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Environmental impact assessment of passenger ferries and cruise vessels: the case study of Crete

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Abstract

Year 2020 was a milestone year for shipping both positively and negatively: the insecurity of people to move freely due to the Covid-19 pandemic imposed travel restrictions, while on the other hand the enforced Directives and Regulations (i.e. fuel sulfur standards) contribute to the reduction of harmful air emissions from shipping. The scope of the paper is to present some important findings regarding induced air emissions in ports due to shipping activities. Two Greek major ports have been used as a case study to estimate fuel-energy consumption and air emissions (CO_2, SO_x, NO_x, PM_{10}) due to passenger ferries and cruise ships for three consecutive years (i.e. 2018-2020). Due to the lack of publically available technical data, a bottom-up methodology has been employed for air emissions estimation which is based on the calculation of SFOC values through a regression analysis that leads to accurate and reliable results.

Keywords: Air emissions; Fuel-Energy consumption; Ports; Bottom-up methodology; Specific Fuel Oil Consumption.

1. Introduction

European coastal zones are typically highly populated and host important social and economic activities, while in the same time they are more densely populated compared to inland areas. There is an almost even distribution of the population between coastal and inland areas in EU as 41.8% of residents live close to the shoreline (European Commission; The EU Blue Economy Report, 2019) while several large EU capitals like Madrid or Paris, or many highly populated cities are far from the coastal regions. On the other hand, ports activities usually take place close to densely populated regions thus making air emissions one of the main sources of urban air pollution (with ships being one of the dominant sources of ports air pollution). Sea transport will definitely follow the growing trends of world trade and although shipping is the most efficient sector of mass

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transport, a universal approach is needed to further improve its energy efficiency and control air emissions.

In terms of emitted greenhouse gases (GHG), total shipping CO_2 emissions have increased by 9.3% between 2012 and 2018, whereas its share of global CO_2 emissions over this period grew incrementally from 2.76 to 2.89%. A smaller increase of 5.4% in absolute terms was observed in CO_2 emissions due to international shipping, which throughout the years represents a relatively constant share of global CO_2 emissions, fluctuating around 2%. The International Maritime Organization (IMO) agreed on an initial GHG emissions reduction strategy with main objective to reduce total annual GHG emissions from shipping by at least 50% by 2050 compared to 2008 levels, while cruise industry was the first to publicly commit as a maritime sector, to reduce total carbon emissions by 40% by 2030 compared to 2008 (Cruise Lines International Association, 2020; Fourth IMO GHG Study, 2020).

One of the main challenges for ports in their relation with the local community is to ensure that cruise and ferry operations remain as sustainable as possible. The potential impact of air pollutants to human health, is emphasized in reports issued by the European Environment Agency (EEA) and the World Health Organization (WHO) in a regularly basis, while air pollution and the effect to air quality is very often the target of regulatory control measures and has constantly high priority in public concern, not only for locals but also for visitors or workers in burdened air quality urban regions and port cities. A worrying fact that justifies the above is that every year, air pollution causes about 400 thousand premature deaths in the EU region and hundreds of billions euros in health-related external costs (European Environment Agency, 2019).

Since 1996, European Sea Ports Organization (ESPO) has been monitoring the environmental priorities of European port authorities. With no doubt, port authorities and port managing bodies have air quality issues in high priority, since more than 90% of European ports are urban and air quality as a result of port activities is a key factor of public "acceptance" (ESPO, 2019). It is clear enough that European Commission has given priority to implement and enforce the European legislation, mainly the comprehensive Directive 2008/50/EC on ambient air quality and cleaner air for Europe (EU Directive 50, 2008). In addition, various regulations have been introduced aiming to emphasize towards measures to tackle air pollution; the most important are: the implementation of the EU Sulphur Directive, the new National Emission Ceiling Directive (EU Directive 2284, 2016), the global sulphur cap (0.5%) on marine fuels from year 2020 (IMO, 2016) and the International Maritime Organization (IMO) MARPOL convention for a gradual decrease of air emissions, i.e. Nitrogen Oxides (NO_x), Sulphur Oxides (SOx) and Particulate Matter (PM_{10}), originating from ship engines and NO_x Tier III requirements for ships built from 2021 onwards when operating in NECAs (North and the Baltic Seas) (IMO, 2017). 2020 was a milestone year for the target of reducing air emissions from shipping due of the implementation of above Directives and Regulations. Ships use scrubbers to comply with fuel sulfur standards by removing sulfur dioxide from the exhaust instead of using lower sulfur fuels which are significantly more expensive. Instead, ships with scrubbers can continue to use cheaper high-sulfur heavy fuel oil (HFO). IMO allows the use of scrubbers as an equivalent compliance option because they are expected to reduce sulfur dioxide emissions by the same, or more, as using compliant fuels.

International Council on Clean Transportation (ICCT) published a report where provides expert advice to Environment and Climate Change Canada to enable them to update their Marine Emission Inventory Tool such that air and water pollution discharges from ships equipped with exhaust gas cleaning systems (EGCSs), also known as "scrubbers" can be estimated for ships. In this report they compiled eight studies representing 23 samples that contained information on air emissions from scrubbers and finally they presented that the relative emissions reduction in the exhaust for a ship using 2.60% sulfur heavy fuel oil (HFO global average fuel sulfur content as of 2019) with a scrubber are -98% for SO_X, -79% for PM (10 or 2.5), no change for NO_X and +2% for CO_2. As we see there is a significant reduction of SO_X and PM air emissions using scrubber and small increase for CO_2 (Comer, Georgeff, & Osipova, 2020).

An important parameter regarding the anticipated health effects of air pollution in ports is the population density of the adjacent residential areas. In Table 1 data regarding population density in representative European ports operating in both freight and cruise/ferries, are presented. Piraeus is one of the most populated areas in Greece, with a population of 163,688 for an area of 11.2 km^2 (population density of 14,615 residents per km^2) (Hellenic Statistical Authority, 2020). Another interesting case is the port of Barcelona, that has two main areas for cruise ships: one at a very short distance (854 m) to the city center, while the other (which hosts the main terminals receiving cruise ships every day) is located at a larger distance (about 2 – 2.5 km) from the Barcelona center. It is very likely that air pollution due to activities related to cruise and ferries can affect the wider urban area of Barcelona and its residents. (Perdiguero & Sanz, 2020).

Table 1: Population density of major freight, cruise and ferry European ports

Port	*Country*	*Population*	*Area (km^2)*	*Population density (habitants/km^2)*
Piraeus	Greece	163,688	11.2	14,615
Genoa	Italy	610,000	78	7,820
Barcelona	Spain	4,588,000	1,072	4,280
Amsterdam	Netherlands	1,140,000	316	3,608
Naples	Italy	3,574,000	1,032	3,463
Balearic Islands	Spain	560,000	168	3,333
Rotterdam	Netherlands	2,770,000	1,028	2,695
Hamburg	Germany	1,976,000	794	2,489
Marseille	France	1,330,000	689	1,930
Antwerp	Belgium	1,013,000	665	1,523
Heraklion	Greece	151,324	108.7	1,392
Souda	Greece	80,224	70	1,146

Source: (Demographia, 2020; Hellenic Statistical Authority, 2020).

As resulted from the available data for the pre-Covid era (for year 2019), the 10 major Mediterranean cruise ports hosted a total of about 18.5 million cruise passenger movements (Table 2). While this is a 9.23% increase compared to its last year (2018) Barcelona reaches an all-time record as a major Mediterranean cruise port for second consecutive year, hosting more than 3 million cruise passenger movements. There is also a continuous increase of the average number of cruise passengers per call that reach a destination, which is the result of larger cruise vessels in duty. Really impressive data of the last two decades are available, which show that in 2019 the average number of hosted passengers per cruise call was 2,279 while back in 2000 each cruise call in the Mediterranean was resulting on average in 813 passenger movements (MedCruise, 2019).

Table 2: Top 10 Mediterranean ports ranked by the total sum of cruise and ferry passengers for year 2019

Rank	*Port (Region)*	*Cruise*		*Ferry*		*Total Pax.*
		Ranking	*Total Pax*	*Ranking*	*Total Pax*	
1	Piraeus (East Med)	8	1,098,091	1	16,551,054	17,649,145
2	Livorno/Piombino/Portoferraio (West Med)	11	888,346	2	10,900,297	11,788,643
3	Messina (West Med)	24	422,732	3	10,755,431	11,178,163
4	Balearic Islands (West Med)	2	2,658,156	4	6,861,048	9,519,204
5	Naples/Salerno/C.di Stabia (West Med)	7	1,454,023	5	6,851,448	8,305,471
6	Sardinian ports (West Med)	21	481,924	6	5,761,759	6,243,683
7	Tenerife ports (West Med)	9	1,067,440	8	5,156,129	6,223,569
8	Split (Adriatic)	25	359,955	7	5,247,834	5,607,789
9	Canarian ports (West Med)	65	1,930	9	5,015,666	5,017,596
10	Barcelona (West Med)	1	3,137,918	21	1,490,644	4,628,562

Source: (MedCruise, 2019)

The top 10 Mediterranean ports in terms of combined cruise and ferry data hosted over 86 million cruise and ferry passengers in 2019 (86,161,825 passengers), as depicted in Table 2. In terms of cruise data, they hosted over 11.5 million cruise passengers in 2019 (11,570,515 passengers). Port of Piraeus (Greece) ranked first both in ferry and total passengers, while it occupied the 8th position in terms of cruise passengers. Barcelona ranked first in cruise passengers, while in ferry and total passengers ranked 21th and 10th respectively.

Cruise industry was expected to have increased trend in 2020 not only in the Mediterranean region but globally also. But as already known the forecasts have been negatively overtaken by Covid-19 pandemic, following the social distancing measures and travel restrictions. Cruise industry was the travel sector, which has been particularly badly hit and nearly devastated. Most of the Cruise lines have decided to lay their ships at anchor, selling or scraping the older ones. Their revenues were nearly zero for months, so they have adopted the above measures in order to save costs. Mediterranean ports in terms of cruise passengers declined remarkably in 2020, as depicted in Table 3. Barcelona, one of the leading Mediterranean cruise ports, reported roughly 199 thousand passengers in 2020, while the total cruise passenger movements at this port reached over 3.1 million in 2019. All 2020 top 10 Mediterranean cruise ports reported significant decrease varying from -67.7% (Tenerife ports) to around -90% and in the case of Piraeus -98.5% and Venice -99.7%.

Table 3: Top 10 Mediterranean ports ranked by the total sum of cruise passengers for year 2020

Rank	*Port*	*Region*	*2020 Total Pax (in thousands)*	*2019 Total Pax (in thousands)*	*% Variation*
1	Tenerife ports	West Med	345.09	1,067	-67,7%
2	Civitavecchia	West Med	206.97	2,652	-92,2%
3	Genoa/Savona	West Med	206.69	2,019	-89,8%
4	Barcelona	West Med	198.84	3,138	-93,7%
5	Balearic Islands	West Med	156.76	2,658	-94,1%
6	Marseille	West Med	123.60	1,866	-93,4%
7	Valletta	West Med	59.18	902	-93,4%
8	Naples/Salerno/C. di Stabia	West Med	28.18	1,454	-98,1%
9	Piraeus	East Med	16.64	1,098	-98,5%
10	Venice	Adriatic	5.24	1,611	-99,7%

Source:
https://www.statista.com/statistics/386715/leading-mediterranean-cruise-ports-passenger-numbers/

2. Methodological framework

2.1 Scope of the study

This paper employs a more accurate bottom-up methodology for the calculation of fuel/energy consumption and air emissions (CO_2, SO_x, NO_x, PM_{10}) for passenger ferries and cruise vessels for two major Greek ports (Souda and Heraklion, both located on Crete island), for years 2018, 2019 and 2020. Heraklion (with population of 151,324 people) is the largest city and the administrative capital of Crete and the fifth largest city in Greece. Souda is the commercial port of Chania city (the second largest in Crete with population of 80,224 people), while both Souda and Heraklion ports are arrival points for ferries to/from Piraeus and for cruise vessels. About PM we estimated the quantities of PM_{10}, as it is reported that *"there is virtually no difference between total PM and PM with sizes less than 10 microns for diesel-based fuels"* (Smith et al., 2015). Additionally, in the most recent Forth IMO GHG Study, PM_{10} are estimated while $PM_{2.5}$ are assumed to represent 92% of PM_{10} (Fourth IMO GHG Study, 2020) providing this way a simple formula to estimate $PM_{2.5}$ also.

The technical details for all passenger ferries and cruise vessels approaching both ports have been elaborated and thus a detailed technical inventory has been created. The inventory contains data for 10 passenger ferries (owned by three different shipping companies) operating every day following various itineraries all year around between the two studied ports and the port of Piraeus in mainland Greece. In addition, 88 different cruise vessels have been studied (which approached both ports mainly during the summer period of the three years). All data regarding ships arrivals and duration of port calls were collected and validated from Port authorities and one of the most reliable web based cruise portal (Hellenic Ports Association, 2022). Additionally, in order to confirm the above data and determine the required duration of each operating phase an extensive search in the related AIS databases has been conducted for the itineraries of this study.

2.2 Methodologies for the estimation of air emissions due to shipping

There are various studies regarding the existing methodologies for estimating ship's air emissions with many relevant case studies accompanied (Doundoulakis & Papaefthimiou, 2021; Maragkogianni, 2017; Maragkogianni & Papaefthimiou, 2015; Moreno-Gutiérrez et al., 2015, 2019; Papaefthimiou, Sitzimis, & Andriosopoulos, 2017; Perdiguero & Sanz, 2020; Trozzi & Lauretis, 2019). Various stakeholders and/or researchers may face difficulties on selecting the best appropriate methodology and specific criteria are needed which vary depending mostly on the availability of relevant data and technical parameters. Two main approaches are available:

1. A top-down approach which is based on fuel consumption reports from the ships and is typically used when there isn't available information about the ship's detailed activity and/or status on various operational phases.
2. A bottom-up approach which is employed when the data availability guarantees detailed calculation of fuel consumption and air emissions at each operational phase (i.e. cruise, maneuvering, at berth) of the ship, thus providing spatial allocation of the air emissions.

Environmental European Agency's (EEA) air pollution emission inventory guidebook (Trozzi & Lauretis, 2019) presents a procedure to select (depending on each case study and data availability) the most appropriate approach between three (called Tiers). Fuel sales reports are used from Tier 1 and 2 as the main parameter for the evaluation of the ships' activity and regarding the emission characteristics they assume an average vessel in order to estimate the emissions inventory. As more accurate methodology is introduced Tier 3 approach which is recommended when technical data/parameters (e.g. engine power and technology, total power installed, fuel type consumed) and detailed data of ships movements are available.

The scope of this paper is not to present the theoretical approach and the calculation methodologies, since this is available from the literature. In a recent publication a bottom-up methodology has been described in detail and this is followed in the current study (Doundoulakis & Papaefthimiou, 2021). Thus the fuel and energy consumption of each ship are calculated and in conjunction with specific emission factors (per fuel or energy consumption) depending on the air pollutant, engine, duty cycle and type of fuel, the air emissions are finally calculated. The quantities of ship's air emissions largely depend on two major factors:

1. **Specific Fuel Oil Consumption (SFOC).** The role of accurate calculation of SFOC is very important for the estimation of fuel/energy consumption. SFOC values at various engine load levels are calculated in the literature either by using adjustment factors (Faber, Freund, Kopke, & Nelissen, 2010; Styhre, Winnes, Black, Lee, & Le-Griffin, 2017) or based on scientific reports of IMO (Third IMO GHG Study, 2014) and/or ENTEC UK (ENTEC, 2002). The used methodology is based on the estimation of SFOC values through regression analysis, that leads to accurate and reliable results (Doundoulakis & Papaefthimiou, 2021).
2. **Emission Factors.** The employed emission factors, which typically due to lack of data are based on the professional or empirical assessment of the researchers.

Depending on the specified air pollutant we use the following equations for CO_2, NO_X, SO_X and PM_{10} (Fourth IMO GHG Study, 2020; Smith et al., 2015):

$$CO_{2\,(g/kWh)} = (3.114 \text{ or } 3.206) \cdot SFOC_{(g_{fuel}/kWh)} \quad (1)$$

where 3.114 for HFO, LSFO and 3.206 for MGO are the CO_2 emission factors based on fuel type.

$$NO_{x}\left(^{g}/_{kWh}\right) = 45 \cdot n^{-0.20} \qquad (2a) \qquad \text{engine manufacture after 01/01/2000}$$

$$NO_{x}\left(^{g}/_{kWh}\right) = 44 \cdot n^{-0.23} \qquad (2b) \qquad \text{engine manufacture after 01/01/2011}$$

$$NO_{x}\left(^{g}/_{kWh}\right) = 9 \cdot n^{-0.20} \qquad (2c) \qquad \text{engine manufacture after 01/01/2016}$$

with n being the engine revolution speed.

$$SO_{x}\left(^{g}/_{kWh}\right) = SFOC\left(^{g_{fuel}}/_{kWh}\right) \cdot 2 \cdot 0.97753 \cdot (\%\ \text{Fuel Sulfur}) \qquad (3)$$

where: 0.97753 is the sulfur conversion factor of S to SO_X and 2 is the molecular weight ratio of SO_X and S.

$$PM_{10,HFO}\left(^{g}/_{kWh}\right) = 1.35 + SFOC\left(^{g_{fuel}}/_{kWh}\right) \cdot 7 \cdot 0.02247 \cdot (\%\ \text{Fuel Sulfur} - 0.0246) \quad (4a)$$

$$PM_{10,MGO}\left(^{g}/_{kWh}\right) = 0.23 + SFOC\left(^{g_{fuel}}/_{kWh}\right) \cdot 7 \cdot 0.02247 \cdot (\%\ \text{Fuel Sulfur} - 0.0024) \quad (4b)$$

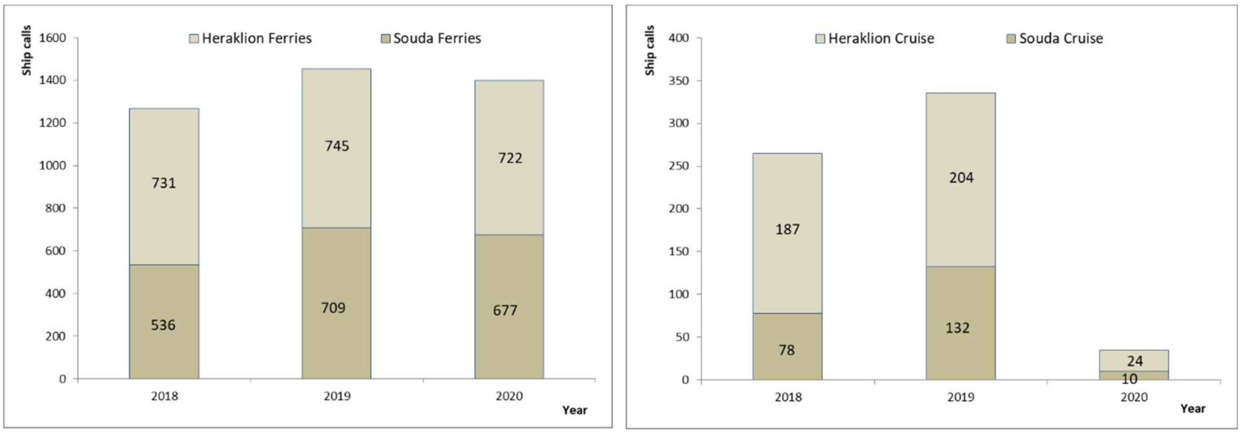
It is well understood from the above equations that:

i. CO_2 emissions depend exclusively on the fuel type, as depicted by equation (1),
ii. NO_X emissions depend exclusively on engine rev. speed (n), as depicted by equations (2a), (2b) and (2c),
iii. SO_X and PM_{10} emissions depend solely on the fuel type and particularly on its sulphur content, as depicted by equations (3), (4a) and (4b).

3. Results and discussion

3.1 Ship calls at the studied ports

Regarding the passenger ferries there was a relatively large increase of 32.3% in arrivals in the port of Souda for the year 2019 (709 arrivals compared to 536 in 2018) and a relatively small decrease of 4.5% for the year 2020 (677 arrivals compared to 709 in 2019), which is depicted in Figure 1a. This is due to the fact that from middle of July 2018 and thereafter ships from a second shipping company approached the port, thus increasing ship calls. For the port of Heraklion, we observe a relatively small increase of 1.9% in the total number of ship arrivals for the year 2019 (745 compared to 731 in 2018) and a relatively small decrease of 3.1% for the year 2020 (722 arrivals compared to 745 in 2019), which are also depicted in Figure 1a.



(a) (b)

Figure 1: Passenger ferries and cruise vessels arrivals at the ports of Souda and Heraklion for years 2018, 2019 and 2020.

In terms of cruise vessels ships circulation (Figure 1b) there was a quite significant increase of 69.2% in arrivals in the port of Souda for 2019 (132 arrivals compared to 78 in 2018) and only 10 arrivals for year 2020 (-92.4%), while for Heraklion port a relatively small increase of 9.1% was observed in the total number of ship arrivals for 2019 (204 in 2019, compared to 187 in 2018) and a quite significant decrease of 88.2% for year 2020 (24 arrivals compared to 204 in 2019). As we see cruise vessels arrivals for year 2020 follow the large decrease recorded in all other Mediterranean cruise ports due to Covid-19 pandemic.

Although the assumption that during 2020 passenger ferries' ship calls would decrease due to Covid-19 pandemic (as happened with cruise sector) seemed reasonable, finally the observed reduction was not so significant. Table 4 depicts the variation of relevant data (passengers, vehicles and freight cargo) for the time period of the three studied years. It is evident that even if the trend of all types (passengers, vehicles, cargo) from 2018 to 2019 is increased, in 2020 there is a significant decrease especially to passengers (around 50% for both ports) and vehicles (-39.7% for Souda and -38% for Heraklion), due to Covid-19 applied travel restrictions and the insecurity of people to move freely. Cargo had a decrease also, but not so large (-15.6% for Souda and -4.8% for Heraklion) like passengers and vehicles. This is because population has continuously needs of goods and freight cargo and this part of transportation is not affected as much as other. All the above significantly affected the income of the shipping companies. The Greek state from the beginning of this crisis realized that passenger ferries are closely linked to the viability of Greek islands, the preservation and increase of their population, the tourist development, the Greek economy and supported shipping companies to compensate for the losses of income due to Covid-19 travel restrictions. This is mainly the reason why we observe significant decrease of transportation units (passengers, vehicles, cargo) and we don't observe similar decrease of ship calls.

Table 4: Transportation of Passengers, Vehicles and Cargo, variation from previous year for Souda and Heraklion ports

Year	*Type*	*Souda*	*Difference from previous year*	*Heraklion*	*Difference from previous year*
2018		883,501	-	1,018,220	
2019	Passengers	943,532	6.8%	1,112,543	9.3%
2020		464,187	-50.8%	560,300	-49.6%
2018		143,777	-	163,543	
2019	Vehicles	163,829	13.9%	182,566	11.6%
2020		98,823	-39.7%	113,108	-38.0%
2018		62,386	-	121,752	
2019	Cargo	70,195	12.5%	117,693	-3.3%
2020		59,258	-15.6%	112,070	-4.8%

3.2 Fuel-Energy consumption

The basic calculation scenario is based in the accurate estimation of SFOC values based on manufacturer's technical datasheet and regression analysis to fit all engine load levels (Doundoulakis & Papaefthimiou, 2021). The calculations for both main (ME) and auxiliary engines (AE) of fuel-energy consumption and air emissions were performed for every ship call of each ferry and cruise vessel approaching the two ports. Also in our continuously effort to enrich our calculation methodology with real parameters we performed some interviews from 1st Engineers and Captains of representative passenger ferries included in our study. The result of this action was to enrich calculation with the assumption that if departure time is less than 3 hours from previous arrival time, they don't switch off main engines, since they need them to be ready (stand-by) for the new departure. This applies only for passenger ferries and only for specific departures during July and August every year.

The annual fuel and energy consumption results (split for ME and AE) are summarized and presented for each sector/port in Table 5.

Table 5: Total annual fuel and energy consumption for passenger ferries and cruise ships for Souda and Heraklion ports

		Main Engines (ME)		*Auxiliary Engines (AE)*		*Sum (ME+AE)*	
Port/Sector	*Year*	*Fuel (t)*	*Energy (kWh)*	*Fuel (t)*	*Energy (kWh)*	*Fuel (t)*	*Energy (kWh)*
Souda Pass.ferries	2018	1,160.621	5,504,666.7	2,565.176	12,714,048.5	3,725.797	18,218,715.2
Souda Cruise ships		87.319	409,068.8	1,344.088	7,069,285.9	1,431.407	7,478,354.7
Heraklion Pass.ferries		1,754.589	8,526,966.6	9,377.877	52,159,058.4	11,132.466	60,686,025.0
Heraklion Cruise ships		148.673	724,724.6	2,408.434	12,575,865.5	2,557.107	13,300,590.1
Total		**3,151.202**	**15,165,426.7**	**15,695.575**	**84,518,258.3**	**18,846.777**	**99,683,685.0**

Souda Pass.ferries	2019	1,747.410	8,362,197.1	5,881.1	29,845,892.6	7,628.510	38,208,089.7
Souda Cruise ships		169.348	777,669.3	1,708.636	9,036,086.8	1,877.984	9,813,756.1
Heraklion Pass.ferries		2,733.563	13,356,848.3	8,121.663	45,077,954.5	10,855.226	58,434,802.8
Heraklion Cruise ships		149.805	733,528.5	2,469.755	12,942,297.4	2,619.560	13,675,825.9
Total		**4,800.126**	**23,230,243.2**	**18,181.154**	**96,902,231.3**	**22,981.280**	**120,132,474.5**
Souda Pass.ferries	2020	1,535.285	7,519,517.7	5,353.660	27,598,808.2	6,888.945	35,118,325.9
Souda Cruise ships		6.534	33,440.9	150.155	811,064.3	156.689	844,505.2
Heraklion Pass.ferries		2,411.153	11,779,995.9	8,896.394	49,946,973.5	11,307.547	61,726,969.4
Heraklion Cruise ships		19.603	100,322.7	450.465	2,433,192.9	470.068	2,533,515.6
Total		**3,972.575**	**19,433,277.2**	**14,850.674**	**80,790,038.9**	**18,823.249**	**100,223,316.1**
Grand Total		**11,923.903**	**57,828,947.1**	**48,727.403**	**262,210,528.5**	**60,651.306**	**320,039,475.6**

As it is normal, there is a significant difference in fuel and energy consumption for AE compared to ME for both sectors in ports. The AE of ships operate continuously during mooring and maneuvering and at a relatively high load, while ME operate for significantly less time during the maneuvering phase and at a lower rate and engine load. In order to have a collective and representative presentation we have compiled in Table 6 a summary of the average fuel-energy consumption per ship call at each port and we observe some interesting findings. Also, the average fuel consumption per ship call is graphically represented in figure 2.

Table 6: Average annual fuel and energy consumption per ship call for Souda and Heraklion ports (ferry, cruise).

Port/Sector	*Ship calls and average mooring duration*			*Average Fuel (t) and Energy (kWh) consumption*		
	2018	*2019*	*2020*	*2018*	*2019*	*2020*
Souda Passenger ferries	536 9h 30m	709 9h 6m	677 9h 40m	6.951 t 33,990.1 kWh	10.760 t 53,890.1 kWh	10.176 t 51,873.5 kWh
Souda Cruise ships	78 10h 13m	132 9h 6m	10 9h 30m	17.893 t 93,479.4 kWh	12.689 t 66,309.2 kWh	15.669 t 84,450.5 kWh
Heraklion Passenger ferries	731 12h 30m	745 10h 5m	722 10h 50m	15.229 t 83,017.8 kWh	14.571 t 78,436.0 kWh	15.661 t 85,494.4 kWh
Heraklion Cruise ships	187 9h 10m	204 10h 30m	24 15h 6m	13.602 t 70,747.8 kWh	12.841 t 67,038.4 kWh	24.742 t 133,342.9 kWh

The most fuel-energy consuming sector per ship call differs for the two ports: the passenger ferries dominate in terms of fuel-energy consumption in Heraklion while for Souda cruise ships prevail for 2018 and is almost the same for 2019. For year 2020 Heraklion cruise has a significant increase on average fuel and energy consumption in port and this is due to longer average duration of stay at port for the cruise vessels (15h 6m). Longer stay means more fuel-energy consumption at port which leads to more air emissions from vessels at port.

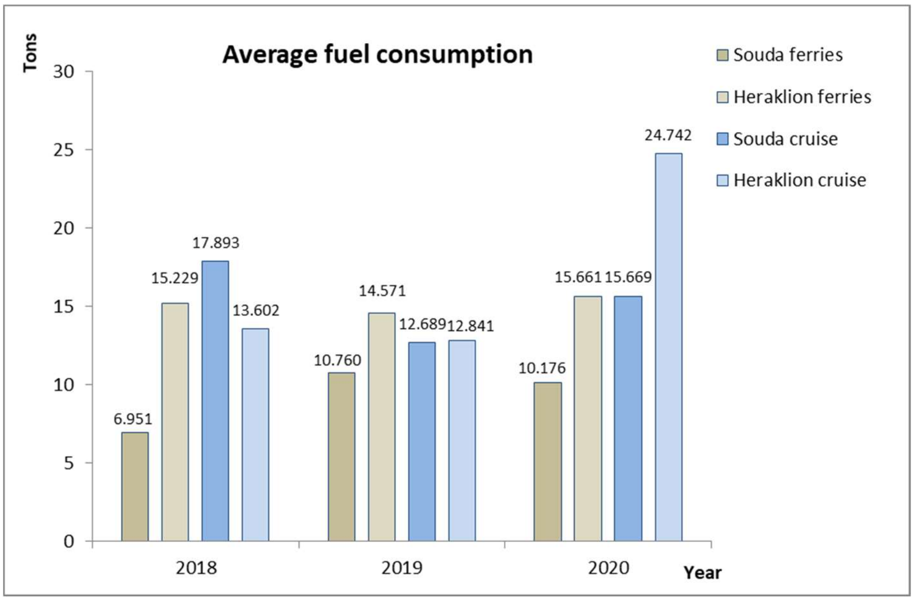


Figure 2: Average fuel consumption per ship calls and sector (ferry, cruise)

3.3 Air Emissions

CO_2 emissions account for about 97.4% for 2018 and 2019 and 98.1% for 2020 in terms of total air emissions, while NO_X, SO_X and PM_{10} quantities are around 1.8%, 0.6% and 0.1% respectively for year 2018 and 2019 and we notice a significant reduction for SO_X (0.1%) and PM_{10} (0.05%) for year 2020 due to new regulations (scrubbers, 0.5% S fuel). Air emissions are not all considered as air pollutants. CO_2 is the primary greenhouse gas emitted through human activities, which is naturally present in the atmosphere as part of the Earth's carbon cycle (the natural circulation of carbon among the atmosphere, oceans, plants, animals etc). Human activities are altering the carbon cycle–both by adding more CO_2 to the atmosphere, and by influencing the ability of natural sinks, like forests and soils, to remove and store CO_2 from the atmosphere. So obviously CO_2 is not a pollutant and we have to present it in our results separately. The detailed annual CO_2 air emissions quantities during three years period 2018-2019-2020 are depicted in Table 7 and graphically presented in figure 3.

Table 7: Annual CO_2 emissions for passenger ferries and cruise ships for Souda and Heraklion ports

Port	*Sector*	*2018 (t)*	*2019 (t)*	*2020 (t)*	*Total (t)*
Souda	Passenger ferries	11,838.131	24,296.325	21,568.220	57,702.676
Souda	Cruise ships	4,581.057	6,005.236	627.180	11,213.473
Heraklion	Passenger ferries	35,529.262	34,550.367	36,030.168	106,109.797
Heraklion	Cruise ships	8,184.408	8,384.526	1,505.233	18,074.167
	Total (t)	**60,132.858**	**73,236.454**	**59,730.801**	**193,100.113**

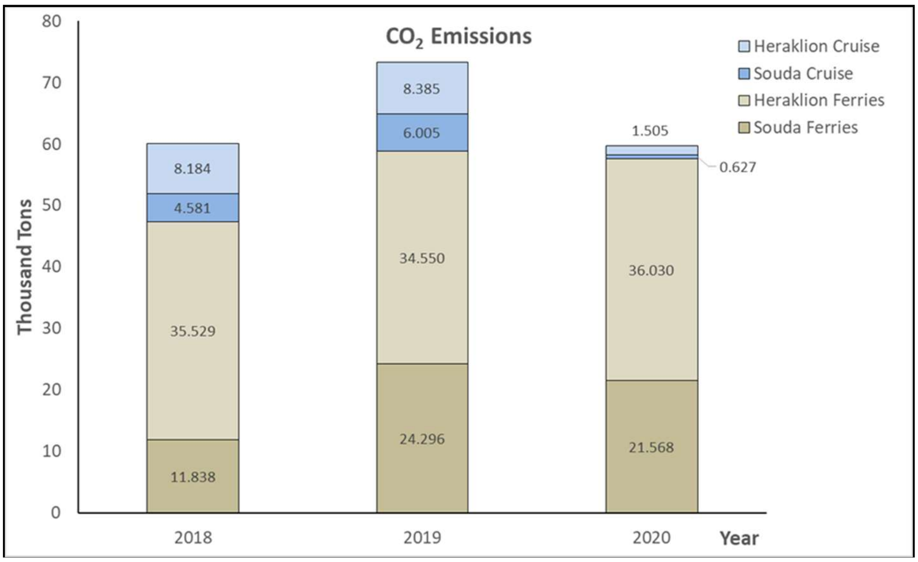


Figure 3: Annual CO_2 emissions for passenger ferries and cruise ships

Gaseous pollutants SO_X, NO_X, PM_{10} are depicted in Table 8 while the percentage of air pollutants content between 2018, 2019, 2020 are graphically presented in figure 4. We notice that passenger ferries at both ports contributed more than cruise vessels at the total of CO_2 air emissions and the same is observed for the other calculated air emissions.

Table 8: Annual air pollutants emissions for passenger ferries and cruise ships for Souda and Heraklion ports

Port	*Sector*	*Year*	*SO_x (t)*	*NO_x (t)*	*PM_{10} (t)*
Souda	Passenger ferries	2018	52.079	215.637	10.231
Souda	Cruise ships		19.504	80.448	4.090
Heraklion	Passenger ferries		286.342	661.509	55.227
Heraklion	Cruise ships		25.472	161.019	6.278
	Total		**383.397**	**1,118.613**	**75.826**
	Content in total (%)		**24.3 %**	**70.9 %**	**4.8 %**
Souda	Passenger ferries	2019	155.804	427.945	29.901
Souda	Cruise ships		29.397	112.526	5.935
Heraklion	Passenger ferries		274.248	637.946	52.494
Heraklion	Cruise ships		26.239	157.995	6.090
	Total		**485.688**	**1,336.412**	**94.420**
	Content in total (%)		**25.3 %**	**69.7 %**	**4.9 %**
Souda	Passenger ferries	2020	13.452	384.066	10.168
Souda	Cruise ships		0.199	5.452	0.231
Heraklion	Passenger ferries		17.870	671.593	18.086
Heraklion	Cruise ships		0.478	13.085	0.554
	Total		**31.999**	**1,074.196**	**29.039**
	Content in total (%)		**2.8 %**	**94.6 %**	**2.6 %**
	Grand Total		**901.084**	**3,529.221**	**199.285**

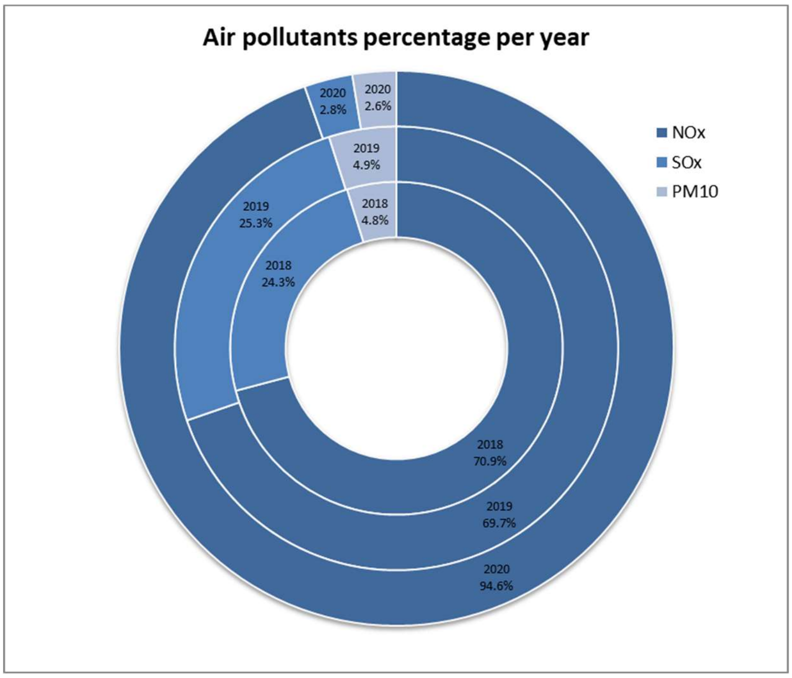


Figure 4: Air pollutants percentage per year for passenger ferries and cruise ships

From Table 8 and figure 4 we observe a large variation in the percentage of air pollutants content between 2018/2019 and 2020 and obviously this is due to new regulations (scrubbers, 0.5% S fuel). While SO_X, NO_X, PM_{10} content percentage was about 25%, 70% and 5% for 2018/2019, in 2020 was 2.8%, 94.6% and 2.6% respectively which confirms the effort to reduce harmful gases from shipping.

4 Conclusions

Cruise industry was the travel sector, which has been significantly affected by Covid-19 pandemic, while passenger ferries have also been negatively influenced, following the social distancing measures and travel restrictions. From the current study of the two ports (Heraklion and Souda), for ships calls a large decrease has been observed for the cruise sector (following other Mediterranean ports decrease, which was over 90% in many cases) but only a small reduction was for passenger ferries. Despite this the results for ferries clearly showed large decrease in terms of transportation of passengers (near 50%) and vehicles (near 40%), which significantly affected the income of the shipping companies. Even if cruise ship calls have been minimized for year 2020, Heraklion cruise vessels has a significant increase on average fuel and energy consumption in port (compared to previous years) and this is due to significant increase on average duration of stay at port, which means higher fuel-energy consumption and air emissions at port.

In terms of air emissions, CO_2 quantities did not vary throughout the three years of the study, since emitted CO_2 is only related to fuel quantity. Regarding SO_X, NO_X and PM_{10} large variations were observed especially in terms of gases content between 2018-2019 and 2020, and this is due to the new regulations (application of scrubbers and 0.5% S fuel) that entered into force from 2020. While SO_X, NO_X, PM_{10} content was about 25%, 70% and 5% respectively before 2020, the values for 2020 were 2.8%, 94.6% and 2.6% respectively, which confirms the positive effect of the efforts to reduce emissions of harmful pollutants from shipping in ports.

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