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Final Report - Annexes

The potential for cost-effective air emission reductions from international shipping through designation of further Emission Control Areas in EU waters with focus on the Mediterranean Sea

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The research project “Assessment of the potential for cost-effective air emission reductions from shipping (SOx, NOx) through designation of further Emission Control Areas in EU waters with focus on Mediterranean Sea” (Specific Agreement 13 under Framework Contract ENV.C.3/FRA/2013/00131) was funded by the European Commission

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Annex 1: Sea regions and zones distinguished in this study

Any analysis of the health and environmental impacts of emission control strategies for maritime activities needs to consider the location of emissions. This report estimates emissions in eight Sea regions (Figure 1.1).

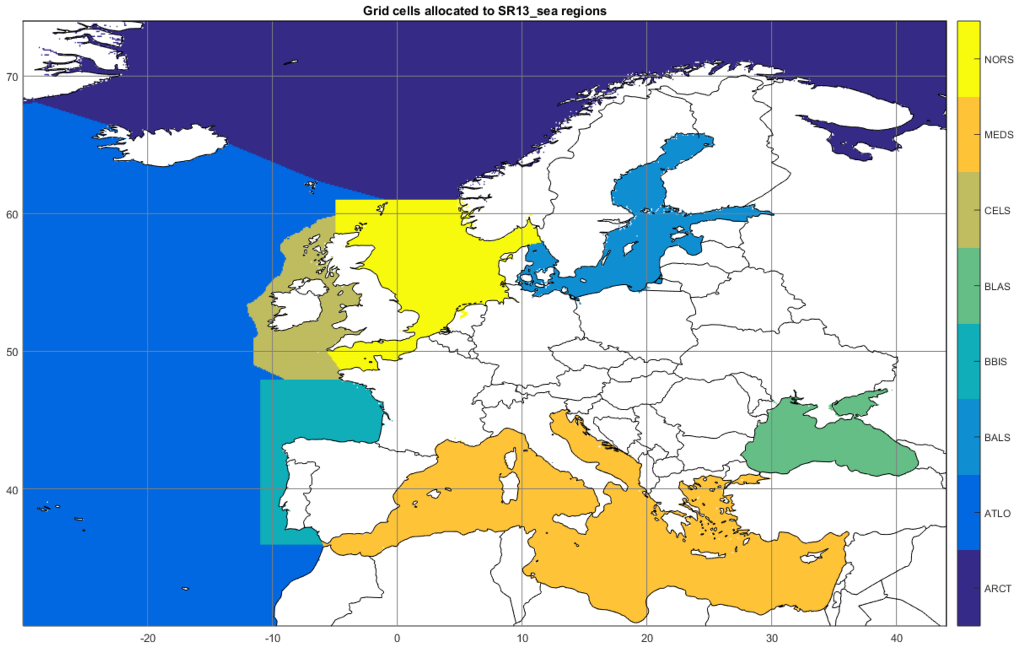

Figure 1.1: Sea regions distinguished in this study

Furthermore, in each of these regions, ship emissions have been distinguished for different zones reflecting differences in legislative jurisdiction enforcement by coastal states, which decline with increasing distance from the coast lines. The United Nations Convention on the Law of the Sea (UNCLOS) defines internal waters (ports), territorial Sea, archipelagic waters (for archipelagic States), the contiguous zone, the exclusive economic zone (EEZ) and the continental shelf. Beyond these maritime zones are the high Seas (Figure 1.2).

This study quantifies emissions for (i) ports and berth activities, (ii) within the internal waters and the territorial Seas (12nm from the internal waters boundary), (iii) within the exclusive economic zones (200nm from the internal waters boundary), and (iv) outside the exclusive economic zones (high Seas). Based on the unofficial EEZ boundaries of the GIS database developed by Flanders Marine Institute (VLIZ) - http://www.vliz.be/vmdcdata/marbound/), in total the analysis distinguishes 28 emission areas around Europe (Table 1.1, Figure 1.4).

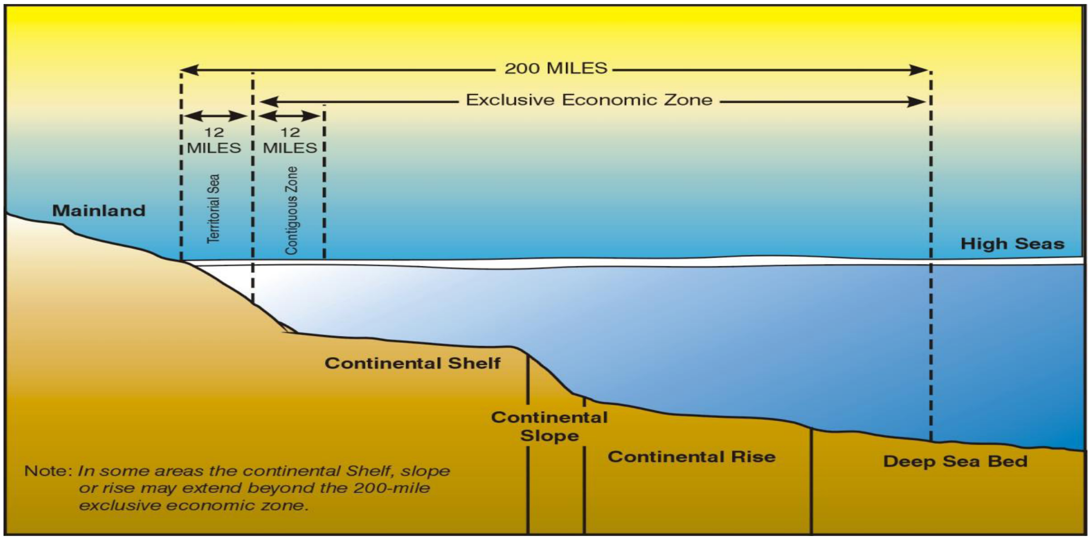

Figure 1.2: The division of the Seas and oceans pursuant to United Nations Convention on the Law of the Sea (UNCLOS)

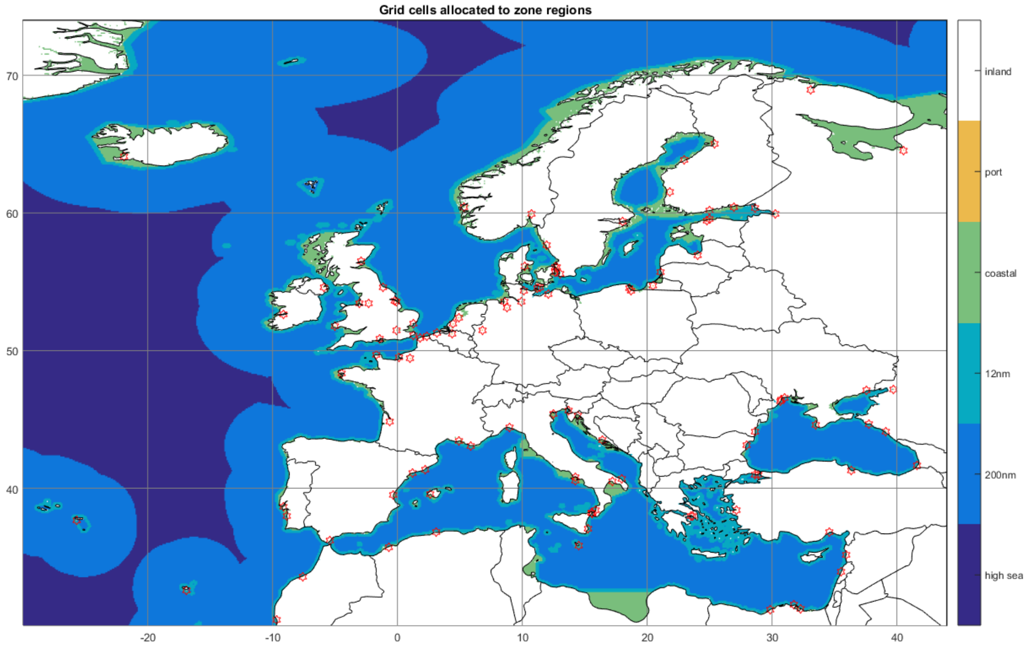

Figure 1.3: Coastal zones distinguished in this study

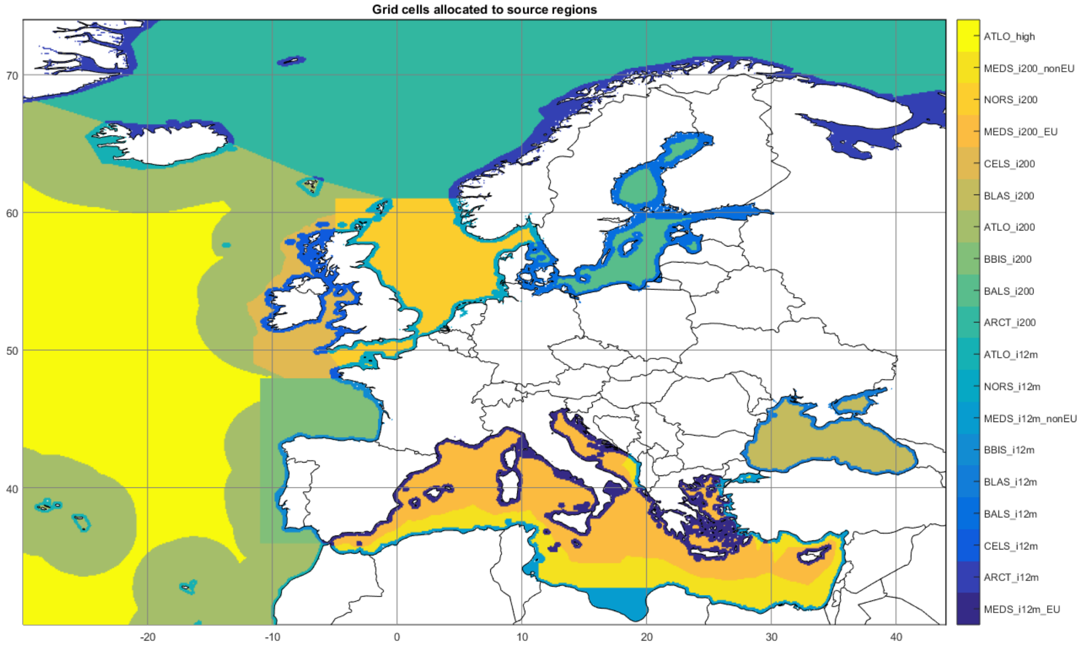

Figure 1.4: Emission source regions distinguished in this study

Table 1.1: Sea regions and zones included in the study

Region and zone
Arctic Sea
Ports/berthing
12 nm zone
Remaining waters
Atlantic Ocean
Ports/berthing
12 nm zone
200 nm zone (excluding 12nm)
High Seas
Baltic Sea
Ports/berthing
12 nm zone
200 nm zone (excluding 12nm)
Bay of Biscay
Ports/berthing
12 nm zone
200 nm zone (excluding 12nm)
Black Sea
Ports/berthing
12 nm zone
200 nm zone (excluding 12nm)
Celtic Sea
Ports/berthing
12 nm zone
200 nm zone (excluding 12nm)
Mediterranean Sea
Ports/berthing EU waters
12 nm zone EU waters
Ports/berthing non-EU waters
12 nm zone non-EU waters
200 nm zone (excluding 12nm) EU waters
200 nm zone (excluding 12nm) non-EU waters
North Sea and English Channel
Ports/berthing
12 nm zone
200 nm zone (excluding 12nm)

Annex 2: The emission inventory for shipping in European Seas in 2015

2.1 Data sources

The emission inventory developed for this study is based on the activity data from the STEAM 3 model developed by the Finnish Meteorological Institute. This is a global inventory of shipping emissions based on AIS[1] activity data for the year 2015. Shipping activity is aggregated to a resolution of 0.1 x 0.1 degree. Results are described in the paper by Johansson et al., 2017. IIASA has gotten access to inventory results, which include gridded emissions for CO_2 and the major pollutants by 11 vessel types. For further analyses, we have aggregated the information to seven types of ships, namely: cargo, container, passenger vessels, RoPax, tankers, vehicle carriers, and other. The latter category includes fishing vessels, service ships, miscellaneous, and unknown.

2.2 Emissions from international shipping

Table 2.1: Fuel consumption from international shipping by vessel type and Sea region in 2015 (PJ)

Region	Cargo	Container	Pass. ships	RoPax	Tanker	Vehicle carrier	Other	Total
Arctic Sea	8.0	1.4	2.6	3.8	7.0	0.2	17.5	40.5
Atlantic Ocean	48.1	70.1	5.2	1.7	41.7	9.6	10.6	187.0
Baltic Sea	32.3	28.1	6.4	43.4	40.3	16.8	11.4	178.6
Bay of Biscay	31.8	68.4	4.8	2.0	39.0	12.3	6.2	164.5
Black Sea	25.9	7.6	0.3	1.7	20.7	1.5	4.7	62.4
Celtic Sea	10.4	16.0	1.6	8.0	12.4	5.4	5.6	59.4
Mediterranean Sea	117.1	253.2	32.8	70.1	156.9	51.2	31.8	713.1
North Sea	52.8	95.9	9.6	28.0	78.6	35.3	58.3	358.4
All Sea regions	326.4	540.7	63.3	158.6	396.3	132.3	146.1	1763.8

Table 2.2: CO_2 emissions from international shipping by vessel type and Sea region in 2015 (million tons)

Region	Cargo	Container	Pass. ships	RoPax	Tanker	Vehicle carrier	Other	Total
Arctic Sea	0.6	0.1	0.2	0.3	0.5	0.0	1.3	3.1
Atlantic Ocean	3.6	5.3	0.4	0.1	3.2	0.7	0.8	14.2
Baltic Sea	2.4	2.1	0.5	3.3	3.1	1.3	0.9	13.5
Bay of Biscay	2.4	5.2	0.4	0.1	3.0	0.9	0.5	12.5
Black Sea	2.0	0.6	0.0	0.1	1.6	0.1	0.4	4.7
Celtic Sea	0.8	1.2	0.1	0.6	0.9	0.4	0.4	4.5
Mediterranean Sea	8.9	19.2	2.5	5.3	11.9	3.9	2.4	54.0
North Sea	4.0	7.3	0.7	2.1	6.0	2.7	4.4	27.2
All Sea regions	24.7	41.0	4.8	12.0	30.0	10.0	11.1	133.7

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[1] The automatic identification system (AIS) is an automatic tracking system used on ships and by vessel traffic services

Table 2.3: Emissions of SO_2 from international shipping by vessel type and Sea region in 2015 (ktons)

Region	Cargo	Container	Pass. ships	RoPax	Tanker	Vehicle carrier	Other	Total
Arctic Sea	7.8	1.4	1.5	3.4	7.0	0.2	15.4	36.7
Atlantic Ocean	47.7	73.9	2.9	1.5	42.5	10.2	9.3	188.2
Baltic Sea	1.5	1.3	0.3	2.0	1.8	0.8	0.5	8.1
Bay of Biscay	31.8	72.2	2.7	1.7	39.7	13.2	5.4	166.7
Black Sea	25.9	8.1	0.2	1.5	21.2	1.6	4.2	62.6
Celtic Sea	10.1	16.7	0.9	6.8	12.4	5.6	4.6	57.2
Mediterranean Sea	116.1	263.4	18.1	58.5	158.1	54.0	26.6	694.8
North Sea	2.4	4.4	0.4	1.3	3.6	1.6	2.7	16.3
All Sea regions	243.3	441.4	26.9	76.7	286.2	87.3	68.7	1230.5

Table 2.4: Emissions of NO_x from international shipping by vessel type and Sea region in 2015 (ktons)

	Cargo	Container	Pass. ship	RoPax	Tanker	Vehicle Carrier	Other	Total
Arctic Sea	12.8	2.4	3.4	4.9	11.1	0.4	23.5	58.6
Atlantic Ocean	77.5	126.0	6.7	2.2	67.1	17.6	14.2	311.3
Baltic Sea	51.6	49.5	8.1	56.0	64.1	30.5	15.1	274.8
Bay of Biscay	51.3	123.0	6.1	2.6	62.7	22.6	8.3	276.7
Black Sea	41.0	13.2	0.4	2.2	32.9	2.6	6.2	98.4
Celtic Sea	16.7	28.6	2.1	10.3	19.8	9.8	7.4	94.8
Mediterranean Sea	188.0	449.9	41.9	90.3	251.1	93.2	42.4	1156.8
North Sea	84.1	166.7	12.3	36.0	124.5	62.5	77.9	564.0
All Sea regions	523.1	959.3	81.0	204.4	633.4	239.2	195.0	2835.4

Table 2.5: Emissions of PM2.5 from international shipping by vessel type and Sea region in 2015 (ktons)

	Cargo	Container	Pass. ship	RoPax	Tanker	Vehicle Carrier	Other	Total
Arctic Sea	1.0	0.2	0.2	0.4	0.9	0.0	2.1	4.8
Atlantic Ocean	6.2	9.4	0.4	0.2	5.4	1.3	1.2	24.2
Baltic Sea	1.2	1.0	0.2	1.6	1.5	0.6	0.4	6.6
Bay of Biscay	4.1	9.2	0.4	0.2	5.1	1.7	0.7	21.4
Black Sea	3.3	1.0	0.0	0.2	2.7	0.2	0.6	8.1
Celtic Sea	1.3	2.1	0.1	0.9	1.6	0.7	0.6	7.4
Mediterranean Sea	15.0	33.6	2.6	7.9	20.3	6.9	3.6	89.8
North Sea	1.9	3.5	0.4	1.0	2.9	1.3	2.1	13.2
All Sea regions	34.0	60.0	4.4	12.5	40.4	12.7	11.4	175.4

Table 2.6: Emissions of Black Carbon (BC) from international shipping by vessel type and Sea region in 2015 (ktons)

	Cargo	Container	Pass. ship	RoPax	Tanker	Vehicle Carrier	Other	Total
Arctic Sea	0.04	0.01	0.01	0.02	0.03	0.00	0.08	0.18
Atlantic Ocean	0.22	0.34	0.02	0.01	0.20	0.05	0.05	0.88
Baltic Sea	0.08	0.07	0.02	0.11	0.10	0.04	0.03	0.45
Bay of Biscay	0.15	0.33	0.02	0.01	0.18	0.06	0.03	0.78
Black Sea	0.12	0.04	0.00	0.01	0.10	0.01	0.02	0.29
Celtic Sea	0.05	0.08	0.01	0.03	0.06	0.03	0.02	0.27
Mediterranean Sea	0.54	1.20	0.14	0.30	0.73	0.25	0.14	3.31
North Sea	0.13	0.24	0.02	0.07	0.20	0.09	0.15	0.90
All Sea regions	1.33	2.30	0.25	0.55	1.60	0.52	0.51	7.05

Table 2.7: Emissions of air pollutants from international shipping by Sea region and zone in 2015, (million tons for CO_2, ktons for other pollutants).

Region and zone	CO_2	SO_2	NO_x	PM2.5	BC
Arctic Sea	3.1	36.7	58.6	4.8	0.18
Ports/berthing	0.1	0.0	0.9	0.0	0.00
12 nm zone	1.4	16.5	26.1	2.2	0.08
Remaining waters	1.6	20.1	31.5	2.6	0.10
Atlantic Ocean	14.2	188.2	311.3	24.2	0.88
Ports/berthing	0.1	0.1	1.6	0.1	0.00
12 nm zone	0.6	7.5	12.2	1.0	0.04
200 nm zone	8.5	113.3	186.2	14.5	0.53
High Seas	5.0	67.3	111.3	8.6	0.31
Baltic Sea	13.4	8.1	274.8	6.6	0.45
Ports/berthing	0.8	0.5	12.4	0.4	0.03
12 nm zone	8.5	5.2	175.1	4.2	0.28
200 nm zone	4.1	2.5	87.3	2.0	0.14
Bay of Biscay	12.5	166.7	276.7	21.4	0.78
Ports/berthing	0.1	0.0	1.1	0.0	0.00
12 nm zone	0.6	8.2	13.4	1.1	0.04
200 nm zone	11.8	158.4	262.3	20.3	0.73
Black Sea	4.7	62.6	98.4	8.1	0.29
Ports/berthing	0.4	5.6	6.7	0.7	0.03
12 nm zone	1.5	20.0	32.0	2.6	0.09
200 nm zone	2.8	37.0	59.6	4.8	0.17
Celtic Sea	4.5	57.2	94.8	7.4	0.27
Ports/berthing	0.1	0.1	2.2	0.1	0.00
12 nm zone	1.3	16.1	25.5	2.1	0.08
200 nm zone	3.1	41.0	67.1	5.3	0.19
Mediterranean Sea	54.1	694.8	1156.8	89.8	3.31
Ports/berthing EU waters	1.3	0.8	19.7	0.6	0.04
12 nm zone EU waters	9.7	121.9	199.1	15.8	0.59
Ports/berthing non-EU waters	0.5	7.2	8.0	0.9	0.03
12 nm zone non-EU waters	6.2	81.8	133.7	10.5	0.38
200 nm zone EU waters	23.8	313.6	517.0	40.3	1.47
200 nm zone non-EU waters	12.5	169.4	279.4	21.6	0.78
North Sea	26.9	16.3	564.0	13.2	0.90
Ports/berthing	1.9	1.2	29.2	1.0	0.06
12 nm zone	9.3	5.6	194.4	4.5	0.31
200 nm zone	15.7	9.5	340.4	7.7	0.52
Total	133.3	1230.5	2835.4	175.4	7.05

2.3 Emissions from national navigation

According to the EMEP guidelines, emissions from seagoing ships travelling between ports in the same country should be accounted for as national emissions and included in the national emission inventories. The focus of our study is on international shipping. In order to avoid double counting, it was necessary to subtract emissions caused by national maritime navigation from the total maritime shipping. IIASA has compiled information on gridded emissions of NO_x from national navigation based on data collected by the EMEP Canter for Emission Inventories and Projections (CEIP). Next, we estimated on this basis fuel consumption and emissions of air pollutants from this category. Results by country are presented in Table 2.8. The spatial distribution of CO_2 emissions is shown in Figure 2.1. The majority of national maritime navigation takes place in territorial waters. Since national navigation covers also shipping on inland waterways, emissions from the latter category have not been included in the correction. Projections of emissions from national maritime navigation are included in national emissions available on-line from the GAINS model[2].

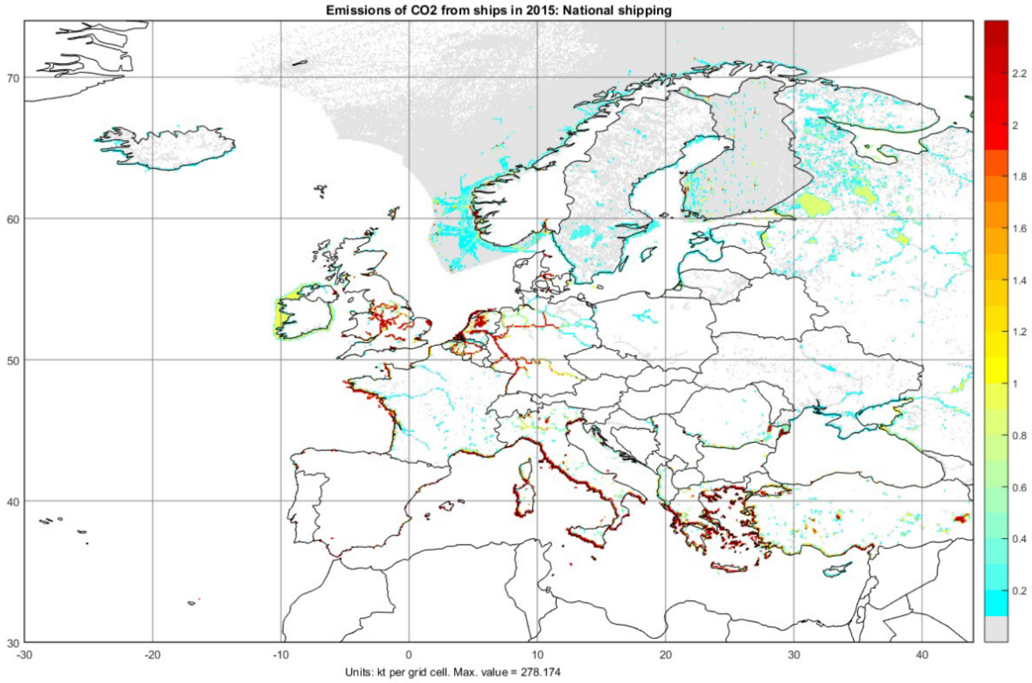

Figure 2.1: Spatial distribution of CO_2 emissions from national navigation (inland and maritime)

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[2] http://gains.iiasa.ac.at/gains/EUN/index.login?logout=1, scenario REF_post2014_CLE. This scenario is based on the PRIMES 2016 energy projection up to 2050 and current air pollution control legislation as in mid-2017.

Table 2.8: Fuel consumption and emissions in 2015 by vessels included in the category "national maritime navigation”

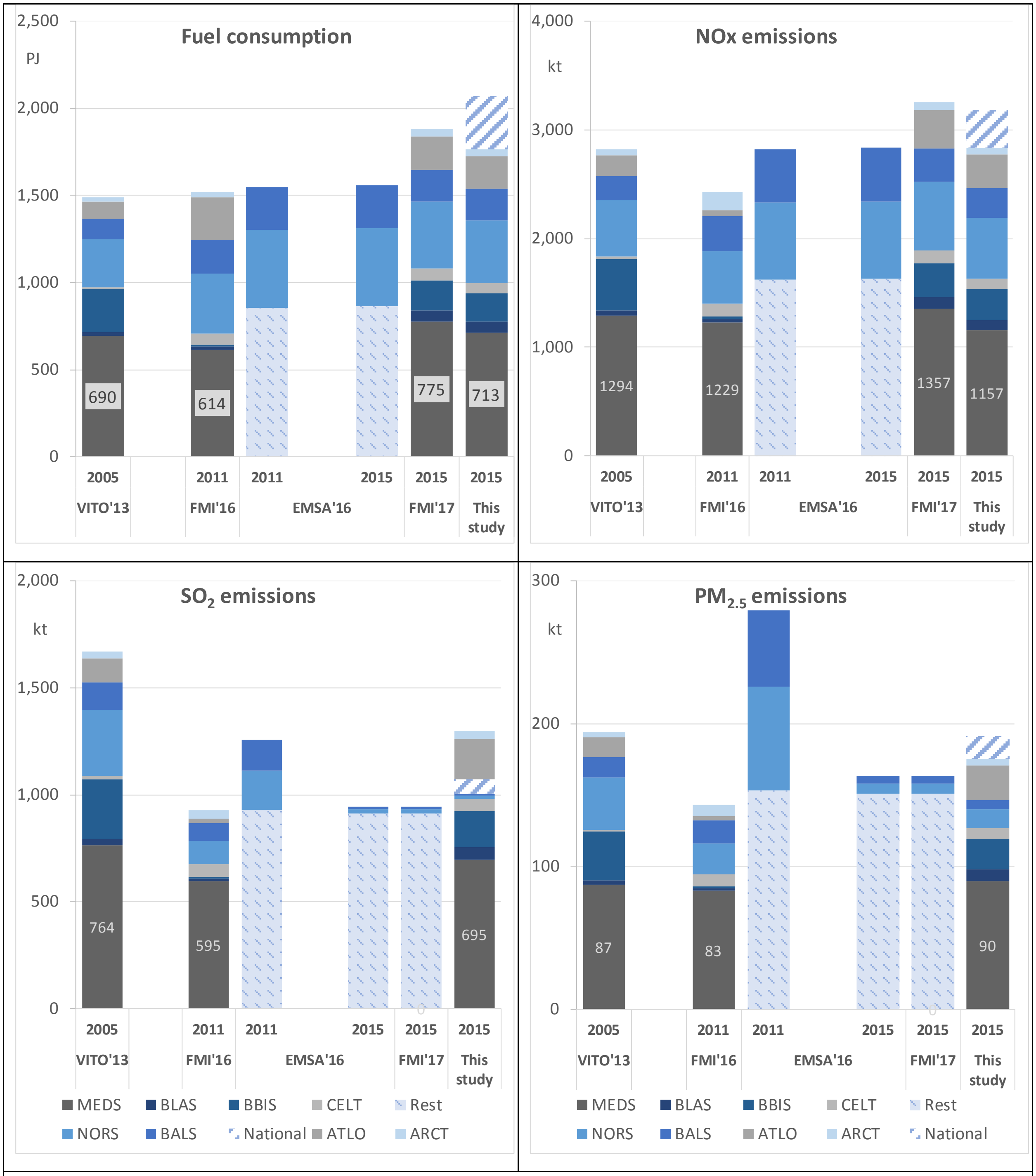
Country	Fuel consumption	Emissions			
		CO_2	NO_x	SO_2	PM2.5
	PJ	Mtons	kilotons		
Albania	0.7	0.05	0.76	0.19	0.04
Belgium	5.8	0.43	6.61	0.26	0.21
Bulgaria	0.2	0.02	0.26	0.02	0.01
Croatia	1.4	0.1	1.58	0.06	0.05
Cyprus	0.1	0.01	0.13	0.01	0
Denmark	6.5	0.48	7.47	0.3	0.24
Estonia	0.4	0.03	0.48	0.02	0.02
Finland	4.9	0.37	5.66	0.22	0.18
France	9.6	0.72	11.05	1.2	0.42
Germany	24.9	1.85	28.59	1.13	0.91
Greece	39.3	2.93	45.2	11.45	2.25
Iceland	0.6	0.04	0.64	0.06	0.02
Ireland	4.7	0.35	5.43	0.21	0.17
Italy	60.7	4.52	69.83	20.91	3.74
Latvia	0.2	0.02	0.24	0.01	0.01
Lithuania	0.2	0.01	0.17	0.01	0.01
Malta	0.3	0.02	0.35	0.05	0.01
Netherlands	9.0	0.67	10.34	0.41	0.33
Norway	15.5	1.16	17.84	0.7	0.57
Poland	0.2	0.01	0.2	0.01	0.01
Portugal	3.3	0.24	3.76	1.73	0.25
Romania	2.9	0.22	3.38	0.87	0.17
Russia	33.3	2.48	38.26	9.39	1.99
Serbia	0.6	0.05	0.71	0.18	0.04
Spain	29.4	2.19	33.84	10.62	1.85
Sweden	3.7	0.27	4.22	0.67	0.19
Turkey	13.0	0.97	15	4.08	0.82
Ukraine	0.9	0.06	0.98	0.32	0.06
United Kingdom	33.3	2.48	38.24	1.51	1.22
Total	305.4	22.74	351.2	66.62	15.79

2.4 Comparison of emission inventories

For the comparison with other emission inventories, we add emissions from national shipping to emissions from international shipping (Figure 2.2). The closest match occurs with the FMI inventory for the year 2015 (Johansson, Jalkanen, and Kukkonen 2017), as gridded CO_2 data by vessel type is the basis for our emission calculation. Our estimate deviates by no more than±7% and ±3% for total fuel consumption and SO_2 emissions respectively. The difference in, e.g., the Mediterranean Sea is due to the different allocation of fuel consumption and emissions from national Sea traffic: FMI'17 includes them in each Sea region as much as they identify by AIS; we have separated out national Sea traffic. For the Mediterranean Sea, the national Sea traffic amounts to 110 to 120 PJ, according to national submissions to EMEP (cf. Table 2.8). Therefore, compared to the FMI'17 inventory we have a 6% higher fuel consumption when national and international Sea traffic are added. The same holds true for the other pollutants; this can be considered a very close agreement.

EMSA estimated fuel consumption by shipping in EU waters between 2011 and 2015 based on recorded activity data. Emission results are given for SECA (i.e., the Baltic and North Seas including the English Channel) and non-SECA areas aggregated. However, the EMSA inventory presumably covers only emissions in European waters within 200 nm (the EEZ), i.e., it does not encompass the Atlantic and Arctic Oceans. For the matching domains, total fuel consumption is within 2% in agreement. Yet, there are notable differences as EMSA2016 estimates 20% to 30% more consumption for the Baltic and North Seas in 2015 than FMI2017 and ourselves; as the total fuel is limited, there is up to 20% less fuel allocated to the Mediterranean Sea than in our inventory. This might need some clarification.

Version 2 of FMI's STEAM model estimates fuel consumption and pollutant emissions for the year 2011 in European waters (Jalkanen, Johansson, and Kukkonen 2016). Compared to the current version 3 (FMI17), fuel consumption is estimated 20% lower for the European waters, yet very close to EMSA's total for the year 2011. Again it is not fully clear how much of the North East Atlantic is included in this assessment. Furthermore, according to EMSA, the ship traffic (or its associated fuel consumption) was roughly stable between 2011 and 2015. If this is true then the difference to the STEAM value for 2015 must either result from changes to the model's calculation scheme, the data coverage and/or a different domain. The significant influence of model developments was already noted for STEAM v2 (Jalkanen et al. 2012); changes of even bigger magnitude also happen, e.g., between successive versions of emission inventories submitted by countries under their international reporting obligations (EMEP). Thus, we must contend that a variation of ±10% of fuel consumption for the whole shipping domain (and some higher variation for smaller Sea areas) are a consequence of inevitable uncertainties, not an error. This uncertainty increases for pollutant emissions as additional uncertainty on the engine operation, possible after-treatment and emission rate is factored in.



VITO'13: International shipping in EU waters only.

FMI'16: STEAM version 2; reference year 2011; spatial extent in Atlantic and Arctic Ocean unknown (Jalkanen, Johansson, and Kukkonen 2016).

FMI'17: STEAM version 3; reference year 2015; global coverage (Johansson, Jalkanen, and Kukkonen 2017)

EMSA16: Data only for SECA and non-SECA areas; disaggregation of SECA between Baltic and North Seas according to shares as in FMI'16.

Figure 2.2: Inventories for shipping emissions in European Seas compared with this work

The VITO estimates (VITO 2013) for international shipping in European Waters were used for the Impact Assessment for the revision of the Thematic Strategy on Air Pollutants. Fuel consumption in the year 2005 is about 6% lower than the consumption estimated for the year 2011 (FMI17 – Johansson et al., 2017, EMSA16); it is 20% lower than our value for 2015, which is compatible with the development of traffic volumes. Yet the detailed distribution differs a bit for the Mediterranean and the Bay of Biscay.

We are not in the position to decide which version is more accurate – and it is actually also not needed for the purposes of the project here: we only need to make sure that our values are in a reasonable absolute range. The main interest here is to look into the difference that various forms of implementation of a possible Emission Control Area in the Mediterranean could have on pollutant emissions and subsequent (coastal) air quality. For this, we need to analyze the difference between scenarios; a possible absolute offset therefore cancels out and does not affect the assessment.

For NO_x emissions from shipping, similar relations as for fuel consumption hold. That is very plausible as there has been – in absence of Tier III - little variation in emissions between vessel and engine types, hence the key driver for variation is the fuel consumption. The only notable exceptions are that STEAM v2 (FMI 16 – Jalkanen, Johansson, and Kukkonen 2016) and our analysis use somewhat lower emission factors resulting in lower total NO_x emissions, compared to what would be expected from fuel consumption alone.

Assessments for SO_2 and $PM_{2.5}$ emissions reflect both, differences in fuel consumption as well as the impact of a marked lowering of the fuel sulphur contents in general and the imposition of a sulphur ECA in the Baltic and North Seas. Inventories therefore agree in drop of SO_2 and PM emissions by roughly 90% for the Baltic and North Seas between 2011 and 2015. All other Sea areas remain unaffected, and their pollutant emissions simply scale with the fuel consumption assumed.

Annex 3: Fuel demand projections

Table 3.1: Fuel demand for international shipping fuel by Sea region; Baseline and "With climate measures" projections (PJ)

Year	Sea region	Baseline projection	With climate measures
2015	Arctic Sea	40	40
2015	Atlantic Ocean	187	187
2015	Baltic Sea	179	179
2015	Bay of Biscay	165	165
2015	Black Sea	62	62
2015	Celtic Sea	59	59
2015	Mediterranean Sea	713	713
2015	North Sea	358	358
2015	Total	1764	1764
2025	Arctic Sea	48	42
2025	Atlantic Ocean	251	209
2025	Baltic Sea	215	190
2025	Bay of Biscay	221	184
2025	Black Sea	80	67
2025	Celtic Sea	77	65
2025	Mediterranean Sea	942	787
2025	North Sea	436	388
2025	Total	2270	1932
2030	Arctic Sea	54	43
2030	Atlantic Ocean	303	226
2030	Baltic Sea	242	199
2030	Bay of Biscay	268	199
2030	Black Sea	94	70
2030	Celtic Sea	91	69
2030	Mediterranean Sea	1128	845
2030	North Sea	496	410
2030	Total	2677	2062
2050	Arctic Sea	70	40
2050	Atlantic Ocean	517	243
2050	Baltic Sea	322	179
2050	Bay of Biscay	440	171
2050	Black Sea	141	62
2050	Celtic Sea	139	61
2050	Mediterranean Sea	1794	734
2050	North Sea	681	364
2050	Total	4103	1854

Annex 4: Emission factors

Fuel type and quality-related emission factors used in our study are presented in Table 4.1. They depend on fuel type and sulphur content of fuels. Emission factors for fine particles originate from paper by Klimont et al. (2017), which in turn was based on a wide review of literature sources. Emissions factors for black carbon take into account recent updates published by the IMO (IMO, 2017). It needs to be stressed, that BC emissions are characterized by large variability and depend on many factors, like fuel quality, engine type and load etc. Thus average emission factors are burdened with high uncertainties.

Table 4.1: Emission factors for marine fuels, kg/GJ

Fuel	Sulfur content	CO_2	SO_2	PM10	PM2.5	BC	OC	VOC	CO
Residual oil	2.5%	76.0	1.19	0.147	0.143	0.0050	0.0360	0.075	0.068
Residual oil	1.5%	76.0	0.71	0.095	0.092	0.0050	0.0295	0.075	0.068
Residual oil	1.0%	76.0	0.47	0.076	0.073	0.0050	0.0240	0.075	0.068
Residual oil	0.5%	75.5	0.23	0.057	0.054	0.0028	0.0200	0.072	0.065
Marine diesel/gas oil	0.4%	75.1	0.18	0.053	0.051	0.0028	0.0194	0.072	0.065
Marine diesel/gas oil	0.1%	75.1	0.05	0.039	0.037	0.0025	0.0170	0.072	0.065
LNG	0.0%	61.1	0.00	0.004	0.004	0.0003	0.0022	0.067	0.174

Table 4.2 presents aggregated NO_x emission factors as used in this study. The factors are for oil-based fuels[3] and are consistent with the factors used for bottom-up analysis in the 3rd IMO GHG Study (IMO, 2015). They take into account typical engine types (slow, medium and high speed) by vessel category (Winnes et al., 2015) and different usage of engines in two operating modes: cruising and at berth/in ports.

Table 4.2: NO_x emission factors by vessel type for oil-based fuels, kg/GJ

Operating mode	ELV type	Cargo	Container	Pass. Ship	RoPax	Tanker	Veh. Carrier	Other
Berth/Ports	Tier I	1.28	1.07	1.29	1.28	1.05	1.08	1.30
Berth/Ports	Tier II	1.08	0.88	1.10	1.08	0.87	0.89	1.09
Berth/Ports	Tier III	0.26	0.23	0.27	0.26	0.24	0.23	0.26
Cruising	Tier I	1.66	1.84	1.32	1.33	1.65	1.87	1.38
Cruising	Tier II	1.45	1.64	1.12	1.13	1.45	1.66	1.17
Cruising	Tier III	0.33	0.37	0.27	0.27	0.34	0.38	0.28

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[3] The NO_x emission factor for LNG engines is assumed at 0.17 kg/GJ (IMO, 2015)

Annex 5: Emission scenarios

5.1 Structure of emission scenarios

Table 5.1: Emission scenarios considered in the study and their abbreviations

Abbreviation	SO$_x$-ECA	NO$_x$-ECA	Particle Filters (PF)
All Seas			
Baseline case			
H1	***No additional SECA***	***No additional NECA***	***No***
H2	***12 nm All Seas***	***No NECA***	***No***
H3	All Seas	No	No
H4	***All Seas, ATLO - only 12 nm***	***No additional NECA***	***No***
H5	***All Seas***	***From 2025***	***No***
H6	All Seas	From 2025 + Retro	No
H7	All Seas	From 2021 + Retro	No
H8	All Seas	From 2021 + Retro	New
H9	All Seas	From 2021 + Retro	New +Retro
H10	***All Seas, ATLO - only 12 nm***	***From 2021 + Retro, no ATLO***	***New + Retro, no ATLO***
With climate measures			
L1	***No additional SECA***	***No additional NECA***	***No***
L2	***12 nm All Seas***	***No NECA***	***No***
L3	All Seas	No	No
L4	***All Seas, ATLO - only 12 nm***	***No additional NECA***	***No***
L5	***All Seas***	***From 2025***	***No***
L6	All Seas	From 2025 + Retro	No
L7	All Seas	From 2021 + Retro	No
L8	All Seas	From 2021 + Retro	New
L9	All Seas	From 2021 + Retro	New +Retro
L10	***All Seas, ATLO - only 12 nm***	***From 2021 + Retro, no ATLO***	***New + Retro, no ATLO***
Mediterranean Sea			
Baseline case			
H1M	***12 nm MEDS EU waters***	***No NECA***	***No***
H2M	***MEDS EU waters***	***No NECA***	***No***
H3M	***MEDS EU waters***	***From 2025 EU waters***	***No***
H4M	***12 nm MEDS All waters***	***No NECA***	***No***
H5M	***All MEDS***	***No***	***No***
H6M	***All MEDS***	***From 2025 all MEDS***	***No***
With climate measures			
L1M	***12 nm MEDS EU waters***	***No NECA***	***No***
L2M	***MEDS EU waters***	***No NECA***	***No***
L3M	***MEDS EU waters***	***From 2025 EU waters***	***No***
L4M	***12 nm MEDS All waters***	***No NECA***	***No***
L5M	***All MEDS***	***No***	***No***
L6M	***All MEDS***	***From 2025 all MED Sea***	***No***

Scenarios for which the benefits analysis was performed are in bold italic

Scenarios H1 and L1 represent the current legislation projection for the Baseline and “With climate measures” marine fuel consumption

5.2 Emissions of air pollutants by scenario

Table 5.2: Emissions of SO_2 by scenario and year, kt

	2015	2020	2025	2030	2035	2040	2045	2050
All Seas								
With climate measures								
L1	1230	294	311	328	325	316	300	275
L2	1230	294	258	273	270	262	250	228
L3	1230	294	85	89	89	86	82	75
L4	1230	294	119	126	124	121	117	111
L5	1230	294	85	89	89	86	82	75
L6	1230	294	85	89	89	86	82	75
L7	1230	294	85	89	89	86	82	75
L8	1230	294	85	89	89	86	82	75
L9	1230	294	85	89	89	86	82	75
L10	1230	294	119	126	124	121	117	111
Baseline case								
H1	1230	308	371	435	507	576	609	640
H2	1230	308	307	361	422	482	510	537
H3	1230	308	100	116	133	150	158	165
H4	1230	308	141	165	191	217	229	242
H5	1230	308	100	116	133	150	158	165
H6	1230	308	100	116	133	150	158	165
H7	1230	308	100	116	133	150	158	165
H8	1230	308	100	116	133	150	158	165
H9	1230	308	100	116	133	150	158	165
H10	1230	308	141	165	191	217	229	242
Mediterranean Sea only								
With climate measures								
L1	695	156	165	175	173	168	158	141
L1M	695	156	142	151	150	145	136	121
L2M	695	156	83	88	88	85	80	71
L3M	695	156	83	88	88	85	80	71
L4M	695	156	126	133	132	128	120	107
L5M	695	156	35	37	36	35	33	30
L6M	695	156	35	37	36	35	33	30
Baseline case								
H1	695	163	198	234	273	312	329	345
H1M	695	163	171	202	237	271	287	302
H2M	695	163	100	118	139	160	169	178
H3M	695	163	100	118	139	160	169	178
H4M	695	163	151	178	209	240	254	267
H5M	695	163	41	49	57	65	69	72
H6M	695	163	41	49	57	65	69	72

Table 5.3: Emissions of NO_x by scenario and year, kt

	2015	2020	2025	2030	2035	2040	2045	2050
All Seas								
With climate measures								
L1	2835	2710	2782	2746	2544	2311	2113	1902
L2	2835	2710	2782	2746	2544	2311	2113	1902
L3	2835	2710	2782	2746	2544	2311	2113	1902
L4	2835	2710	2782	2746	2544	2311	2113	1902
L5	2835	2710	2753	2392	1895	1339	943	628
L6	2835	2710	2650	1970	1191	688	639	588
L7	2835	2710	2330	1714	1014	666	639	588
L8	2835	2710	2330	1714	1014	666	639	588
L9	2835	2710	2330	1714	1014	666	639	588
L10	2835	2710	2393	1859	1229	908	885	840
Baseline case								
H1	2835	2794	3235	3532	3886	4198	4306	4500
H2	2835	2794	3235	3532	3886	4198	4306	4500
H3	2835	2794	3235	3532	3886	4198	4306	4500
H4	2835	2794	3235	3532	3886	4198	4306	4500
H5	2835	2794	3199	2959	2711	2213	1716	1388
H6	2814	2794	3050	2361	1672	1213	1253	1326
H7	2835	2794	2631	2020	1415	1179	1253	1326
H8	2835	2794	2631	2020	1415	1179	1253	1326
H9	2835	2794	2631	2020	1415	1179	1253	1326
H10	2835	2794	2715	2236	1773	1642	1753	1867
Mediterranean Sea only								
With climate measures								
L1	1157	1110	1189	1234	1199	1154	1084	966
L1M	1157	1110	1189	1234	1199	1154	1084	966
L2M	1157	1110	1189	1234	1199	1154	1084	966
L3M	1157	1110	1178	1106	964	801	666	520
L4M	1157	1110	1189	1234	1199	1154	1084	966
L5M	1157	1110	1189	1234	1199	1154	1084	966
L6M	1157	1110	1171	1028	822	590	416	257
Baseline case								
H1	1157	1148	1404	1632	1892	2161	2291	2415
H1M	1157	1148	1404	1632	1892	2161	2291	2415
H2M	1157	1148	1404	1632	1892	2161	2291	2415
H3M	1157	1148	1391	1426	1471	1452	1370	1314
H4M	1157	1148	1404	1632	1892	2161	2291	2415
H5M	1157	1148	1404	1632	1892	2161	2291	2415
H6M	1157	1148	1384	1299	1210	1008	791	620

Table 5.4: Emissions of PM 2.5 by scenario and year, kt

	2015	2020	2025	2030	2035	2040	2045	2050
All Seas								
With climate measures								
L1	175	86	91	95	95	92	88	80
L2	175	86	86	90	89	87	83	76
L3	175	86	69	73	72	70	67	61
L4	175	86	72	76	76	73	70	65
L5	175	86	69	73	72	70	67	61
L6	175	86	69	73	72	70	67	61
L7	175	86	69	73	72	70	67	61
L8	175	86	58	48	36	21	10	6
L9	175	86	52	35	16	7	7	6
L10	175	86	58	43	26	17	17	17
Baseline case								
H1	175	89	107	125	144	163	172	180
H2	175	89	101	118	136	154	163	171
H3	175	89	81	94	109	123	129	135
H4	175	89	85	99	114	129	136	143
H5	175	89	81	94	109	123	129	135
H6	175	89	81	94	109	123	129	135
H7	175	89	81	94	109	123	129	135
H8	175	89	68	60	54	36	20	14
H9	175	89	61	41	23	12	13	14
H10	175	89	67	52	39	32	34	36
Mediterranean Sea only								
With climate measures								
L1	90	38	41	43	43	41	39	35
L1M	90	38	38	41	40	39	37	33
L2M	90	38	33	35	34	34	31	28
L3M	90	38	33	35	34	34	31	28
L4M	90	38	37	39	39	38	35	32
L5M	90	38	28	30	30	29	27	24
L6M	90	38	28	30	30	29	27	24
Baseline case								
H1	90	40	49	57	67	77	81	85
H1M	90	40	46	54	64	73	77	81
H2M	90	40	39	46	54	62	66	69
H3M	90	40	39	46	54	62	66	69
H4M	90	40	44	52	61	70	74	78
H5M	90	40	34	40	47	53	56	59
H6M	90	40	34	40	47	53	56	59

Table 5.5: Emissions of black carbon (BC) by scenario and year, kt

	2015	2020	2025	2030	2035	2040	2045	2050
All Seas								
With climate measures								
L1	7.0	4.7	5.0	5.3	5.2	5.1	4.9	4.5
L2	7.0	4.7	4.9	5.2	5.2	5.0	4.8	4.4
L3	7.0	4.7	4.7	4.9	4.9	4.8	4.6	4.2
L4	7.0	4.7	4.7	5.0	5.0	4.8	4.6	4.2
L5	7.0	4.7	4.7	4.9	4.9	4.8	4.6	4.2
L6	7.0	4.7	4.7	4.9	4.9	4.8	4.6	4.2
L7	7.0	4.7	4.7	4.9	4.9	4.8	4.6	4.2
L8	7.0	4.7	4.0	3.3	2.4	1.4	0.7	0.4
L9	7.0	4.7	3.6	2.4	1.1	0.5	0.5	0.4
L10	7.0	4.7	3.7	2.7	1.6	1.0	1.0	1.0
Baseline case								
H1	7.0	5.0	5.9	6.9	7.9	9.0	9.4	9.9
H2	7.0	5.0	5.8	6.8	7.8	8.8	9.3	9.8
H3	7.0	5.0	5.5	6.4	7.4	8.4	8.8	9.2
H4	7.0	5.0	5.6	6.5	7.5	8.5	8.9	9.3
H5	7.0	5.0	5.5	6.4	7.4	8.4	8.8	9.2
H6	7.0	5.0	5.5	6.4	7.4	8.4	8.8	9.2
H7	7.0	5.0	5.5	6.4	7.4	8.4	8.8	9.2
H8	7.0	5.0	4.7	4.1	3.7	2.5	1.3	0.9
H9	7.0	5.0	4.1	2.8	1.6	0.8	0.9	0.9
H10	7.0	5.0	4.4	3.3	2.3	1.8	2.0	2.1
Mediterranean Sea only								
With climate measures								
L1	3.3	2.0	2.1	2.2	2.2	2.1	2.0	1.8
L1M	3.3	2.0	2.1	2.2	2.2	2.1	2.0	1.8
L2M	3.3	2.0	2.0	2.1	2.1	2.0	1.9	1.7
L3M	3.3	2.0	2.0	2.1	2.1	2.0	1.9	1.7
L4M	3.3	2.0	2.0	2.2	2.2	2.1	2.0	1.8
L5M	3.3	2.0	1.9	2.0	2.0	2.0	1.8	1.7
L6M	3.3	2.0	1.9	2.0	2.0	2.0	1.8	1.7
Baseline case								
H1	3.3	2.1	2.5	3.0	3.5	4.0	4.2	4.4
H1M	3.3	2.1	2.4	2.8	3.3	3.8	4.0	4.2
H2M	3.3	2.1	2.4	2.8	3.3	3.8	4.0	4.2
H3M	3.3	2.1	2.4	2.8	3.3	3.8	4.0	4.2
H4M	3.3	2.1	2.3	2.8	3.2	3.7	3.9	4.1
H5M	3.3	2.1	2.3	2.7	3.2	3.6	3.8	4.0
H6M	3.3	2.1	2.3	2.7	3.2	3.6	3.8	4.0

5.3 Emissions by Sea zone in the Mediterranean Sea

5.3.1 Baseline fuel demand

Table 5.6: Emissions of SO_2 in the Mediterranean Sea by sea zone for alternative SO_2 ECA scenarios, kt

Year	Region and zone	H1	H1M	H2M	H4M	H5M
2025	**Mediterranean Sea**	198.0	170.5	99.8	150.6	41.5
2025	Ports/berthing EU waters	1.0	1.0	1.0	1.0	1.0
2025	12 nm zone EU waters	34.7	7.2	7.2	7.2	7.2
2025	Ports/berthing non-EU waters	2.1	2.1	2.1	0.4	0.4
2025	12 nm zone non-EU waters	23.0	23.0	23.0	4.7	4.7
2025	200 nm zone EU waters	89.0	89.0	18.3	89.0	18.3
2025	200 nm zone non-EU waters	48.2	48.2	48.2	48.2	9.9
2030	**Mediterranean Sea**	233.5	201.8	118.3	178.3	48.9
2030	Ports/berthing EU waters	1.1	1.1	1.1	1.1	1.1
2030	12 nm zone EU waters	40.0	8.3	8.3	8.3	8.3
2030	Ports/berthing non-EU waters	2.5	2.5	2.5	0.5	0.5
2030	12 nm zone non-EU waters	27.1	27.1	27.1	5.6	5.6
2030	200 nm zone EU waters	105.0	105.0	21.6	105.0	21.6
2030	200 nm zone non-EU waters	57.8	57.8	57.8	57.8	11.8
2040	**Mediterranean Sea**	311.8	271.4	159.9	240.1	65.2
2040	Ports/berthing EU waters	1.5	1.5	1.5	1.5	1.5
2040	12 nm zone EU waters	50.9	10.5	10.5	10.5	10.5
2040	Ports/berthing non-EU waters	3.5	3.5	3.5	0.7	0.7
2040	12 nm zone non-EU waters	35.9	35.9	35.9	7.4	7.4
2040	200 nm zone EU waters	140.3	140.3	28.8	140.3	28.8
2040	200 nm zone non-EU waters	79.7	79.7	79.7	79.7	16.3
2050	**Mediterranean Sea**	345.3	301.7	178.2	267.0	72.1
2050	Ports/berthing EU waters	1.6	1.6	1.6	1.6	1.6
2050	12 nm zone EU waters	54.9	11.3	11.3	11.3	11.3
2050	Ports/berthing non-EU waters	4.0	4.0	4.0	0.8	0.8
2050	12 nm zone non-EU waters	39.7	39.7	39.7	8.1	8.1
2050	200 nm zone EU waters	155.4	155.4	31.9	155.4	31.9
2050	200 nm zone non-EU waters	89.8	89.8	89.8	89.8	18.4

Table 5.7: Emissions of PM2.5 in the Mediterranean Sea by sea zone for ECA scenarios, kt

Year	Region and zone	H1	H8	H9	H1M	H2M	H4M	H5M
2025	**Mediterranean Sea**	48.6	28.4	25.3	46.0	39.2	44.1	33.7
2025	Ports/berthing EU waters	0.8	0.7	0.6	0.8	0.8	0.8	0.8
2025	12 nm zone EU waters	8.5	4.9	4.4	5.8	5.8	5.8	5.8
2025	Ports/berthing non-EU waters	0.5	0.3	0.3	0.5	0.5	0.4	0.4
2025	12 nm zone non-EU waters	5.6	3.2	2.9	5.6	5.6	3.8	3.8
2025	200 nm zone EU waters	21.6	12.5	11.1	21.6	14.9	21.6	14.9
2025	200 nm zone non-EU waters	11.7	6.8	6.0	11.7	11.7	11.7	8.0
2030	**Mediterranean Sea**	57.4	25.3	17.1	54.3	46.4	52.1	39.8
2030	Ports/berthing EU waters	0.9	0.6	0.4	0.9	0.9	0.9	0.9
2030	12 nm zone EU waters	9.8	4.3	2.9	6.7	6.7	6.7	6.7
2030	Ports/berthing non-EU waters	0.6	0.3	0.2	0.6	0.6	0.4	0.4
2030	12 nm zone non-EU waters	6.6	2.9	1.9	6.6	6.6	4.5	4.5
2030	200 nm zone EU waters	25.5	11.2	7.5	25.5	17.5	25.5	17.5
2030	200 nm zone non-EU waters	14.0	6.1	4.1	14.0	14.0	14.0	9.6
2040	**Mediterranean Sea**	76.7	15.7	5.3	72.9	62.2	69.9	53.2
2040	Ports/berthing EU waters	1.2	0.4	0.1	1.2	1.2	1.2	1.2
2040	12 nm zone EU waters	12.4	2.5	0.9	8.6	8.6	8.6	8.6
2040	Ports/berthing non-EU waters	0.9	0.2	0.1	0.9	0.9	0.6	0.6
2040	12 nm zone non-EU waters	8.7	1.8	0.6	8.7	8.7	6.0	6.0
2040	200 nm zone EU waters	34.1	6.9	2.4	34.1	23.5	34.1	23.5
2040	200 nm zone non-EU waters	19.4	3.9	1.3	19.4	19.4	19.4	13.3
2050	**Mediterranean Sea**	85.1	5.9	5.9	81.0	69.2	77.7	59.1
2050	Ports/berthing EU waters	1.3	0.1	0.1	1.3	1.3	1.3	1.3
2050	12 nm zone EU waters	13.4	0.9	0.9	9.3	9.3	9.3	9.3
2050	Ports/berthing non-EU waters	1.0	0.1	0.1	1.0	1.0	0.7	0.7
2050	12 nm zone non-EU waters	9.7	0.7	0.7	9.7	9.7	6.7	6.7
2050	200 nm zone EU waters	37.9	2.6	2.6	37.9	26.1	37.9	26.1
2050	200 nm zone non-EU waters	21.8	1.5	1.5	21.8	21.8	21.8	15.1

Table 5.8: Emissions of NO_x in the Mediterranean Sea by sea zone for alternative NO_x ECA scenarios, kt

Year	Region and zone	H1	H8	H3M	H6M
2025	**Mediterranean Sea**	1404	1343	1391	1384
2025	Ports/berthing EU waters	22	21	22	22
2025	12 nm zone EU waters	232	223	229	229
2025	Ports/berthing non-EU waters	10	9	10	10
2025	12 nm zone non-EU waters	162	155	162	159
2025	200 nm zone EU waters	629	601	619	619
2025	200 nm zone non-EU waters	349	334	349	344
2030	**Mediterranean Sea**	1632	1052	1426	1299
2030	Ports/berthing EU waters	25	17	20	20
2030	12 nm zone EU waters	264	173	212	212
2030	Ports/berthing non-EU waters	11	7	11	9
2030	12 nm zone non-EU waters	187	121	187	149
2030	200 nm zone EU waters	731	471	582	582
2030	200 nm zone non-EU waters	412	263	412	326
2040	**Mediterranean Sea**	2160.7	535.3	1451.6	1007.7
2040	Ports/berthing EU waters	31.3	8.6	15.4	15.4
2040	12 nm zone EU waters	334.0	83.2	158.6	158.6
2040	Ports/berthing non-EU waters	15.2	4.2	15.2	7.4
2040	12 nm zone non-EU waters	246.7	61.0	246.7	115.3
2040	200 nm zone EU waters	969.4	239.5	451.4	451.4
2040	200 nm zone non-EU waters	564.1	138.8	564.1	259.6
2050	**Mediterranean Sea**	2415	584	1314	620
2050	Ports/berthing EU waters	34	9	10	10
2050	12 nm zone EU waters	365	89	94	94
2050	Ports/berthing non-EU waters	17	5	17	5
2050	12 nm zone non-EU waters	275	66	275	70
2050	200 nm zone EU waters	1084	262	277	277
2050	200 nm zone non-EU waters	640	154	640	163

5.3.2 With climate measures fuel demand

Table 5.9: Emissions of SO_2 in the Mediterranean Sea by sea zone for alternative SO_2 ECA scenarios, kt

Year	Region and zone	L1	L1M	L2M	L4M	L5M
2025	**Mediterranean Sea**	165.5	142.3	83.2	125.6	34.7
2025	Ports/berthing EU waters	0.8	0.8	0.8	0.8	0.8
2025	12 nm zone EU waters	29.3	6.1	6.1	6.1	6.1
2025	Ports/berthing non-EU waters	1.7	1.7	1.7	0.4	0.4
2025	12 nm zone non-EU waters	19.2	19.2	19.2	4.0	4.0
2025	200 nm zone EU waters	74.4	74.4	15.3	74.4	15.3
2025	200 nm zone non-EU waters	40.0	40.0	40.0	40.0	8.2
2030	**Mediterranean Sea**	174.9	150.8	88.4	133.2	36.6
2030	Ports/berthing EU waters	0.9	0.9	0.9	0.9	0.9
2030	12 nm zone EU waters	30.3	6.3	6.3	6.3	6.3
2030	Ports/berthing non-EU waters	1.9	1.9	1.9	0.4	0.4
2030	12 nm zone non-EU waters	20.3	20.3	20.3	4.2	4.2
2030	200 nm zone EU waters	78.6	78.6	16.1	78.6	16.1
2030	200 nm zone non-EU waters	43.0	43.0	43.0	43.0	8.8
2040	**Mediterranean Sea**	168.1	145.1	85.1	128.2	35.2
2040	Ports/berthing EU waters	0.8	0.8	0.8	0.8	0.8
2040	12 nm zone EU waters	29.1	6.0	6.0	6.0	6.0
2040	Ports/berthing non-EU waters	1.8	1.8	1.8	0.4	0.4
2040	12 nm zone non-EU waters	19.5	19.5	19.5	4.0	4.0
2040	200 nm zone EU waters	75.5	75.5	15.5	75.5	15.5
2040	200 nm zone non-EU waters	41.4	41.4	41.4	41.4	8.5
2050	**Mediterranean Sea**	140.8	120.9	70.8	106.7	29.5
2050	Ports/berthing EU waters	0.7	0.7	0.7	0.7	0.7
2050	12 nm zone EU waters	25.0	5.2	5.2	5.2	5.2
2050	Ports/berthing non-EU waters	1.5	1.5	1.5	0.3	0.3
2050	12 nm zone non-EU waters	16.4	16.4	16.4	3.4	3.4
2050	200 nm zone EU waters	63.1	63.1	13.0	63.1	13.0
2050	200 nm zone non-EU waters	34.0	34.0	34.0	34.0	7.0

Table 5.10: Emissions of PM2.5 in the Mediterranean Sea by sea zone for alternative ECA scenarios, kt

Year	Region and zone	L1	L8	L9	L1M	L2M	L4M	L5M
2025	**Mediterranean Sea**	40.6	27.7	26.8	38.4	32.8	36.8	28.2
2025	Ports/berthing EU waters	0.7	0.7	0.6	0.7	0.7	0.7	0.7
2025	12 nm zone EU waters	7.1	4.8	4.7	4.9	4.9	4.9	4.9
2025	Ports/berthing non-EU waters	0.4	0.3	0.3	0.4	0.4	0.3	0.3
2025	12 nm zone non-EU waters	4.7	3.2	3.1	4.7	4.7	3.2	3.2
2025	200 nm zone EU waters	18.0	12.2	11.8	18.0	12.4	18.0	12.4
2025	200 nm zone non-EU waters	9.7	6.5	6.3	9.7	9.7	9.7	6.7
2030	**Mediterranean Sea**	43.0	23.8	18.7	40.7	34.7	39.0	29.8
2030	Ports/berthing EU waters	0.7	0.6	0.4	0.7	0.7	0.7	0.7
2030	12 nm zone EU waters	7.4	4.1	3.2	5.1	5.1	5.1	5.1
2030	Ports/berthing non-EU waters	0.5	0.2	0.2	0.5	0.5	0.3	0.3
2030	12 nm zone non-EU waters	4.9	2.7	2.1	4.9	4.9	3.4	3.4
2030	200 nm zone EU waters	19.1	10.5	8.3	19.1	13.1	19.1	13.1
2030	200 nm zone non-EU waters	10.4	5.7	4.5	10.4	10.4	10.4	7.2
2040	**Mediterranean Sea**	41.4	12.2	3.2	39.2	33.5	37.6	28.8
2040	Ports/berthing EU waters	0.7	0.3	0.1	0.7	0.7	0.7	0.7
2040	12 nm zone EU waters	7.1	2.1	0.6	4.9	4.9	4.9	4.9
2040	Ports/berthing non-EU waters	0.4	0.1	0.0	0.4	0.4	0.3	0.3
2040	12 nm zone non-EU waters	4.7	1.4	0.4	4.7	4.7	3.3	3.3
2040	200 nm zone EU waters	18.4	5.4	1.4	18.4	12.7	18.4	12.7
2040	200 nm zone non-EU waters	10.1	2.9	0.8	10.1	10.1	10.1	6.9
2050	**Mediterranean Sea**	34.8	3.1	2.4	32.9	28.1	31.5	24.2
2050	Ports/berthing EU waters	0.6	0.1	0.1	0.6	0.6	0.6	0.6
2050	12 nm zone EU waters	6.1	0.5	0.4	4.2	4.2	4.2	4.2
2050	Ports/berthing non-EU waters	0.4	0.0	0.0	0.4	0.4	0.3	0.3
2050	12 nm zone non-EU waters	4.0	0.4	0.3	4.0	4.0	2.8	2.8
2050	200 nm zone EU waters	15.4	1.4	1.1	15.4	10.6	15.4	10.6
2050	200 nm zone non-EU waters	8.3	0.7	0.6	8.3	8.3	8.3	5.7

Table 5.11: Emissions of NO_x in the Mediterranean Sea by sea zone for alternative NO_x ECA scenarios, kt

Year	Region and zone	L1	L8	L3M	L6M
2025	**Mediterranean Sea**	1189	1143	1178	1171
2025	Ports/berthing EU waters	19	19	19	19
2025	12 nm zone EU waters	199	191	196	196
2025	Ports/berthing non-EU waters	8	8	8	8
2025	12 nm zone non-EU waters	137	132	137	135
2025	200 nm zone EU waters	532	511	524	524
2025	200 nm zone non-EU waters	294	282	294	290
2030	**Mediterranean Sea**	1234	856	1106	1028
2030	Ports/berthing EU waters	19	14	16	16
2030	12 nm zone EU waters	202	141	169	169
2030	Ports/berthing non-EU waters	9	6	9	7
2030	12 nm zone non-EU waters	142	98	142	118
2030	200 nm zone EU waters	552	383	460	460
2030	200 nm zone non-EU waters	310	213	310	257
2040	**Mediterranean Sea**	1154	288	801	590
2040	Ports/berthing EU waters	18	5	10	10
2040	12 nm zone EU waters	188	47	97	97
2040	Ports/berthing non-EU waters	8	2	8	4
2040	12 nm zone non-EU waters	132	33	132	68
2040	200 nm zone EU waters	517	129	264	264
2040	200 nm zone non-EU waters	291	72	291	148
2050	**Mediterranean Sea**	966	235	520	257
2050	Ports/berthing EU waters	16	4	5	5
2050	12 nm zone EU waters	161	39	43	43
2050	Ports/berthing non-EU waters	7	2	7	2
2050	12 nm zone non-EU waters	112	27	112	30
2050	200 nm zone EU waters	432	105	114	114
2050	200 nm zone non-EU waters	239	58	239	63

Annex 6: Emission controls and their costs

We assess costs of implementing emission reduction measures based on information about available technologies from literature sources. We calculate annual costs for each technology, including both: investments, operating and maintenance costs associated with measures that reduce emissions of SO_2 and NO_x. All costs are given in Euro 2005. Prices and costs expressed in US$ have been converted to Euro using the 2005 exchange rate of 1€ = 1.243 US$. We have used the following deflators for costs expressed in prices of different years: 1 $€_{2005}$ = 1.10 $€_{2010}$, 1.11 $€_{2012}$, 1.15 $€_{2015}$, and 1.17 $€_{2017}$. We present costs per unit of fuel used (GJ) by a given ship category and per ton of pollutant abated. For measures that require investments, we assume a four percent real discount rate to convert investment outlays into annual costs.

In the literature, investment costs are expressed per unit of rated power of vessel engines. These costs are converted into costs per unit of fuel used using vessel-type specific annual operating hours per year. Cost assessments include the year-specific penetration of control technologies. Costs of technologies assume their commercialization and production at a sufficiently high scale. We did not attempt to assess learning effects, which might further reduce costs in the longer run compared with the costs that are currently regarded as relevant for the period 2020 to 2030.

We assume a 25 years lifetime of control equipment for new vessels and – in case of retrofits – 12.5 years for existing ones. Further, we assume that retrofitting of existing vessels can be performed only on a fraction of existing vessels due to technical constraints and due to a limited remaining lifetime of vessels. Penetration rates for retrofits are different for SO_2 and NO_x, and are explained in the relevant sections describing control costs for individual pollutants.

6.1 Options to reduce sulphur emissions

The scenarios developed in this report assume that the reduction of SO_2 emissions is achieved by successive sulfur caps on fuel under the auspices of the IMO[4] and the European Union's sulphur standards for marine fuels[5]. Reduction in SO_2 emissions needs to be achieved either using low sulfur marine fuels or by taking equivalent measures (exhaust gases scrubbing). The costs of these two alternatives are discussed below.

6.1.1 Use of low sulphur fuels

Our base case assessment of expected fuel premiums when ships change marine fuel grades (from 2025 onwards) is based on MECL, 2017[6]. These figures (after conversion to 2005 Euro) are presented in Table 6.1. It needs to be stressed that a rather high variability of prices might emerge around 2020, caused by the introduction of the IMO global 0.5% S standard. Prices are expected to stabilize after 2025, and therefore our study adopted these price expectations for the long-term.

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[4] Annex VI to MARPOL Convention

[5] Directive (EU) 2016/802

[6] Original prices are given in $US\$_{2017}$. Conversion factor to $€_{2005}$ is 0.687

Table 6.1: Cost premiums for changing fuel standards according to MECL, 2017 (base case)

Fuel	Price		Price difference			
			€/GJ		€/t SO2 abated	
	€/t	€/GJ	RO to MD	MD to MGO	RO to MD	MD to MGO
Residual oil (RO) ~ 2.5 % S	275	6.7	-	-	-	-
Marine diesel (MD) ~0.5% S	363	8.5	1.79	-	2,055	-
Marine gasoil (MGO) 0.1% S	401	9.4	2.69	0.90	2,454	4,958

6.1.2 Exhaust gas cleaning systems (scrubbers)

An alternative to using low sulfur fuels is the use of exhaust gas cleaning systems, called scrubbers to reduce SO_2 emissions by an equivalent amount. Scrubbers bring exhaust gas into contact with a buffered alkalinity so that SO_2 is trapped and converted to sulfate ions. Three different types are used today, i.e., open loop, closed loop and hybrid scrubbers (CE DELFT, 2015). Open loop scrubbers utilize untreated seawater, using the natural alkalinity of the seawater to neutralize the sulfur from exhaust gases. The negative characteristic of an open loop system is that they discharge washwater effluents. They also consume more energy compared to a closed loop system. On the other side, seawater scrubbers do not require chemical additives like caustic soda (NaOH), which is needed in a closed loop system. Open loop scrubbers cannot be used on waters with low salinity (e.g., in the Baltic Sea) and on ecologically sensitive waters where discharge of washwater effluents is not allowed.

Closed loop scrubbers are not dependent on the type of the water the vessel is operating in, because exhaust gases are neutralized with NaOH, which is added to freshwater in a closed system. Circulating water is processed after the scrubber and dosed with caustic soda in order to restore the alkalinity of washwater. The amount of water needed in a closed loop process is about half of the flow in an open loop system.

Hybrid scrubbers give the possibility to either use closed loop or open loop technology. Hybrid scrubbers are generally used as an open loop system when the vessel is operating in the open sea, and as a closed loop system when operating in harbor estuaries or ports, where water discharge is prohibited. Among the different types of scrubbers, hybrid scrubbers are likely to become increasingly common because of their flexibility. Thus in our study we adopted parameters characteristic for the hybrid devices, assuming that they will operate in an open mode at open seas. For the Baltic Sea, where the alkalinity of water is not high enough, we assume the closed mode. For territorial waters (12 nm from coast) we assume operation in the closed mode over 10% of time. These assumptions can be easily changed if more information will become available.

Scrubber parameters are summarized in Table 6.2. We conclude that scrubbers operate during the whole time of operation at sea, which (after Åström et al., 2017) is approximately 5500 hours per year. Based on these assumptions, unit costs are presented in Table 6.3 for residual oil with 2.4 % S[7] and an emission

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[7] Average S content for marine residual oil in European waters in 2016 (compare EMSA, 2017)

reduction to either 0.5% or 0.1% S equivalent depending on sea region. For the open loop mode, unit SO_2 reduction costs are much lower than the costs of using low sulfur fuels.

Table 6.2 Cost parameters for scrubbers (hybrid systems)

Item	Unit	Value
Capital investment		
New scrubbers	€/kW	225
Retrofits	€/kW	338
Variable operating and maintenance cost components		
Closed mode:		
NaOH price	€/l	0.55
NaOH use (RO 2.4 to 0.5% S)	l/MWh	10.3
NaOH use (RO 2.4 to 0.1% S)	l/MWh	13.2
NaOH use (MD 0.4 to 0.1% S)	l/MWh	1.28
Water price	€/t	20.3
Water use	l/MWh	100
Sludge disposal	€/l	0.09
Sludge volume	l/MWh	0.20
Fuel penalty	%	1.0%
Open mode		
Fuel penalty	%	2.0%

Sources: Capital investments – CE DELFT, 2015; Caustic soda use – AEA Technology, 2007; all other parameters – Åström et al., 2017. Average sulfur content of RO and MD in European waters in 2016 according to EMSA, 2017.

Table 6.3: SO_2 control costs with scrubbers for different fuels and modes of operation

Fuel/vessel type	€/GJ fuel % in a closed mode			€/t SO2 abated % in a closed mode		
	0%	10%	100%	0%	10%	100%
New vessels						
Residual oil ((RO) in SECA	0.56	0.66	1.60	506	602	1,461
Residual oil ((RO) outside SECA	0.56	0.64	1.41	637	736	1,619
Marine diesel to MGO in SECA	0.59	0.62	0.84	3,257	3,391	4,596
Existing vessels, retrofits						
Residual oil ((RO) in SECA	1.35	1.46	2.40	1,233	1,328	2,187
Residual oil ((RO) outside SECA	1.35	1.44	2.21	1,551	1,649	2,533
Marine diesel to MGO in SECA	1.39	1.41	1.63	7,643	7,777	8,983

The assumed share of oil fuels by vessels equipped with scrubbers is presented in Table 6.4. As a starting point we have taken analysis done up to 2035 for the whole world fleet by IBIA (MECL, 2017). It assumes that in 2020 about 3800 vessels, using about nine percent of world maritime bunkers, will be equipped with scrubbers. Since other sources (e.g., IHS Markit, 2018) are less optimistic, we have assumed that fuel consumed by vessels with scrubbers will be only 40% of that projected by IBIA in 2020 and 55% in 2030. Further we assumed that at least 20% of vessels of all types will use low sulfur fuels. We are aware that predicting the use of scrubbers as a compliance measure is burdened with many uncertainties, like:

- acceptance in ports worldwide of washwater from open loop scrubbers since their composition may hamper the compliance with existing water quality legislation
- price differentials between high and low sulphur oil
- future requirements to reduce CO_2 emissions.

In April 2018 the IMO has adopted an initial strategy to reduce at least 50% greenhouse gas (GHG) emissions from the global shipping sector by 2050, compared to 2008. This might cause the necessity to replace heavy fuel oil or middle distillates with alternative fuels or even change the propulsion systems and thus decrease the uptake of scrubbers. Another issue is the availability of residual oil in the future. Some sources (e.g., Jordan and Hickin, 2017) anticipate that residual oil could become a niche fuel and will not be available in all ports. With these caveats we calculate the difference in compliance costs in case scrubbers will be used as a technology to control SO_2 emissions.

Table 6.4: Share of sulphur control measures by vessels using oil, % total oil-based fuel

	Scrubbers		Low sulphur
Year	New	Retrofits	fuel
2020	2%	1%	96%
2025	14%	5%	81%
2030	23%	7%	70%
3035	30%	9%	61%
2040	52%	0%	48%
2045	65%	0%	35%
2050	80%	0%	20%

6.2 Options to reduce NO_x emissions

We consider two technologies that reduce NO_x emissions from marine engines using oil. Advanced internal engine modifications (AIEM) allow to reach Tier II emission standards. Tier III is possible through exhaust gas recirculation in combination with water in fuel injection (EGR+WIF) or through selective catalytic reduction (SCR). Since (according to Åström et al., 2017) the EGR+WIF is more expensive per unit of NO_x reduction, we include only SCR as a way to reduce emissions to the Tier III level. SCR is an exhaust gas after treatment technology that achieves NO_x abatement of more than 80 %. It has to be installed separately for each engine of a ship and needs urea as a sorbent.

Engines driven by liquefied natural gas (LNG) meet the SECA and NECA standards without any additional control measures. The future penetration rates of LNG are very uncertain. Development of LNG as a maritime fuel depends on many factors, for which analysis is beyond the scope of this study. Thus, we limit our calculations to the baseline uptake of LNG as described in Annex 3. Wider use of LNG is likely to decrease compliance costs. Thus the estimates of this study can be interpreted as upper limits of costs related to the creation of new emission control areas (ECAs).

Investment costs for AIEM increase with vessel size. Based on Åström, 2017 we estimate that these costs are in the range of 120 to 150 thousand Euro/vessel for ships with total rated power of engines between 7 and 17 MW. Table 6.5 presents the parameters of the SCR systems installed on ships, based on Åström et al., 2017.

Table 6.5: Cost parameters for SCR systems

Item	Unit	Value
Capital investment		
New vessels	€/kW	62
Retrofits	€/kW	93
Variable operating and maintenance cost components		
Urea price (100% urea)	€/t	166
Urea consumption	g/kWh	6.5
Costs of catalyst use	€/MWh	0.46
Catalyst replacement labor	hours/year	8
Labor costs	€/h	32

Unit costs of NO_x controls with SCR depend on the time vessels operate in regions where Tier III emission standards are required. We have estimated the costs based on two variants of operating time. The first (short time) corresponds to the values for the North Sea and Baltic Sea NECAs, as published by Åström et al., 2017. Time spent by vessels in NECAs is likely to increase when more NO_x emission control areas will be established in the future. Therefore, in the scenarios with new NECAs we assume doubling of the operating time in NECAs up to a limit of 5500 h/year, which is the average time spent by vessels at Sea. It is characteristic that ferries (RoRo and RoPax vessels) as well as other vessels (fishing, service and miscellaneous ships) spend long time within a given Sea basin. In turn, cargo, container ships and tankers travel longer distances and their time in NECAs is limited.

Table 6.6: Average installed power of engines (MW/vessel[8]) and time spent at Sea (hours/year) by vessel category as used in calculation of NO_x control costs

	Cargo	Container	Passenger Ships	RoPax	Tankers	Vehicle carriers	Others
Installed power, MW	8.4	11.4	17.3	7.6	12.4	8.7	6.9
Hours at Sea per year							
Tier II (AIEM)	5500	5500	5500	5500	5500	5500	5500
Tier III (SCR) – NECA only in BALS and NORS	750	1200	1500	4300	1050	2150	5500
Tier III (SCR) – NECA also in other seas	1500	2400	3000	5500	2100	4300	5500

Costs of controlling NO_x emissions per unit of fuel used are presented in Table 6.7. Table 6.8 shows costs per ton of NO_x abated. Cost of Tier II control are relatively low – 80 to 150 €/t NO_x. Costs of SCR heavily depend on the operating time in NECAs. For new vessels with long time in NECA (RoPax, vehicle carrier, service ships, fishing vessels, etc.), costs range is in the order 300 €/t NO_x, but ships travelling long distances and thus with limited time in NECA have much higher unit costs. This also refers to retrofits, which are more expensive because of higher capital outlays and lower amortization time.

Table 6.7: Unit costs of controlling NO_x emissions, €/GJ fuel

Control stage	Cargo	Container	Passenger Ships	RoPax	Tankers	Vehicle carriers	Others
Tier II (AIEM)	0.029	0.024	0.015	0.031	0.022	0.030	0.032
Tier III (SCR) - new vessels							
NECA only in BALS and NORS	1.067	0.733	0.585	0.321	0.802	0.495	0.291
NECA also in other Seas	0.640	0.461	0.381	0.289	0.494	0.342	0.291
Tier III (SCR) - retrofits							
NECA only in BALS and NORS	2.639	1.758	1.355	0.591	1.960	1.070	0.502
NECA also in other Seas	1.411	0.973	0.765	0.500	1.073	0.629	0.502

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[8] Sum of rated power of the main and auxiliary engines

Table 6.8: Unit costs of controlling NO_x emissions, €/t NO_x abated

Control stage	Cargo	Container	Passenger Ships	RoPax	Tankers	Vehicle carriers	Others
Tier II (AIEM)	145	115	80	153	113	145	154
Tier III (SCR) - new vessels							
NECA only in BALS and NORS	818	508	565	306	623	338	267
NECA also in other Seas	490	319	368	276	384	233	267
Tier III (SCR) - retrofits							
NECA only in BALS and NORS	2,023	1,218	1,309	563	1,524	731	461
NECA also in other Seas	1,082	674	739	477	834	430	461

6.3 Particle filters

Investment cost data for installing particle filters are based on data from Vito, 2013. They are consistent with the values reported by Corbett et al., 2010. Operating time of particle filter has been assumed as for the variant with NECAs on all European seas. The calculations adopt a removal efficiency of fine particles and black carbon of 90%. This is rather a conservative estimate, since other sources report the efficiency higher than 95%.

Table 6.9: Capital investments and lifetime of particle filters

	Investments	Lifetime
	€/kW	years
New vessels	30	25
Retrofits	45	12.5

Table 6.10: Unit costs of controlling PM emissions from shipping through the use of particle filters

(a) €/GJ fuel

Vessel type	Cargo	Container	Passenger Ship	RoPax	Tanker	Vehicle Carrier	Other
New vessels	0.205	0.131	0.098	0.054	0.148	0.073	0.054
Retrofits	0.591	0.378	0.284	0.156	0.427	0.212	0.156

(b) €/t PM2.5 abated

Control stage	Cargo	Container	Passenger Ship	RoPax	Tanker	Vehicle Carrier	Other
New vessels	6,148	3,933	2,954	1,620	4,445	2,207	1,627
Retrofits	17,742	11,349	8,525	4,675	12,828	6,369	4,695

6.4 Costs of emission control scenarios

Table 6.11: Current legislation (CLE) emission control costs, all European Seas, base cost premium for low S marine fuels, Billion €/a. The table includes costs for international and national shipping.

Case	2030	2040	2050
H1 (baseline)			
No scrubbers	4.7	6.3	7.0
With scrubbers	4.0	4.3	3.7
L1 (with climate measures)			
No scrubbers	3.7	3.7	3.2
With scrubbers	3.1	2.5	1.8

Table 6.12: SO_2 emission control costs for international shipping, baseline fuel demand, Million €/a

		No scrubbers			With scrubbers		
		Current Legislation (H1)	SOx-ECA		Current Legislation (H1)	SOx-ECA	
Year	Sea region		All zones	12 nm		All zones	12 nm
2025	**Arctic Sea**	68	109	87	61	95	77
2025	**Atlantic Ocean**	286	448	295	255	390	263
2025	**Baltic Sea**	501	501	501	472	472	472
2025	**Bay of Biscay**	340	533	350	303	463	311
2025	**Black Sea**	119	189	148	107	165	131
2025	**Celtic Sea**	116	182	135	104	158	119
2025	**Mediterranean Sea**	1425	2228	1669	1275	1943	1480
2025	**North Sea**	1032	1032	1032	901	901	901
2025	**Total**	3887	5221	4216	3478	4588	3755
2030	**Arctic Sea**	75	121	97	63	97	79
2030	**Atlantic Ocean**	343	536	353	283	425	291
2030	**Baltic Sea**	557	557	557	506	506	506
2030	**Bay of Biscay**	406	634	416	335	502	343
2030	**Black Sea**	138	219	171	115	175	141
2030	**Celtic Sea**	136	212	157	113	169	128
2030	**Mediterranean Sea**	1682	2628	1967	1400	2095	1613
2030	**North Sea**	1157	1157	1157	924	924	924
2030	**Total**	4493	6064	4874	3740	4894	4025
2040	**Arctic Sea**	88	142	114	58	87	72
2040	**Atlantic Ocean**	474	741	487	304	442	311
2040	**Baltic Sea**	661	661	661	527	527	527
2040	**Bay of Biscay**	554	866	568	355	516	363
2040	**Black Sea**	178	282	220	115	171	141
2040	**Celtic Sea**	178	276	203	116	167	129
2040	**Mediterranean Sea**	2253	3516	2622	1465	2123	1665
2040	**North Sea**	1400	1400	1400	850	850	850
2040	**Total**	5786	7882	6274	3792	4884	4058
2050	**Arctic Sea**	91	146	118	44	61	52
2050	**Atlantic Ocean**	562	877	577	259	345	264
2050	**Baltic Sea**	689	689	689	480	480	480
2050	**Bay of Biscay**	621	969	636	286	380	290
2050	**Black Sea**	193	305	238	91	125	109
2050	**Celtic Sea**	194	302	221	92	121	100
2050	**Mediterranean Sea**	2499	3897	2901	1184	1573	1308
2050	**North Sea**	1479	1479	1479	606	606	606
2050	**Total**	6329	8665	6858	3041	3691	3209

Table 6.13: SO_2 emission control costs for international shipping, ‘with climate measures’ fuel demand, Million €/a

		No scrubbers			With scrubbers		
		Current Legislation (L1)	SOx-ECA		Current Legislation (L1)	SOx-ECA	
Year	Sea region		All zones	12 nm		All zones	12 nm
2025	**Arctic Sea**	58	94	75	52	82	66
2025	**Atlantic Ocean**	238	373	246	213	325	219
2025	**Baltic Sea**	444	444	444	418	418	418
2025	**Bay of Biscay**	283	443	291	252	385	259
2025	**Black Sea**	100	159	124	89	139	110
2025	**Celtic Sea**	98	153	113	88	133	101
2025	**Mediterranean Sea**	1190	1861	1395	1065	1623	1237
2025	**North Sea**	916	916	916	800	800	800
2025	**Total**	3327	4442	3604	2977	3906	3211
2030	**Arctic Sea**	59	94	75	49	76	62
2030	**Atlantic Ocean**	255	400	263	211	317	217
2030	**Baltic Sea**	458	458	458	416	416	416
2030	**Bay of Biscay**	302	472	310	250	374	256
2030	**Black Sea**	104	164	129	86	131	106
2030	**Celtic Sea**	103	160	119	85	127	97
2030	**Mediterranean Sea**	1259	1968	1474	1048	1569	1209
2030	**North Sea**	956	956	956	764	764	764
2030	**Total**	3496	4673	3784	2910	3775	3126
2040	**Arctic Sea**	56	90	72	37	55	45
2040	**Atlantic Ocean**	251	392	258	161	234	165
2040	**Baltic Sea**	439	439	439	350	350	350
2040	**Bay of Biscay**	291	455	299	187	271	191
2040	**Black Sea**	99	157	123	64	95	79
2040	**Celtic Sea**	99	154	114	64	93	72
2040	**Mediterranean Sea**	1211	1892	1417	788	1144	900
2040	**North Sea**	918	918	918	558	558	558
2040	**Total**	3363	4497	3639	2209	2802	2360
2050	**Arctic Sea**	50	81	65	24	34	29
2050	**Atlantic Ocean**	264	413	272	122	163	124
2050	**Baltic Sea**	381	381	381	265	265	265
2050	**Bay of Biscay**	240	376	247	111	148	113
2050	**Black Sea**	85	135	105	40	55	48
2050	**Celtic Sea**	84	131	98	40	53	44
2050	**Mediterranean Sea**	1012	1583	1188	481	642	535
2050	**North Sea**	785	785	785	323	323	323
2050	**Total**	2901	3884	3140	1406	1684	1482

Table 6.14: NO_x emission control costs for international shipping, Million €/a[9]

Year	Sea region	Baseline			With climate measures		
		Current Legislation (H1)	Tier III from 2025		Current Legislation (L1)	Tier III from 2025	
			With retrofits	No retrofits		With retrofits	No retrofits
2025	**Arctic Sea**	1	6	1	1	3	1
2025	**Atlantic Ocean**	4	40	6	3	16	5
2025	**Baltic Sea**	27	45	19	23	22	16
2025	**Bay of Biscay**	4	34	6	3	14	4
2025	**Black Sea**	1	13	2	1	5	2
2025	**Celtic Sea**	1	11	2	1	5	1
2025	**Mediterranean Sea**	15	138	24	11	57	17
2025	**North Sea**	55	94	38	48	46	33
2025	**Total**	109	381	98	90	167	79
2030	**Arctic Sea**	1	19	6	1	11	4
2030	**Atlantic Ocean**	6	137	44	4	74	27
2030	**Baltic Sea**	64	95	43	49	57	33
2030	**Bay of Biscay**	5	118	38	4	64	23
2030	**Black Sea**	2	45	14	1	24	9
2030	**Celtic Sea**	2	37	12	1	20	8
2030	**Mediterranean Sea**	23	470	152	15	256	95
2030	**North Sea**	135	199	90	103	121	69
2030	**Total**	238	1119	399	178	627	268
2040	**Arctic Sea**	2	34	18	1	17	11
2040	**Atlantic Ocean**	10	251	141	5	114	68
2040	**Baltic Sea**	151	144	99	96	84	64
2040	**Bay of Biscay**	9	216	122	5	98	59
2040	**Black Sea**	3	81	44	2	38	22
2040	**Celtic Sea**	3	66	37	2	31	19
2040	**Mediterranean Sea**	36	858	484	20	396	238
2040	**North Sea**	323	304	210	202	177	133
2040	**Total**	536	1955	1157	331	957	613
2050	**Arctic Sea**	2	28	27	1	15	14
2050	**Atlantic Ocean**	12	234	225	5	110	104
2050	**Baltic Sea**	197	129	129	103	69	69
2050	**Bay of Biscay**	10	194	187	4	76	71
2050	**Black Sea**	3	70	67	1	30	28
2050	**Celtic Sea**	3	59	56	1	25	23
2050	**Mediterranean Sea**	40	767	737	17	310	292
2050	**North Sea**	426	275	275	215	142	142
2050	**Total**	692	1756	1703	349	777	744

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[9] when NO_x ECA (Tier III) standards are extended to other Sea regions, the costs for the existing NO_x ECA zones (the Baltic Sea and the North Sea) decrease compared with the current legislation case because the operating hours of SCR installations become longer

Table 6.15: PM emission control costs for international shipping, Million €/a[10]

		Baseline		With climate measures	
Year	Sea region	With retrofits	No retrofits	With retrofits	No retrofits
2025	**Arctic Sea**	3	1	1	1
2025	**Atlantic Ocean**	22	6	9	5
2025	**Baltic Sea**	15	4	6	4
2025	**Bay of Biscay**	19	5	7	4
2025	**Black Sea**	7	2	3	2
2025	**Celtic Sea**	6	2	2	1
2025	**Mediterranean Sea**	74	21	29	18
2025	**North Sea**	31	9	13	8
2025	**Total**	176	51	70	43
2030	**Arctic Sea**	6	2	3	2
2030	**Atlantic Ocean**	49	17	25	12
2030	**Baltic Sea**	32	11	18	9
2030	**Bay of Biscay**	42	15	22	10
2030	**Black Sea**	16	6	9	4
2030	**Celtic Sea**	13	4	7	3
2030	**Mediterranean Sea**	164	58	86	40
2030	**North Sea**	67	24	39	18
2030	**Total**	389	137	209	97
2040	**Arctic Sea**	10	6	5	3
2040	**Atlantic Ocean**	76	47	35	24
2040	**Baltic Sea**	45	27	25	17
2040	**Bay of Biscay**	65	40	30	20
2040	**Black Sea**	25	15	12	8
2040	**Celtic Sea**	19	12	9	6
2040	**Mediterranean Sea**	254	156	118	80
2040	**North Sea**	95	58	54	36
2040	**Total**	588	360	289	194
2050	**Arctic Sea**	8	8	4	4
2050	**Atlantic Ocean**	67	67	31	31
2050	**Baltic Sea**	36	36	19	19
2050	**Bay of Biscay**	55	55	21	21
2050	**Black Sea**	21	21	9	9
2050	**Celtic Sea**	16	16	7	7
2050	**Mediterranean Sea**	215	215	85	85
2050	**North Sea**	77	77	39	39
2050	**Total**	496	496	214	214

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[10] The table shows the results for the case when particle filters are phased-in from 2021

Table 6.16: Incremental emission control costs relative to the current legislation, Million €/a. Costs cover international and national shipping

	No scrubbers			With scrubbers		
Scenario	2030	2040	2050	2030	2040	2050
All European Seas						
L2	363	343	305	291	217	142
L3	1252	1201	1049	940	659	344
L4	1116	1066	811	840	590	261
L5	1354	1534	1489	1042	993	784
L6	1714	1877	1523	1401	1336	818
L7	1726	1852	1505	1414	1311	800
L8	1823	2047	1719	1510	1505	1014
L9	1991	2188	1719	1679	1646	1014
L10	1750	1908	1349	1475	1432	799
H2	455	555	595	360	333	233
H3	1646	2163	2402	1229	1159	715
H4	1462	1909	2101	1095	1028	634
H5	1818	2835	3458	1401	1831	1771
H6	2332	3367	3511	1915	2362	1825
H7	2556	3521	3482	2139	2516	1796
H8	2693	3881	3978	2276	2876	2292
H9	2945	4109	3978	2528	3105	2292
H10	2579	3557	3393	2211	2675	1925
Mediterranean Sea only						
L1M	179	166	149	146	109	76
L2M	499	473	406	380	268	145
L3M	559	653	617	439	448	356
L4M	269	253	222	215	158	101
L5M	764	728	617	576	403	208
L6M	854	992	933	666	667	524
H1M	219	255	271	176	156	110
H2M	646	826	902	487	449	278
H3M	736	1143	1366	577	766	741
H4M	339	416	448	267	246	171
H5M	1001	1309	1444	750	705	435
H6M	1141	1803	2182	890	1199	1174

Annex 7: Benefits assessment

7.1 Overview

The methods used for quantification of the health damage associated with each scenario follow use of the impact pathway approach (Figure 7.1) as used previously for analysis of proposals made in the context of the EU's Thematic Strategy on Air Pollution and Clean Air Programme (Holland, 2014a, b) using the ALPHA-Riskpoll (ARP) model (Holland et al, 2013). For the present analysis the model has been extended to include countries in North Africa and the Middle East.

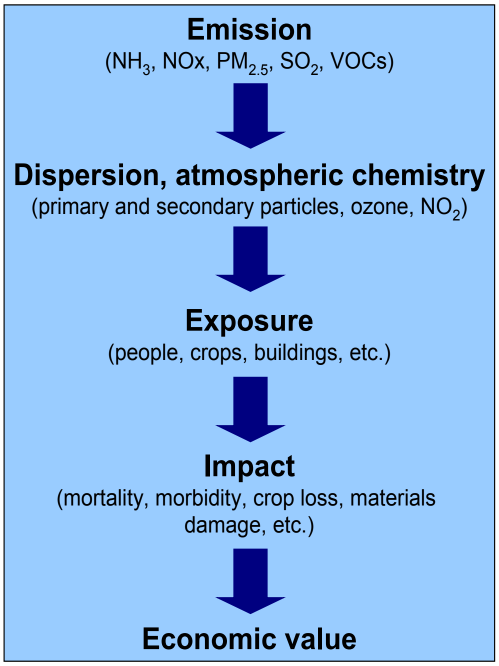

Figure 7.1: Impact Pathway Approach, tracing the consequences of pollutant release from emission to impact and economic value.

Key inputs to the analysis, in addition to information on population-weighted pollution exposure data for ozone and fine particles from the GAINS model were:

- Population data: UN Medium Projections (UN, 2017)
- Health response functions: WHO-Europe's HRAPIE (Health Risks of Air Pollution in Europe) study (WHO, 2013; Holland, 2014a)
- Valuation data: Estimates adopted for the EU's Clean Air Package of 2013 (Holland, 2014b). Valuation data are given in Euro, at 2005 prices to match the cost data used in GAINS.

The health effects quantified, in line with the HRAPIE recommendations, are shown in Table 7.1. The rating in the second column distinguishes those effects that can be quantified with most confidence ("A") from those quantified with less confidence ("B"). Those effects marked with an asterisk were recommended by the HRAPIE team for inclusion in cost-benefit analysis.

Table 7.1: List of health impacts – HRAPIE recommendations. Full details of response functions and other inputs to the analysis are provided by Holland (2014a, b).

Impact / population group	Rating	Population	Exposure metric
All cause mortality from chronic exposure	B	Over 30 years	O_3, SOMO35, summer months
All cause mortality from acute exposure	A*/A	All ages	O_3, SOMO35 (A*), SOMO10 (A)
Cardiac and respiratory mortality from acute exposure	A	All ages	O_3, SOMO35 (A*), SOMO10 (A)
Respiratory Hospital Admissions	A*/A	Over 65 years	O_3, SOMO35 (A*), SOMO10 (A)
Cardiovascular hospital admissions	A*/A	Over 65 years	O_3, SOMO35 (A*), SOMO10 (A)
Minor Restricted Activity Days (MRADs)	B*/B	All ages	O_3, SOMO35 (B*), SOMO10 (B)
All cause mortality from chronic exposure as life years lost or premature deaths	A*	Over 30 years	$PM_{2.5}$, annual average
Cause-specific mortality from chronic exposure	A	Over 30 years	$PM_{2.5}$, annual average
Infant Mortality	B*	1 month to 1 year	$PM_{2.5}$, annual average
Chronic bronchitis in adults	B*	Over 27 years	$PM_{2.5}$, annual average
Bronchitis in children	B*	6 – 12 years	$PM_{2.5}$, annual average
All cause mortality from acute exposure	A	All ages	$PM_{2.5}$, annual average
Respiratory Hospital Admissions	A*	All ages	$PM_{2.5}$, annual average
Cardiovascular Hospital Admissions	A*	All ages	$PM_{2.5}$, annual average
Restricted Activity Days (RADs)	B*	All	$PM_{2.5}$, annual average
Including lost working days	B*	15 to 64 years	$PM_{2.5}$, annual average
Asthma symptoms in asthmatic children	B*	5 to 19 years	$PM_{2.5}$, annual average
All cause mortality from chronic exposure	B*	Over 30 years	NO_2 annual mean >20ug.m^{-3}
All cause mortality from acute exposure	A*	All ages	NO_2 annual mean
Bronchitis in children	B*	5 – 14 years	NO_2 annual mean
Respiratory hospital admissions	A*	All ages	NO_2 annual mean

Results for mortality in terms of the numbers of deaths associated with exposure to ozone and to $PM_{2.5}$ are quantified by both the GAINS model and ARP. A like for like comparison of mortality results, expressed as number of deaths for both pollutants, demonstrates consistency in quantification across the two models.

7.2 Population at risk

A difference between the GAINS and ARP modelling concerns the treatment of the population at risk. Within GAINS, health assessment is performed taking a constant population, that of 2010. This enables the modelling to be based on changes in exposure levels and, hence individual risk: this approach is appropriate in the context of cost-effectiveness analysis, stripping out demographic change which will be largely unaffected by air pollution policy, to give a clearer impression of how risk will change over time.

The benefits assessment, however, matches the year of each scenario with projected population and population age structure in each country to quantify likely benefits in each year, relative to impacts in the same year under current legislation. Accounting for population change in the benefits analysis avoids inconsistency in estimates of overall cost and overall benefit, bearing in mind that future emissions will be partly a function of the population.

The relationship between air pollution and the population in any country will change over time. For example, childhood mortality rates are falling: whilst this is not significant for most EU states given already low rates, it is significant for some of the countries of the Middle East and North Africa that are included. Similarly, the relative proportions of people in different age bands will change, which feeds through into the analysis because most of the response functions used are age-specific. Life-table analysis (Miller et al, 2011) has found that population response to fine particles changes with life expectancy (Figure 7.2). Given the close relationship between life expectancy and response observed in the Figure, observed relationships are factored into the analysis of life years lost to $PM_{2.5}$ using projected life expectancy data from UN (2017). The same approach has not, however, been applied to estimates of future deaths for which the analysis presented here is not based on life tables but on projected mortality rates.

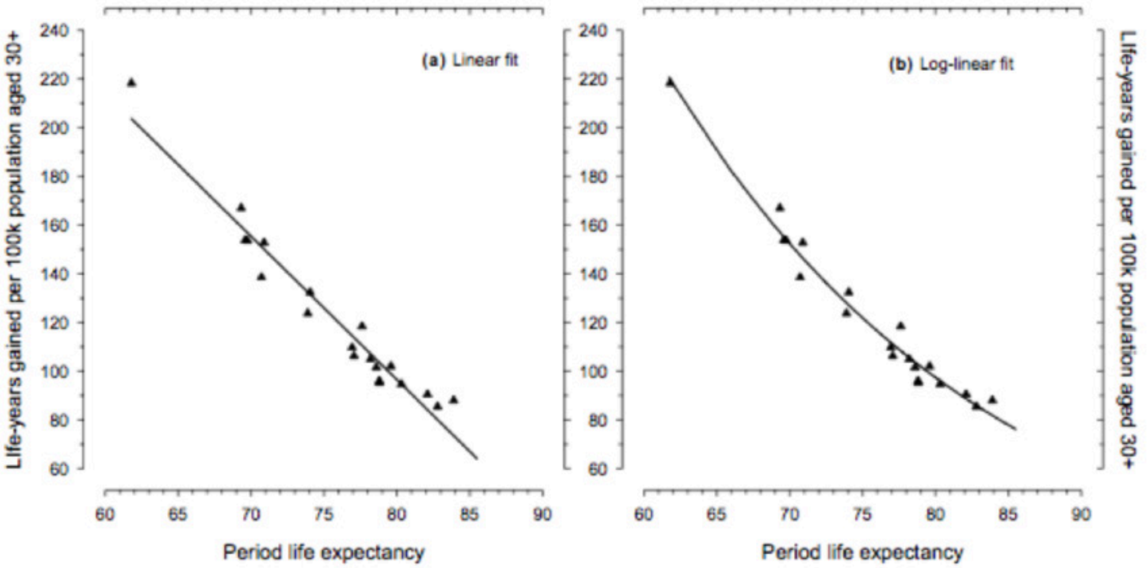

Figure 7.2: Linear and log-linear relationships between life expectancy and life years gained per 100,000 people in the population aged over 30 years per unit change in $PM_{2.5}$ exposure. Points represent men and women in 10 countries.

7.3 Strategy for Health Impact Assessment

For the purpose of the present study it was necessary to consider whether the HRAPIE recommendations could be extended beyond the European region to the countries of Northern Africa and the Middle East. Other studies, such as the Global Energy and Climate Outlook 2017 (JRC, 2017) have adopted recommendations from the Global Burden of Disease programme (GBD, 2015) in some cases for all countries, and in others for all countries outside of Europe and North America. The logic for taking different approaches in different regions is as follows:

- The epidemiological literature on air pollution, especially for studies around long-term exposure, has been dominated by work in North America and Europe. Debate in support of policy work in those regions has concluded that mortality can most robustly be quantified against response relationships related to all-cause mortality (all-cause, but excluding deaths from accidents, violence, etc.), rather than a suite of cause-specific functions (ischaemic heart disease, chronic obstructive pulmonary disease, lower respiratory infections and lung cancer). Reasons for this preference concern the larger amount of data available on all-cause mortality, and in Europe, unexplained variability between countries in attribution of deaths to specific causes.
- Adoption of the same functions in other regions has not been generally recommended given differences in health status relative to North America and Europe. Examples include high levels of HIV/AIDs, malaria or malnutrition. On this basis, an approach based on use of cause-specific response functions for mortality seems more reasonable, accepting the caveats made in the previous paragraph about data availability and variability.
- Another reason for seeking an alternative approach concerns very high levels of air pollution in major countries including China and India, much higher than the levels observed in the European and North American literature.

Recognizing the second and third of these issues has led GBD to adopt non-linear and cause-specific mortality functions. For the present study it has been necessary to assess which set of functions seems likely to provide the most robust analysis for North Africa and the Middle East.

This has involved consideration of data on:

- Cardiovascular morbidity (WHO, 2015)
- Respiratory morbidity (WHO, 2015)
- Life expectancy (UN, 2017)
- Background pollution levels.

Data for cardiovascular and respiratory morbidity and life expectancy are summarized in Table 7.2, with information by country shown in Figure 7.3 to Figure 7.5.

Table 7.2. Average rates of cardiovascular and respiratory disease (both per 1000 people) and life expectancy across different country groupings. Data sources: Adapted from WHO (2015) and UN (2017).

	Cardiovascular DALYs	Respiratory DALYs	Life expectancy 2030
EU15	49.9	14.0	82.5
EU13	103.0	10.9	78.4
EU28	74.6	12.6	80.6
EEA	37.5	11.9	83.7
Europe Non-EU	119.8	9.5	75.6
Africa, Middle East	55.3	7.7	76.9

The prevalence of cardiovascular DALYs in the North Africa and Middle East countries included here is very similar to rates across the EU28. Respiratory DALYs are lower. Life expectancy is lower than for the EU in 2030, but not dissimilar to life expectancy in the EU at the period over which the epidemiology studies on which the $PM_{2.5}$ chronic mortality function is based were carried out. On this evidence it is concluded that there are not differences in health state that are so significant to warrant following an alternative to the HRAPIE approach.

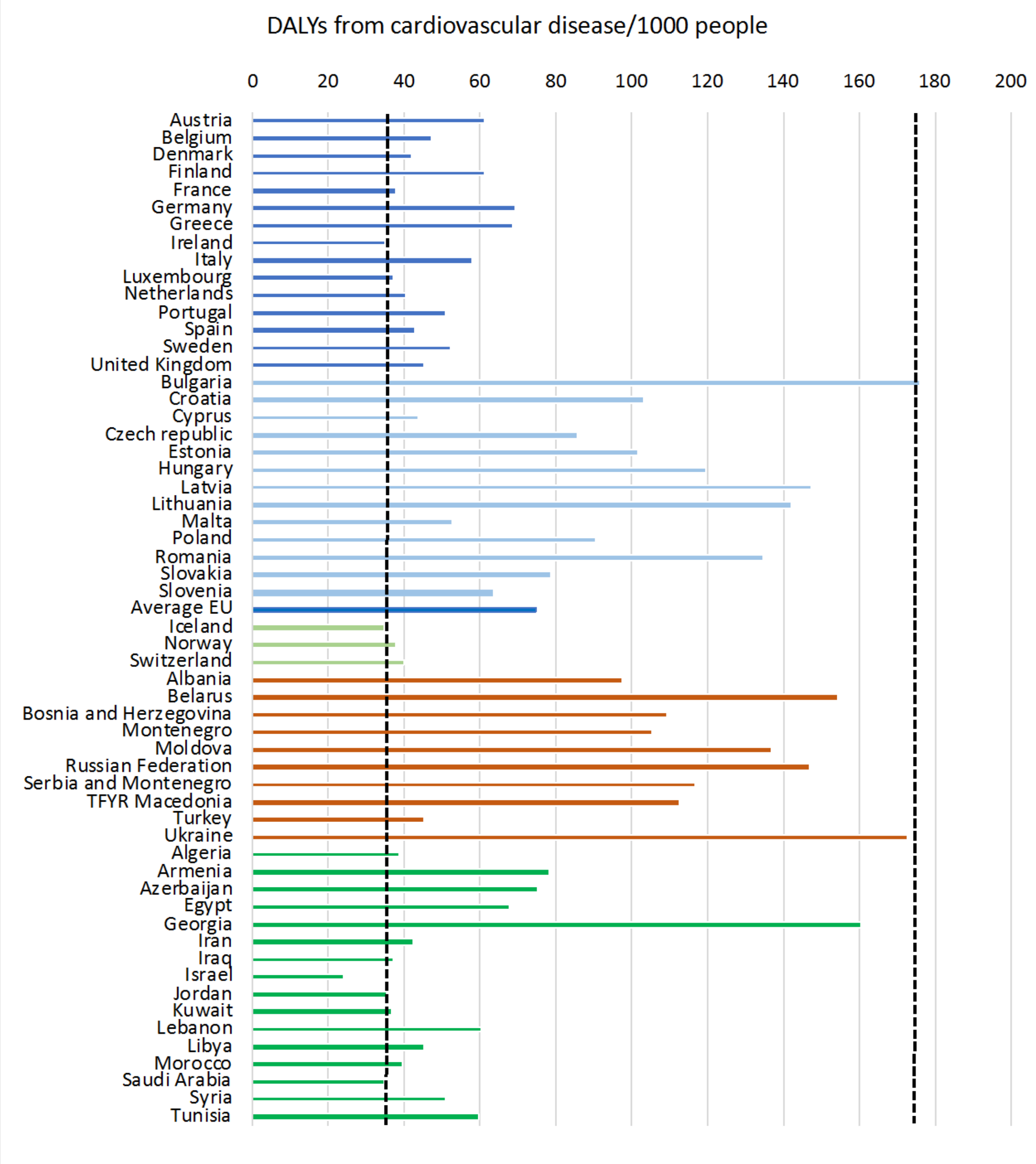

Figure 7.3: Variation in DALYs from cardiovascular disease in 2015 across the countries included in the analysis. Dark blue: EU15. Light blue: EU13. Light green: EEA. Orange: Europe outside the EU and EEA. Green: North Africa and Middle East. Data source: Adapted from WHO (2015). Dashed vertical lines show the range across EU Member States.

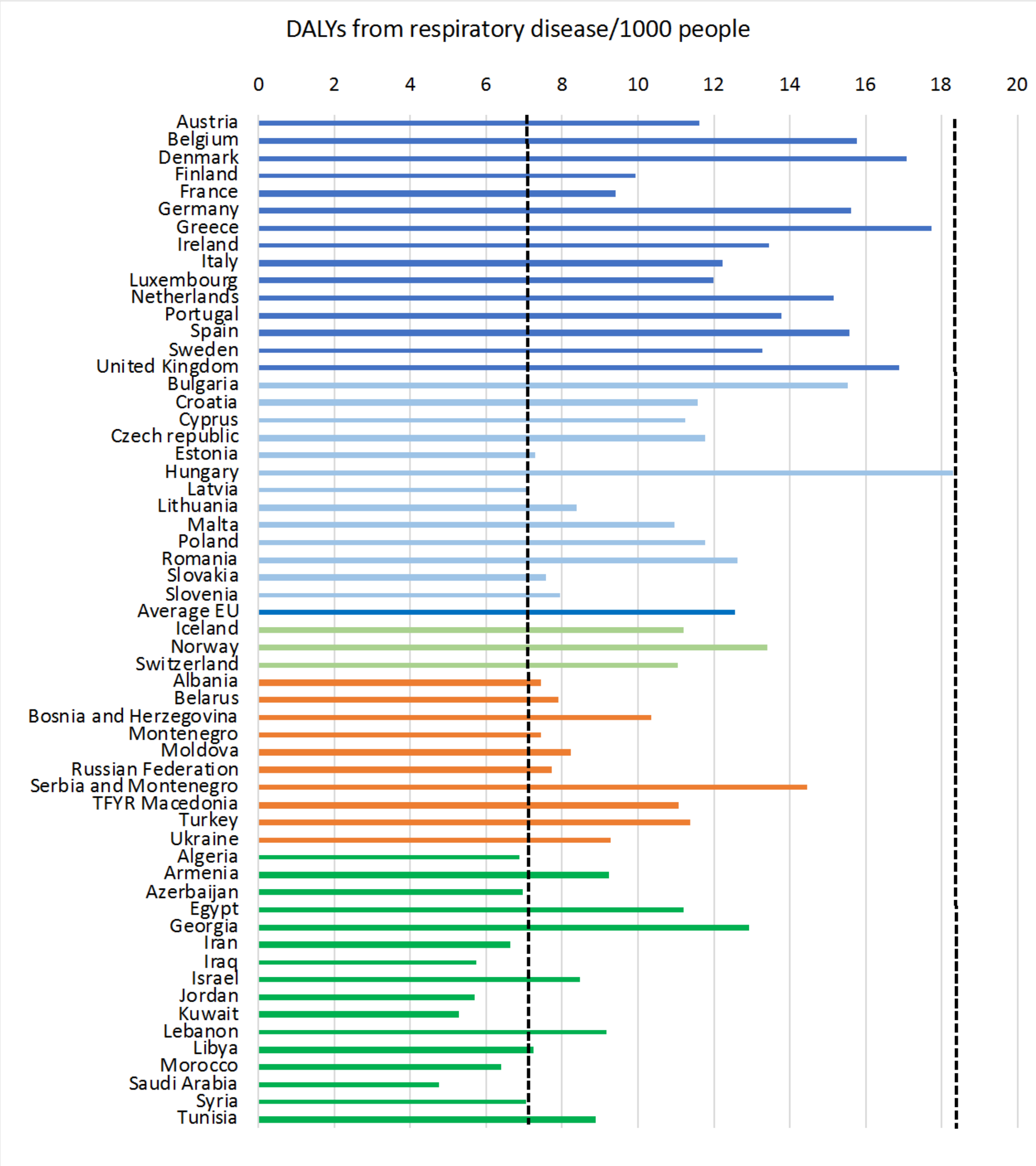

Figure 7.4: Variation in DALYs from respiratory disease in 2015 across the countries included in the analysis. Dark blue: EU15. Light blue: EU13. Light green: EEA. Orange: Europe outside the EU and EEA. Green: North Africa and Middle East. Data source: Adapted from WHO (2015). Dashed vertical lines show the range across EU Member States

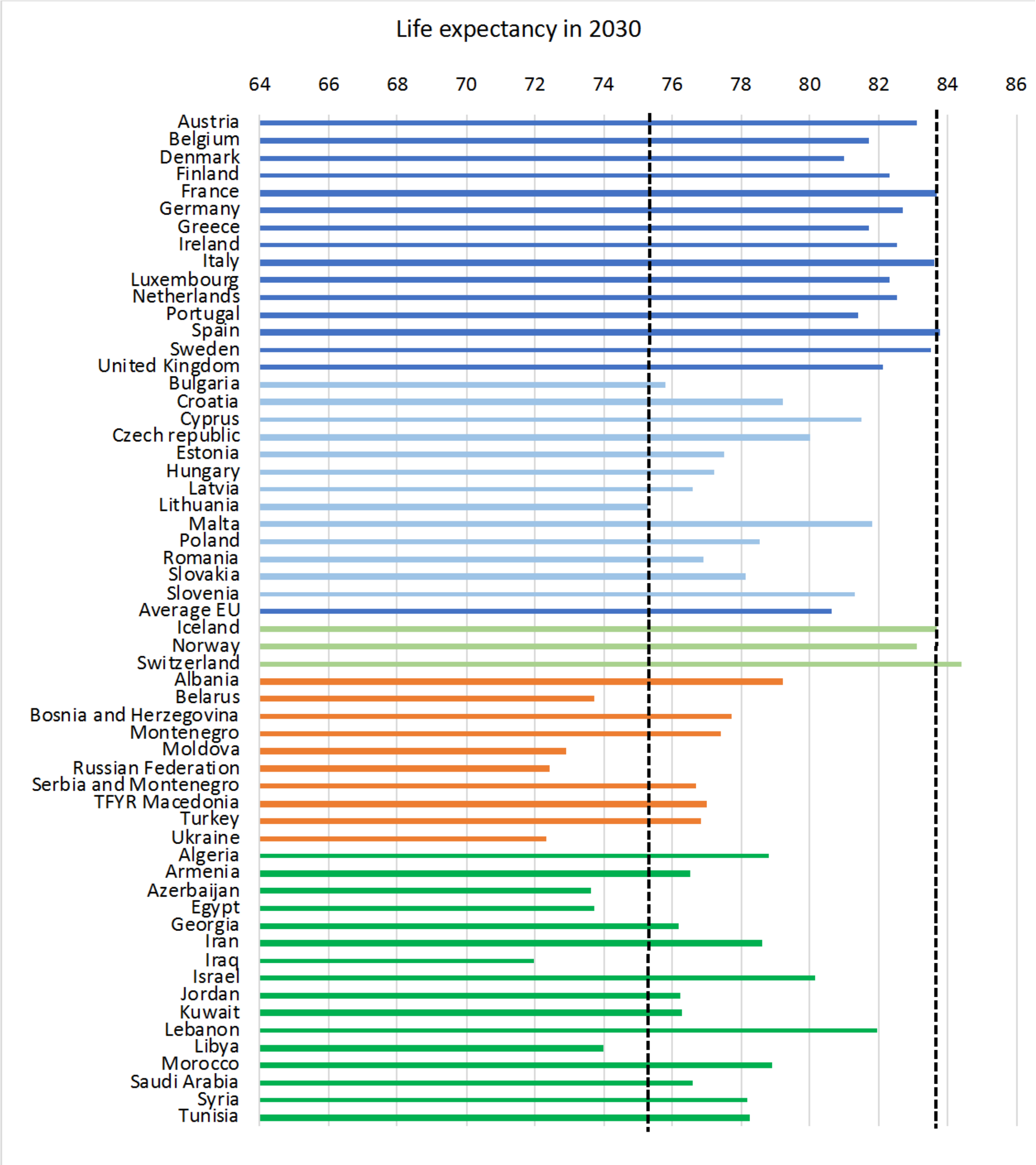

Figure 7.5: Variation in forecast life expectancy in 2030 across the countries included in the analysis. Dark blue: EU15. Light blue: EU13. Light green: EEA. Orange: Europe outside the EU and EEA. Green: North Africa and Middle East. Data source: UN (2017). Dashed vertical lines show the range across EU Member States.

With respect to pollutant exposure, 2016 data suggests that levels in a number of the additional countries considered here are well above those experienced in Europe (Figure 7.6). In part this will be a function of location, with natural dusts (especially from the Sahara) providing a major burden. However, the World Bank data series goes back to 1990, and shows a significant increase in exposure in the period from 1990 to 2016, suggesting that a significant part of exposure is linked to anthropogenic sources. As this report looks forward, to the years 2030 to 2050, it seems likely given current interest in air pollution worldwide, that control measures will be introduced to bring down concentrations in the worst affected areas. It is notable that one country in the region, Israel, comes halfway down the list and above a number of EU Member States. This suggests, at least, that improved pollution controls in the region are possible. Of the seven countries with concentrations in excess of 40 ug.m^{-3} only Egypt makes a significant contribution to benefits, the other six making a total contribution up to approximately 5% either because they have low populations and/or are at some distance from the Mediterranean.

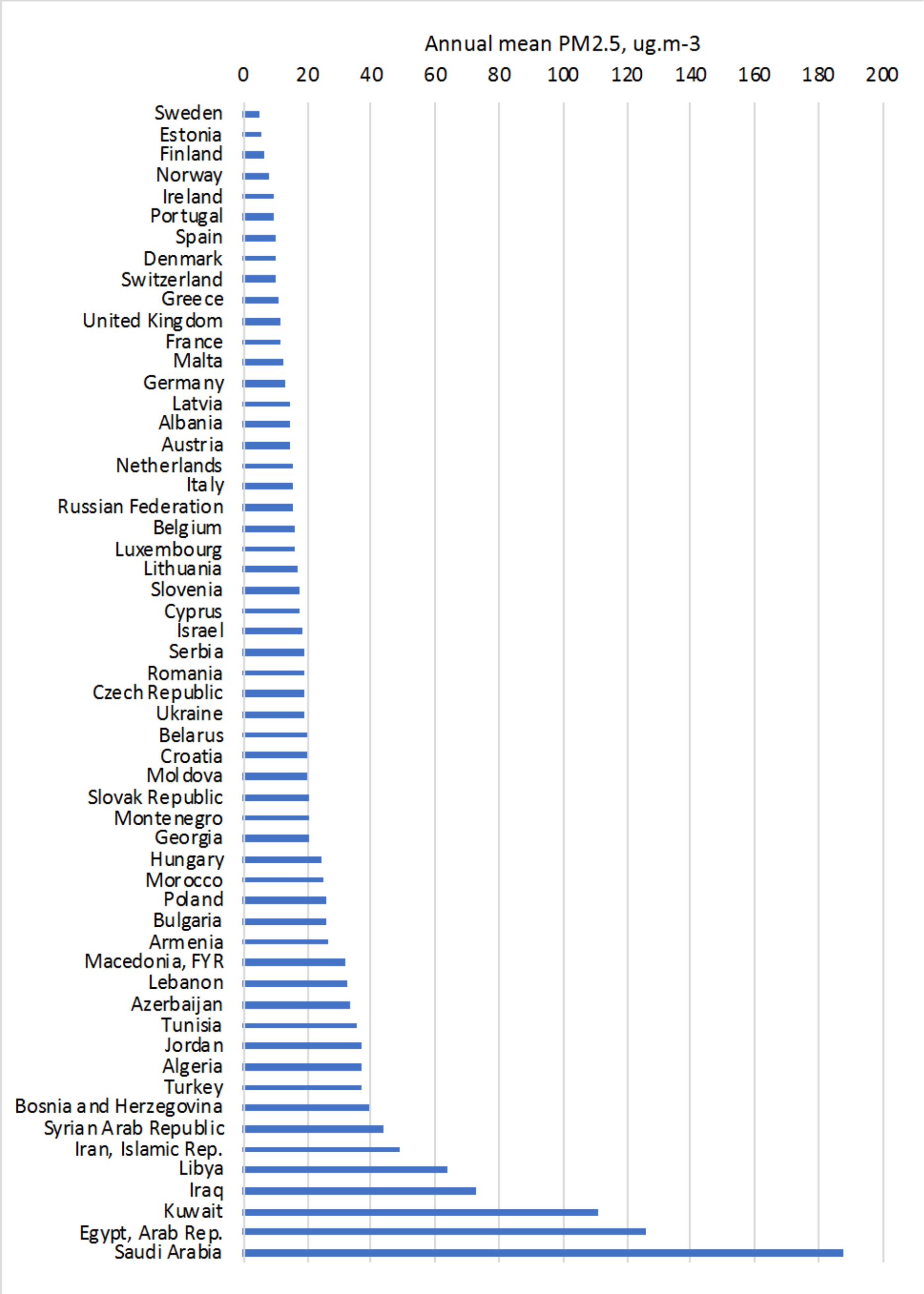

Figure 7.6: Annual mean PM2.5 concentration in 2016 in the countries considered here. Source: https://data.worldbank.org/indicator/en.atm.pm25.mc.m3?year_high_desc=true

In summary, on the grounds of health factors alone, the decision to adopt the HRAPIE functions across the modelled domain rather than follow Global Burden of Disease recommendations for countries outside of Europe seems justified. A question arises because of the high $PM_{2.5}$ concentrations in some countries, particularly Egypt. However, given various factors including the possible lower toxicity of natural dusts that will contribute significantly to exposure in desert countries, the potential for emission reductions prior to the scenarios of interest here and the uncertainties involved in derivation of the GBD functions, the decision to adopt HRAPIE in all countries is justified, particularly given conservatism in some other parts of the analysis such as mortality valuation.

7.3.1 Strategy for economic valuation

Analysis has adopted the values selected for previous analysis in support of the development of EU air quality policy, expressed in €, price year 2005 to match the year used by the GAINS model for the cost estimation. Unit values were described by Holland (2014b) and are shown in Table 7.3.

Table 7.3. Updated values for the health impact assessment (price year 2005)

Impact / population group	Unit cost	Unit
Ozone effects		
Mortality from chronic exposure as:		
Life years lost, or	40,000 / 57,700 / 138,700	€/life year lost (VOLY)
Premature deaths	1.09 / 2.22 / 2.8 million	€/death (VSL)
Mortality from acute exposure	40,000 / 57,700 / 138,700	€/life year lost (VOLY)
Respiratory Hospital Admissions	2,220	€/hospital admission
Cardiovascular Hospital Admissions	2,220	€/hospital admission
Minor Restricted Activity Days (MRADs)	42	€/day
$PM_{2.5}$ effects		
Mortality from chronic exposure as:		
Life years lost, or	40,000 / 57,700 / 138,700	€/life year lost (VOLY)
Premature deaths	1.09 / 2.22 / 2.8 million	€/death (VSL)
(all-cause and cause-specific mortality)		
Infant Mortality	1.6 to 3.3 million	€/case
Chronic Bronchitis in adults	53,600	€/new case of chronic bronchitis
Bronchitis in children	588	€/case
Respiratory Hospital Admissions	2,220	€/hospital admission
Cardiac Hospital Admissions	2,220	€/hospital admission
Restricted Activity Days (RADs)	92	€/day
Work loss days	130	€/day
Asthma symptoms, asthmatic children	42	€/day

Six values are listed against mortality valuation for adults, three providing a range for mortality valued in terms of life years lost (the value of a life year, VOLY) and three for morality valued against deaths (the value of statistical life, VSL). The values are taken from a valuation study carried out under the EU's research programmes in the early 2000s, supplemented by an additional EU survey for VOLY (Desaigues et al, 2011) and a meta-analysis carried out for OECD (2012). There are grounds for considering most of the values used here to be conservative: the OECD study provides the highest estimate and reflects results from a much larger body of literature than the others. For the final results in the present study the variation in mortality valuation leads to roughly a factor 4 difference across the range (between the lowest estimate of the VOLY and highest estimate of the VSL). In keeping with other work carried out for the European Commission, preference here is given to results based on the mid-estimate of VOLY (€57,700) and mid-estimate of VSL (€2.22 million), though as already noted, this range may be conservative. The quantification only includes response functions included in the 'core set' recommended by WHO/HRAPIE.

Consistent values are applied across the entire modelled domain reflecting the need for a common decision across all parties that would incur costs and receive benefits. Individual willingness to pay varies with income. Consideration was given to reducing the EU average figures used previously to reflect the lower willingness to pay assumed to be linked to lower per capita incomes in most of the non-EU countries brought into the present analysis. However, this would fail to recognize increased incomes linked to economic growth across the modelled region by the time of the scenarios considered here (the period 2030-2050) and associated increases in willingness to pay. Analysis carried out for the CIRCLE study (OECD, 2016) factored this effect of increased willingness to pay into analysis on a country by country basis. Using the data from that assessment it is noted here that by 2030:

- The average PPP-adjusted incomes for all of the countries considered here will exceed the 2005 EU level by 2030, and
- The average PPP-adjusted incomes across the Middle Eastern and North African countries will exceed the 2005 EU level by 2050.

Accounting for this, the retention of the 2005 EU values appears slightly conservative (reinforcing the potential conservatism in mortality valuation referred to above), though has the advantage of being both transparent relative to earlier analysis and pragmatic.

7.4 Non-health impacts

Analysis under the ECLAIRE study (Holland et al, 2015) quantified impacts of ozone on crop production, forest production and climate sequestration and loss of biodiversity. The best estimate of these effects was equivalent to around 5% of total health impacts. Inclusion of damage to materials would increase this figure, but only slightly.

7.5 Benefits of the emission control scenarios

Analysis preformed with the ALPHA-Riskpol model reveals that the most important monetary benefit from controlling emissions of air pollutants is reduction of premature mortality. Table 7.4 presents the premature deaths avoided due to measures (on top of the Current Legislation) on shipping in all European Seas. Implementation of SO_x- and NO_x ECA measures as in the Baseline activity scenario (H5) allows avoiding 5.6 thousand premature deaths in in 2030 and about 15 thousand in 2050. Adding particle filters in all sea regions except ATLO (scenario H10) adds additional 1400 deaths avoided in 2050. Values for the case "With climate measures" are 20 to 60 percent lower depending on the scenario and year. Values for measures in the Mediterranean Sea are shown in Table 7.5. Here the implementation of SO_x and NO_x ECA (scenarios H6M and L6M) allow reducing premature deaths by 11.1 and 4.9 thousand cases in 2050, which is more than three quarters of the effects if the measures were applied in all Seas.

The effects from shipping measures in 2050 are comparable with the reduction of mortality from implementation of the NEC Directive ceilings for land sources in 2030 (19,800 thousand of deaths avoided - Amann et al., 2017b) and the number of fatal road accidents in the EU – 25,500 in 2015; EU's strategy to improve road safety aims at decreasing these fatalities to 15,000 in 2020 (EC, 2016b).

Table 7.4: Premature deaths avoided due to decrease of PM2.5 concentrations, cases/yr for scenarios with control measures in all sea regions

		Scenario			
Year	Country group	H2	H4	H5	H10
Baseline					
2030	All countries	1,857	4,414	5,575	8,019
2030	EU-28	810	1,686	2,145	3,556
2030	Europe non-EU incl. Turkey	366	555	668	1,047
2030	Middle East and North Africa	682	2,173	2,762	3,416
2040	All countries	2,514	6,466	10,611	14,098
2040	EU-28	956	2,153	3,657	5,517
2040	Europe non-EU incl. Turkey	511	781	1,231	1,818
2040	Middle East and North Africa	1,047	3,532	5,723	6,763
2050	All countries	2,917	7,793	14,698	16,102
2050	EU-28	980	2,282	4,545	5,256
2050	Europe non-EU incl. Turkey	594	907	1,623	2,008
2050	Middle East and North Africa	1,343	4,605	8,530	8,838
		L2	L4	L5	L10
With climate measures					
2030	All countries	1,504	3,411	4,177	5,976
2030	EU-28	677	1,334	1,637	2,690
2030	Europe non-EU incl. Turkey	293	432	509	786
2030	Middle East and North Africa	534	1,645	2,031	2,500
2040	All countries	1,577	3,669	5,819	8,111
2040	EU-28	656	1,298	2,111	3,373
2040	Europe non-EU incl. Turkey	307	449	685	1,055
2040	Middle East and North Africa	613	1,922	3,024	3,683
2050	All countries	1,475	3,393	6,420	7,068
2050	EU-28	577	1,097	2,154	2,521
2050	Europe non-EU incl. Turkey	273	404	731	907
2050	Middle East and North Africa	625	1,892	3,535	3,640

Table 7.5: Premature deaths avoided due to decrease of PM2.5 concentrations, cases/year for scenarios with control measures in the Mediterranean Sea. All other sea regions at the CLE level

Year	Country group	Scenario					
		H1M	H2M	H3M	H4M	H5M	H6M
Baseline							
2030	All countries	903	1,864	2,331	1,533	3,487	4,242
2030	EU-28	629	1,105	1,358	654	1,210	1,487
2030	Europe non-EU incl. Turkey	60	114	156	262	346	415
2030	Middle East and North Africa	213	645	817	617	1,931	2,340
2040	All countries	1,106	2,530	4,165	2,098	5,174	7,985
2040	EU-28	739	1,381	2,183	772	1,523	2,420
2040	Europe non-EU incl. Turkey	69	150	293	375	509	732
2040	Middle East and North Africa	298	999	1,689	950	3,141	4,832
2050	All countries	1,225	2,923	5,630	2,483	6,336	11,174
2050	EU-28	759	1,449	2,660	797	1,608	2,959
2050	Europe non-EU incl. Turkey	90	185	407	461	610	973
2050	Middle East and North Africa	375	1,289	2,563	1,224	4,118	7,242
		L1M	L2M	L3M	L4M	L5M	L6M
With climate measures							
2030	All countries	776	1,500	1,830	1,256	2,709	3,204
2030	EU-28	538	895	1,074	560	969	1,162
2030	Europe non-EU incl. Turkey	56	107	134	216	280	320
2030	Middle East and North Africa	182	499	622	481	1,460	1,722
2040	All countries	770	1,541	2,475	1,313	2,938	4,430
2040	EU-28	516	862	1,336	533	935	1,451
2040	Europe non-EU incl. Turkey	54	106	181	228	296	420
2040	Middle East and North Africa	200	573	958	552	1,706	2,559
2050	All countries	732	1,417	2,738	1,242	2,757	4,890
2050	EU-28	463	743	1,360	478	803	1,478
2050	Europe non-EU incl. Turkey	53	88	200	203	271	436
2050	Middle East and North Africa	216	586	1,178	561	1,683	2,976

Detailed results of benefits by type, country, year and scenario are available (upon request) from EMRC.

Annex 8: Comparison of benefits with costs

This Annex compares monetary benefits resulting from reduction of shipping emissions with the costs of the scenarios. As described in the previous section, the calculations have been performed using two valuations of premature deaths: value of life years lost (VOLY) and value of statistical life (VSL). Costs of SO_2 control have been calculated for two variants: (i) assuming that compliance with the legislation is achieved exclusively with the use of low sulphur fuels (0.1% S for SECA regions), and (ii) that some vessels use scrubbers. Assumptions on the use of scrubbers are discussed in Annex 6:.

8.1 Base case price differential for low sulphur fuels

Table 8.2 and Table 8.1 present the results for measures that can be implemented in all European Seas for the Baseline and the "With climate measures" energy demand scenarios and base case price differential for low sulphur fuels. In case when compliance with SECA requirements is achieved with the use of low sulphur fuels the costs are higher, especially at the end of time horizon, where the penetration of scrubbers (which are cheaper) is high. For instance, in the scenario H4 (SECA in all Seas except ATLO outside the territorial waters) the incremental costs in 2050 are reduced from about 2.1 billion €/yr to only 0.6 billion €/year. Benefits for the case when VSL is used as a measure of the value of premature death are approximately twice as high compared with results obtained with the VOLY indicator. In all cases the benefits resulting from reduction of pollution in the Middle East and Africa (within the model domain) contribute at least 40% to the total effects. For majority of the scenarios this contribution is even higher than 50 percent. Benefits to costs ratios (B/C) are quite high. If sulphur scrubbers are allowed, the average for all four scenarios in 2050 is 26 with VSL and 12 with VOLY. SECA scenario H4 has the B/C ratios of more than four for all years with VOLY and no scrubbers. B/C increases to about 30 in 2050 when scrubbers are allowed and VSL is used for valuation of chronic mortality. Scenarios that assume implementation of NO_x ECAs in addition to SO_x ECA have also quite high B/C ratios.

Table 8.1: Benefits and costs for all European seas, m€/year. Baseline shipping activity (Case H); values in the table represent the difference from the CLE case (H1). Base case price differential for low sulphur fuels

Scenario	H2	H4	H5	H10	H2	H4	H5	H10
Benefits	**mid VOLY**				**mid VSL**			
2030	2,384	5,987	7,806	11,016	4,694	11,200	14,405	20,859
2040	2,965	7,973	14,017	18,212	6,319	16,300	27,750	36,792
2050	3,216	8,902	18,430	19,784	7,308	19,563	38,591	41,958
Cost, no scrubbers								
2030	455	1462	1818	2579	455	1462	1818	2579
2040	555	1909	2835	3557	555	1909	2835	3557
2050	595	2101	3458	3393	595	2101	3458	3393
Benefits/costs ratio								
2030	5.2	4.1	4.3	4.3	10.3	7.7	7.9	8.1
2040	5.3	4.2	4.9	5.1	11.4	8.5	9.8	10.3
2050	5.4	4.2	5.3	5.8	12.3	9.3	11.2	12.4
Cost, with scrubbers								
2030	360	1095	1401	2211	360	1095	1401	2211
2040	333	1028	1831	2675	333	1028	1831	2675
2050	233	634	1771	1925	233	634	1771	1925
Benefits/costs ratio								
2030	6.6	5.5	5.6	5.0	13.0	10.2	10.3	9.4
2040	8.9	7.8	7.7	6.8	19.0	15.9	15.2	13.8
2050	13.8	14.0	10.4	10.3	31.3	30.8	21.8	21.8

Table 8.2: Benefits and costs of policy scenarios for all European seas, m€/year. Shipping activity “With climate policies” (Case L); values in the table represent the difference from the CLE scenario (L1). Base case price differential for low sulphur fuels

Scenario	L2	L4	L5	L10	L2	L4	L5	L10
Benefits			**mid VOLY**			**mid VSL**		
2030	1,909	4,595	5,793	8,141	3,797	8,651	10,765	15,513
2040	1,824	4,471	7,571	10,318	3,958	9,242	15,167	21,127
2050	1,589	3,818	7,927	8,539	3,693	8,511	16,822	18,379
Cost, no scrubbers								
2030	363	1116	1354	1750	363	1116	1354	1750
2040	343	1066	1534	1908	343	1066	1534	1908
2050	305	811	1489	1349	305	811	1489	1349
Benefits/costs ratio								
2030	5.3	4.1	4.3	4.7	10.5	7.8	8.0	8.9
2040	5.3	4.2	4.9	5.4	11.5	8.7	9.9	11.1
2050	5.2	4.7	5.3	6.3	12.1	10.5	11.3	13.6
Cost, with scrubbers								
2030	291	840	1042	1475	291	840	1042	1475
2040	217	590	993	1432	217	590	993	1432
2050	142	261	784	799	142	261	784	799
Benefits/costs ratio								
2030	6.6	5.5	5.6	5.5	13.0	10.3	10.3	10.5
2040	8.4	7.6	7.6	7.2	18.2	15.7	15.3	14.8
2050	11.2	14.6	10.1	10.7	26.0	32.6	21.5	23.0

Table 8.3 and Table 8.4 show the results for the scenarios assuming measures in the Mediterranean Sea only. Also here the B/C ratios are quite high, in particular for the scenarios covering the whole Mediterranean Sea.

Table 8.3: Benefits and costs of policy scenarios in the Mediterranean Sea, million €/year. Baseline shipping activity (Case H); values in the tables represent the difference from the CLE scenario (H1). Base case price differential for low sulphur fuels

Scenario	H1M	H2M	H3M	H4M	H5M	H6M	H1M	H2M	H3M	H4M	H5M	H6M
Benefits			**mid VOLY**						**mid VSL**			
2030	910	2,158	2,839	1,923	4,808	6,043	1,989	4,422	5,701	3,612	8,599	10,700
2040	1,149	2,834	5,094	2,546	6,614	10,915	2,761	6,342	10,815	5,287	13,076	20,870
2050	1,205	3,074	6,644	2,790	7,445	14,369	3,050	7,301	14,698	6,230	15,929	29,276
Cost, no scrubbers												
2030	219	646	736	339	1001	1141	219	646	736	339	1001	1141
2040	255	826	1143	416	1309	1803	255	826	1143	416	1309	1803
2050	271	902	1366	448	1444	2182	271	902	1366	448	1444	2182
Benefits/costs ratio												
2030	4.2	3.3	3.9	5.7	4.8	5.3	9.1	6.8	7.7	10.6	8.6	9.4
2040	4.5	3.4	4.5	6.1	5.1	6.1	10.8	7.7	9.5	12.7	10.0	11.6
2050	4.5	3.4	4.9	6.2	5.2	6.6	11.3	8.1	10.8	13.9	11.0	13.4
Cost, with scrubbers												
2030	176	487	577	267	750	890	176	487	577	267	750	890
2040	156	449	766	246	705	1199	156	449	766	246	705	1199
2050	110	278	741	171	435	1174	110	278	741	171	435	1174
Benefits/costs ratio												
2030	5.2	4.4	4.9	7.2	6.4	6.8	11.3	9.1	9.9	13.5	11.5	12.0
2040	7.4	6.3	6.6	10.3	9.4	9.1	17.7	14.1	14.1	21.5	18.6	17.4
2050	11.0	11.1	9.0	16.3	17.1	12.2	27.8	26.3	19.8	36.5	36.6	24.9

Table 8.4: Benefits and costs of policy scenarios in the Mediterranean Sea, m€/year. With climate policies shipping activity (Case L); values in the tables represent the difference from the CLE scenario (L1). Base case price differential for low sulphur fuels

Scenario	L1M	L2M	L3M	L4M	L5M	L6M	L1M	L2M	L3M	L4M	L5M	L6M
Benefits			**mid VOLY**						**mid VSL**			
2030	874	1,806	2,283	1,635	3,782	4,586	1,947	3,778	4,676	3,180	6,890	8,265
2040	799	1,704	2,977	1,557	3,705	5,941	1,924	3,859	6,404	3,305	7,418	11,538
2050	717	1,472	3,179	1,362	3,181	6,166	1,822	3,538	7,128	3,112	6,923	12,781
Cost, no scrubbers												
2030	179	499	559	269	764	854	179	499	559	269	764	854
2040	166	473	653	253	728	992	166	473	653	253	728	992
2050	149	406	617	222	617	933	149	406	617	222	617	933
Benefits/costs ratio												
2030	4.9	3.6	4.1	6.1	5.0	5.4	10.9	7.6	8.4	11.8	9.0	9.7
2040	4.8	3.6	4.6	6.2	5.1	6.0	11.6	8.2	9.8	13.1	10.2	11.6
2050	4.8	3.6	5.2	6.1	5.2	6.6	12.2	8.7	11.6	14.0	11.2	13.7
Cost, with scrubbers												
2030	146	380	439	215	576	666	146	380	439	215	576	666
2040	109	268	448	158	403	667	109	268	448	158	403	667
2050	76	145	356	101	208	524	76	145	356	101	208	524
Benefits/costs ratio												
2030	6.0	4.8	5.2	7.6	6.6	6.9	13.3	9.9	10.6	14.8	12.0	12.4
2040	7.3	6.4	6.7	9.8	9.2	8.9	17.6	14.4	14.3	20.9	18.4	17.3
2050	9.5	10.1	8.9	13.5	15.3	11.8	24.0	24.3	20.0	30.9	33.3	24.4

8.2 Sensitivity analysis: Higher costs of low sulphur fuels

To check the robustness of the findings in the previous section, calculations have also been performed for a conservatively high estimate of the costs of low sulphur fuels. Following the assumptions of the REMPEC study conducted by EERA/FMI (EERA and FMI, 2018), cost premiums for switching from MARPOL VI to SO_x ECA-compliant fuels are about 70% higher (Table 8.5[11]).

Table 8.5: Cost premiums for the sensitivity analysis based on the assumptions in EERA/FMI (2018)

Fuel	Price		Price difference			
			€/GJ		€/t SO2 abated	
	€/t	€/GJ	RO to MD	MD to MGO	RO to MD	MD to MGO
Residual oil (RO) ~ 2.5 % S	283	6.9	-	-	-	-
Marine diesel (MD) ~0.5% S	507	11.9	4.98	-	5,708	-
Marine gasoil (MGO) 0.1% S	573	13.4	6.51	1.53	5,931	8,432

For the Baseline fuel consumption and the CLE emission controls the compliance costs are 12 billion € in 2030 and more than 17 billion € in 2050 if no scrubbers are used (Table 8.6). With climate measures, costs amount to more than nine billion € in 2030 and decrease to less than eight billion € in 2050 due to

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[11] Prices from the original study (in US $\$_{2018}$) have been converted to €$_{2005}$ using conversion factor 1€$_{2005}$=1.5 US$\$_{2018}$.

lower fuel consumption. For high fuel premium scrubbers would be much more cost-effective, and let decrease costs for current legislation by about one fourth in 2030 and by two thirds in 2050.

Table 8.6: Emission control costs for the current legislation (CLE), all European Seas, assuming high cost premiums for low S marine fuels, billion €/year

Case	2030	2040	2050
H1 (baseline)			
No scrubbers	12.0	15.7	17.4
With scrubbers	9.1	8.8	6.0
L1 (with climate measures)			
No scrubbers	9.3	9.1	7.9
With scrubbers	7.0	5.1	2.8

Control costs on top of current legislation for the scenarios considered in our study are shown in Table 8.7. For the scenarios where SECA compliance is achieved with the use of low sulfur gasoil, higher incremental costs cause a decrease of the benefit/costs ratio by 30 to 40% compared to the baseline cost assumptions. This difference is lower in 2050 for the scenarios with sulfur scrubbers.

Table 8.7: Incremental emission control costs relative to the current legislation assuming high cost premiums for low S marine fuels, Million €/year

	No scrubbers			With scrubbers		
Scenario	2030	2040	2050	2030	2040	2050
All European Seas						
L2	565	536	472	433	311	180
L3	2077	1995	1738	1522	1043	498
L4	1845	1767	1229	1354	928	356
L5	2179	2329	2178	1623	1377	938
L6	2539	2672	2212	1983	1720	972
L7	2551	2647	2194	1995	1695	953
L8	2648	2841	2408	2092	1889	1168
L9	2816	2982	2408	2260	2031	1168
L10	2479	2609	1766	1989	1770	893
H2	722	897	966	548	498	316
H3	2747	3632	4039	2005	1868	1079
H4	2435	3201	3527	1780	1652	951
H5	2919	4304	5095	2177	2540	2135
H6	3433	4836	5148	2691	3072	2188
H7	3656	4990	5119	2915	3226	2160
H8	3794	5350	5615	3052	3586	2655
H9	4045	5578	5615	3304	3814	2655
H10	3551	4848	4819	2896	3299	2242
Mediterranean Sea only						
L1M	266	249	221	208	150	92
L2M	811	772	658	599	412	202
L3M	870	952	869	659	592	412
L4M	420	397	345	321	228	128
L5M	1261	1206	1017	926	634	297
L6M	1351	1470	1333	1016	898	613
H1M	334	401	428	257	226	145
H2M	1061	1371	1502	779	712	411
H3M	1151	1689	1965	869	1030	874
H4M	539	674	730	408	371	233
H5M	1664	2194	2423	1217	1132	653
H6M	1804	2688	3161	1357	1626	1391

Annex 9: References

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