA) in the Mediterranean Sea with results showing significant reductions on PM, SO_2 and NO_x emissions from international shipping, saving more than 6 000 lives every year and up to 14 billion € in health costs (REMPEC, 2019; Rouïl et al., 2019). Thus, further studies are needed to understand and quantify the implications of the CAP2020 implementation in terms of NO_2 emissions and respective health impacts as well as the implementation of a NECA in the Iberian Peninsula region.

Regarding the PM_{10} ship-related health endpoints (mainly morbidity health endpoints), decreases were around 10%. Sofiev et al. (2018) reported reductions of 54% in morbidity due to childhood asthma, estimated from exposure to $PM_{2.5}$ pollution. The estimates made in this study for the scenario where ship emissions were considered were compared, despite some methodological differences, with those performed by the European Environment Agency (EEA) for 2015 and reported in the Air quality in Europe – 2018 report (EEA, 2018). For $PM_{2.5}$ and NO_2 the estimated premature deaths and YLL of the present study were lower than those reported by EEA for Portugal and Spain. The lower estimates of the present study compared to the EEA estimates may be related to the air quality and population data that were used. For the EEA report, a methodology that combined the monitoring data air quality stations with information from maps of interpolated air pollutant concentrations from the EMEP model and other supplementary data (such as altitude and meteorology) was used. Moreover, although demographic and health-related data (same exposure–response relationships from the HRAPIE project) were obtained from the same sources for both studies, in the EEA study a population density map with a resolution of 1x1 km was used, whereas in the present study the population densities were calculated for each parish (based on Eurostat population data).

As far as known, this study was the first where ERFs functions for cause-specific health impacts attributable to $PM_{2.5}$ were used to estimate the burden of disease from ship-related emissions. Some findings from the present study were comparable to those from previous studies in the literature. In previous studies, Lelieveld et al. (2015) and Giannadaki et al. (2016) estimated premature mortality (number of deaths) on a global scale attributed to long-term exposure to $PM_{2.5}$ (annual mean concentrations) for the year 2010 also using the ERFs from Burnett et al. (2014) (considering stroke, IHD, COPD, LC for the population ≥ 30 years, and ALRI for children < 5 years). Authors estimated that the cardiovascular diseases (stroke and IHD) were those that accounted for the majority of premature deaths, which was similar to what was found in this study for shipping emissions. Moreover, according to the GDB results (IHME, 2019) for 2015 the leading causes of premature deaths for Portugal and Spain (for all sources) were also the cardiovascular diseases. Concerning the YLL, the leading causes for Portugal were also the cardiovascular diseases, however for Spain LC had the second higher contribution. Although the number of premature deaths as a result of LC was smaller than for stroke and COPD, for LC people died younger, which was reflected in more years of life lost. As mention in the results, mortality due to IHD and stroke was evaluated for different age groups and for both diseases and for both Portugal and Spain, the majority of deaths (more than 70%), occurred for the group aged 70 years or older.

The reasons for the variations among the different age groups were the differences in baseline mortality rate, as the older people are more sensitive to $PM_{2.5}$ exposure than younger age groups, as well as the fact that the population of the Iberian Peninsula is mainly working-aged and elderly (>65 years) (Kashnitsky and Schöley, 2018).

Findings from this study concerning the spatial distribution of health impacts were similar to those found by other authors in other world areas. Corbett et al. (2007), Liu et al. (2016) and Sofiev et al. (2018) also found the most considerable health impacts near ports and coastal regions densely populated and where high ship-related PM concentrations coincided. It is essential to notice that, although Madrid is not a coastal city, a substantial number of deaths and YLL were estimated in this study for that city. Although Madrid registered a high number of deaths, the number of deaths/100 000 inhabitants was substantially lower than that registered for the coastal cities with the highest mortality (Barcelona, Valencia and Algeciras). For Madrid, $PM_{2.5}$ and NO_2 ship-related concentrations contributed to 1.4 deaths/100 000 inhabitants and 0.7 deaths/100 000 inhabitants, respectively, in comparison to those of Barcelona, Valencia and Algeciras that varied between 12.5 and 24.1 deaths/100 000 inhabitants for $PM_{2.5}$ and 36.5 and 57.5 deaths/100 000 inhabitants for NO_2. The combination of long-range transport of pollution, and the high population density in Madrid (the largest Spanish municipality by population) may be a possible explanation for these results. Nevertheless, these results should be analysed with caution because they may be related to model overestimations, although the EMEP/MSC-W model showed a good spatial correlation of annual mean concentrations for NO_2, SO_2, and $PM_{2.5}$ (Karl et al., 2019; Nunes et al., 2020). Using a different methodology, Liu et al., (2016) found substantial health effects caused by emissions from ships in some urban centres of East Asia, far from the coastal areas, due to the factors above referred. These evidences demonstrate that shipping can have a high impact on coastal cities and affect inland populations' health, notwithstanding less intensely.

Some comparisons with other health impact assessment studies for long-term mortality impacts from shipping in other regions and other sectors and cities could be made concerning the number of premature deaths from $PM_{2.5}$ all-cause mortality. Although Viana et al. (2020) used a different concentration–response function, it was reported for Barcelona 60–177 premature deaths due to $PM_{2.5}$ ship-related emissions for 2011, which is in line with the estimations of the present study (144 premature deaths for Barcelona). The authors also reported an average of 5.5 annual premature deaths/100 000 inhabitants for the 8 cities studied located in the Mediterranean region, which is lower than that found in this study for the 4 coastal cities with a higher number of deaths (11.4 premature deaths/100 000 inhabitants). As already described in other studies, the impact of shipping in terms of premature deaths/100 000 inhabitants is lower than the reported for urban vehicular traffic for some European cities. Despite this, 20.4 deaths/100 000 inhabitants were estimated in the present study for the city of Valencia, which is relatively close to the reported by Malmqvist et al. (2018) for vehicle traffic in Malmö (28.5 premature deaths/100 000 inhabitants). Broome et al. (2016) found 0.3 premature deaths/100 000 inhabitants attributable to $PM_{2.5}$ ship-related exhaust emissions in Sydney, and although the authors acknowledged some underestimations of the results, they were significantly lower than the values reported in the present study for coastal cities and for other European areas in the Mediterranean region (Viana et al., 2020).

As was verified for mortality, cardiovascular diseases lead to higher hospital admissions than respiratory diseases. Based on these results, it seemed that the primary health effect of PM ship-related emissions is its adverse effects on the cardiovascular system. Brandt et al. (2013) that assessed health-cost externalities of the contribution from international shipping to air pollution in Europe using EVA (Economic Valuation of Air pollution) model also found a higher number of cardiovascular hospital admissions than respiratory hospital admissions.

The health costs of the shipping related air pollution represented around 0.06% (for VOLY approach of $PM_{2.5}$ cause-specific) to 0.72% (for VSL approach of PM and NO_2 all-cause burden) of the Iberian Peninsula GDP (GDP for Portugal plus GDP for Spain) in 2015 from the Eurostat database (Eurostat, 2020). The highest external costs were found when the VSL valuation of mortality was used. As mentioned above, the mortality costs due to ship emissions have been calculated using two approaches: i) using a more traditional approach based on the value of preventing a premature death using the value of statistical life (VSL) and ii) taking into account the variation in life expectancy using the year of life value (VOLY). As expected, the results of both approaches were substantially different, as the VOLY approach explicitly assigns a lower value to accumulated reductions in mortality risk for older age groups (fewer years of life lost). Both approaches were used because in recent years there has been increasing recognition that it is also significant to observe changes in life expectancy and not just the number of deaths to calculate costs from air pollution (Desaigues et al., 2011, 2007). Epidemiological studies have been suggesting that air pollution causes a small loss in life expectancy (a few months on average, but can range from few days to some years), which makes air pollution a very specific case (Friedrich et al., 2004; Rabl, 2003). For this reason, some researchers have been considering VOLY a more appropriate parameter for estimating mortality cost linked to air pollution than VSL (Jeanrenaud et al., 2007). Despite this, there are still some agencies (e.g. US Environmental Protection Agency and OECD) and researchers that continue to use the number of deaths as the impact indicator for monetary valuation (Desaigues et al., 2011; OECD, 2012, 2011). Accordingly, in this study, the two approaches were maintained to facilitate future comparisons with the results obtained in other studies. According to WHO and some recent studies, morbidity costs related to human health impacts from exposure to air pollution represent around 10% of the overall costs, which are similar to the estimations of this study (7.6% of total costs).

5. Uncertainties and limitations

Using a health impact assessment methodology leads to inevitable uncertainties, and their analysis is a critical issue that should include all steps, from the air pollution to the health impact assessments and their monetisation (WHO, 2016b, 2014). Regarding the evaluation of the concentrations due to shipping emissions in the Iberian Peninsula, EMEP/MSC-W model has been showing a good spatial correlation of annual mean concentrations for NO_2, SO_2, and PM (Karl et al., 2019; Nunes et al., 2020). Nonetheless, some overestimations may occur, thus results have to be analysed with caution.

Regarding the exposure assessment, the most significant uncertainties came from the choice of the pollutants, the general shape of the ERFs and their applicability from region to region, and in the assessment of the population exposed (Ostro et al., 2004).

The choice of pollutants is a preponderant issue because air pollution is a known complex mix of gases, as is the one from shipping. Although PM (especially the $PM_{2.5}$ fraction) is the most widely used and accepted indicator, due to the nature of emissions from ships, in the present study, the health impacts associated with exposure to NO_2 were also evaluated, despite the considerable uncertainties associated with the use of the ERFs for this pollutant. To avoid double-counting of health effects and associated costs (e.g. mortality due to a specific-cause is a part of all-cause mortality), and as sometimes the individual contribution of each pollutant for the general mix of gases is unclear, the HRAPIE recommendations were followed. Even so, some double-counting of effects and consequent costs could have happened. The quantification of the impact for one pollutant from single-pollutant models may include effects attributable to another with which it is correlated. Moreover, despite baseline incidences for all-cause and cause-specific mortality, as well as morbidity are diagnostically independent, may not be entirely cause-independent.

The choice of the ERFs derived from epidemiological studies leads to unavoidable uncertainties due to the high variability of the estimates. Despite this, to minimise the uncertainties related to ERFs. Log-linear functions widely implemented in studies for Europe, and with international acceptance, were used. Most of these studies have been conducted and replicated for cities in developed countries in Europe and North America, so their applicability in the Iberian Peninsula is reasonably safe. Also, whenever possible, upper and lower coefficients based on the 95% confidence intervals were applied to estimate the relative risks. However, only the statistical uncertainties related to the risk estimates were ensured. To expand the analysis, IERs established by Burnett et al. (2014) representing the current best understanding in terms of the epidemiological evidence on the mortality impacts of $PM_{2.5}$ were used. These are based on novel pieces of evidence provided by cohort studies of air pollution using advanced statistical techniques, and are geographically representative of the Iberian Peninsula. Furthermore, it is important to point out that recent evidence suggests that long-term exposure to certain PM components and sources such as sulfate and elemental carbon may be more toxic than generic $PM_{2.5}$. Also, $PM_{2.5}$ can contribute not only to cardiovascular diseases and lung diseases but also to metabolic diseases and other adverse outcomes (Ostro et al., 2018).

As above referred, other sources of uncertainty included assumptions about the geospatial distribution of the studied population and the baseline incidences. Although the analysis was carried out at the parish level, the baseline incidences were only available at the country level. Despite this, and to try to minimise the uncertainties, whenever possible, the same data source for Portugal and Spain was used. To allocate the concentrations to each parish, and since sometimes for the same parish the concentrations differed, it was assumed that the population was evenly distributed throughout the parish. Also, uncertainties associated with the population data used are to be expected, since they refer to the 2011 censuses (latest data available).

A final point of uncertainty includes assumptions about the cost assessment of health impacts. The uncertainties that could not be minimised came from the inherent costs of the health effects related to a specific pollutant that are frequently ignored, due to the lack of epidemiological evidence. Furthermore, as the VSL and VOLY values are estimated using the Willingness to Pay (WTP) technique, usually using personal interviews to assess how much an individual is willing to spend to improve health or avoid death, the values are sensitive to the perception of each individual. Despite this, uncertainties regarding the location and year for which the VSL and VOLY values were minimised using the benefits transfer approach that takes into account differences in income levels for different locations (in this case Portugal and Spain regarding the EU) and between different years (values updated for the year 2015). The default VSL value was calculated based on a comprehensive review of VSL studies by the OECD with 261 values from 28 studies, considered by an international advisory group as the best currently available evidence (WHO, 2017). As already referred, the VOLY was derived from a WTP study conducted for 9 European countries including Spain which can be considered representative of the Iberian Peninsula and a robust approach. Moreover, estimate costs associated with morbidity is more complicated than to assess those associated with mortality, and there is still no unanimity concerning which health end-points should be considered (OECD, 2014; WHO Regional Office for Europe and OECD, 2015). Despite this, in the present study recommendations made in HRAPIE project, consolidated in the report "Social Costs of Morbidity Impacts of Air Pollution" made by the OECD in 2016 were followed to assess the morbidity and costs of the ship-related emissions (Hunt et al., 2016).

6. Conclusions

This study allowed estimating the health and economic impacts of ship-related air pollution in the Iberian Peninsula for 2015. The number of deaths and YLL of the exposure to long-term NO_2 were almost similar to all-cause mortality $PM_{2.5}$ ship-related air pollution. Although the mortality results attributed to NO_2 exposure were similar to those of $PM_{2.5}$, compared to the scenario without shipping emissions, the contribution of the NO_2 emissions from ships for the number of deaths and years of life lost was considerably higher. These results highlight the relevance of shipping emissions to the increase of ambient air NO_2 concentrations and their respective effects on human health. In the future, it is important to deepen the discussion about the possible implementation of Emission Control Areas in the Atlantic Ocean and the Mediterranean Sea. Estimated all-cause premature deaths attributable to $PM_{2.5}$ ship-related emissions represented an average increase of 7.7% for the Iberian Peninsula when compared to the scenario without shipping contribution.

The spatial distribution of the health impacts showed that in general the most severely afflicted areas were the coastal ones (close to major ports), mainly along the south coast of Spain.

Costs of around 9 100 million € yr^{-1} (for value of statistical life approach - VSL) and 1 825 million € yr^{-1} (for value of life year approach - VOLY) were estimated for PM and NO_2 all-cause burden of disease. For $PM_{2.5}$ cause-specific mortality, a cost of around 3 475 million € yr^{-1} (for VSL approach) and 851 million € yr-1 (for VOLY approach) were estimated. Costs due to PM and NO_2 all-cause burden represented around 0.72% and 0.15% of the Iberian Peninsula gross domestic product in 2015, respectively for VSL and VOLY approaches. For $PM_{2.5}$ cause-specific mortality, costs represented around 0.28% and 0.06%, respectively, for VSL and VOLY approaches. These results show that air pollution from ships has a considerable impact on health and associated costs affecting the Iberian Peninsula.

Concerning the estimations for CAP2020 scenario, if regulations had been applied in 2015, reductions of around 50% on $PM_{2.5}$ ship-related mortality and of 10% for morbidity health endpoints would have been achieved. The application of the policy before 2020 would have brought significant reductions in ship-related mortality and is expected to significantly reduce the health impacts in the future.

Based on the best available methodologies, the results of this study intended to give for the first time a view of the health-economic burden of ship emissions in the Iberian Peninsula. They can be a great support and a powerful tool for decision-making by understanding the health and economic benefits that may be associated with the implementation of measures to mitigate the shipping emissions and improve the air quality of this region.

CRediT authorship contribution statement

RAON performed the data curation for the health impact calculations and monetary valuation, did the interpretation of the results and wrote the manuscript. JPJ and HH provided the ship emission data. MCMA, FGM, JMG and JPJ reviewed the paper and helped in the interpretation of the results. FCC, VDG, and JMG gave support in the interpretation of the results for Spain and reviewed the paper. SIVS designed the study and assisted in modelling scenarios and in writing the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106763.

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