ΠΟΛΥΤΕΧΝΕΙΟ ΚΡΗΤΗΣ
TECHNICAL UNIVERSITY OF CRETE

SCHOOL OF PRODUCTION ENGINEERING
AND MANAGEMENT

Comparison of methodologies for the calculation of air emissions in shipping. Model development and optimization of fuel consumption

Thesis submitted for the partial fulfillment of the requirements for the degree of

Doctor of Philosophy (PhD)

by

EMMANOUIL DOUNDOULAKIS

Supervisor: Professor Spiros Papaefthimiou

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& ΔΙΟΙΚΗΣΗΣ

ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

Σύγκριση μεθοδολογιών υπολογισμού εκπεμπόμενων αέριων ρύπων στη ναυτιλία και ανάπτυξη μοντέλου βελτιστοποίησης της κατανάλωσης καυσίμων

από

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(Ονοματεπώνυμο διδάκτορα)

ΔΟΥΝΔΟΥΛΑΚΗΣ ΕΜΜΑΝΟΥΗΛ του ΕΛΕΥΘΕΡΙΟΥ

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ABSTRACT

Shipping is an important and growing source of air emissions, which affect climate change, but also have extremely adverse effects both on ecosystems and on the health and quality of life of citizens. The International Maritime Organization (IMO) and the E.U. recognizing this potential problem, albeit relatively belatedly, has taken two key steps:

1) From the beginning of January 2020, a maximum sulfur content limit has been imposed on marine fuels, in order to limit in this way the gaseous emissions of Sulfur Oxides (SO_X) as well as Particulate Matters (PM)
2) Since June 2013 it has defined a three-step strategy for the gradual integration of maritime transport into the European policy to reduce greenhouse gas emissions, where as a first step, ship owners arriving at or departing from EU ports, they should monitor, calculate and report to the E.U. the air emissions of carbon dioxide (CO_2) for each year, starting from 2018 (EU MRV 757/2015). At a later stage, targets are expected to be set to reduce these air emissions, while ultimately further reduction measures will include the management and exchange of CO_2, within the framework of the European Trading System (ETS).

However, given that ship-owners do not publically publish data on the air emissions of their ships, nor on the fuel consumption, we are forced to apply various calculating methodologies to estimate them and it is of great importance to apply the most reliable and exact method, depending on available data. One of the most important goals of our work is to implement such a calculation method and to compare with real-reported date proving by this way its reliability and accuracy.

All the available options for the parameters involved in the various calculation methodologies were analyzed, the most correct ones were selected and four calculation scenarios were implemented. The proposed basic scenario is based on a detailed estimation of the Specific Fuel Oil Consumption (SFOC) through regression analysis as well as the power of the ships' engines according to the manufacturer.

As a case study we examined the air emissions (CO_2, SO_X, NO_X, $PM_{2.5}$ and PM_{10}) from all passenger ships (passenger ferries and cruise vessels) in the main ports of Crete (Souda and Heraklion) over a period of five years, from 2017 to 2021. For any researcher dealing with the calculation of air emissions due to shipping, the question is almost about the accuracy of the methodology and results. Since the actual fuel consumption and air emissions were not available a few years ago, the EMSA/MRV-THETIS database which implemented as a result of the EU-MRV Regulation 757/2015 is a very useful tool to retrieve the actual fuel consumption and CO_2 emissions from all ships approaching European ports. One of the major objectives was to compare the four different calculation scenarios with data from the EMSA/MRV-THETIS database and establish by this way the reliability and accuracy of the proposed methodology. From this comparative analysis we found out that the results of the basic scenario methodology are the ones that are very close (6-12%) to those published by the EU MRV.

Based on the accuracy of the calculated air emissions following basic scenario methodology, we complete our study by calculating their external costs. These costs cover effects on human health, damage to materials and buildings, damage to biodiversity and crop losses caused by gaseous pollutants. Also, in line with the 'polluter pays' policy which appears to be the EU's gradual approach to the commitment to reduce greenhouse gas emissions from shipping, we understand that the upcoming EU policy for the shipping sector is the EU ETS.

As we have seen by calculating external costs, these are a significant percentage of shipping companies' revenue (they are about 25-35% in the last years from 2019 onwards) which means that if the companies are asked to pay, then there will be a significant revenue loss, with the worst case scenario being that they will not be able to absorb this cost and probably pass it on to the ticket fare of each passenger / vehicle / truck ticket. With this aim, an analysis and determination of this additional cost was made (we called it "Externalities Surcharge") which shows the potential burden on tickets that will arise in case shipping companies are asked to pay for the air emissions they cause during the approach of their vessels in the ports of Crete.

ΣΥΝΤΟΜΗ ΠΕΡΙΛΗΨΗ

Η ναυτιλία αποτελεί μια σημαντική και αναπτυσσόμενη πηγή αέριων εκπομπών, που επιδρούν στην κλιματική αλλαγή, αλλά έχουν και εξαιρετικά δυσμενείς επιπτώσεις τόσο στα οικοσυστήματα όσο και στην υγεία και την ποιότητα ζωής των πολιτών. Ο Διεθνής Ναυτιλιακός Οργανισμός (IMO) αλλά και η Ε.Ε. αναγνωρίζοντας αυτό το δυνητικό πρόβλημα, έστω και σχετικά καθυστερημένα, έχει λάβει δύο βασικά μέτρα:

1) Από τις αρχές Ιανουαρίου 2020 έχει επιβληθεί ανώτατο όριο περιεκτικότητας του Θείου στα ναυτιλιακά καύσιμα, ώστε να περιοριστούν με αυτό τον τρόπο οι αέριες εκπομπές οξειδίων του Θείου (SO_X) καθώς και αιωρούμενων σωματιδίων (PM)
2) Από τον Ιούνιο του 2013 έχει καθορίσει μια στρατηγική τριών βημάτων για τη σταδιακή ενσωμάτωση των θαλάσσιων μεταφορών στην ευρωπαϊκή πολιτική για τη μείωση των εκπομπών αερίων του θερμοκηπίου, όπου ως πρώτο βήμα, οι πλοιοκτήτες πλοίων που προσεγγίζουν ή αναχωρούν από λιμάνια της Ε.Ε. θα πρέπει να παρακολουθούν, να υπολογίζουν και να αναφέρουν στην Ε.Ε. τις αέριες εκπομπές διοξειδίου του άνθρακα (CO_2) για κάθε έτος, ξεκινώντας από το 2018 (EU MRV 757/2015). Σε επόμενο στάδιο αναμένεται να τεθούν στόχοι μείωσης αυτών των αέριων εκπομπών, ενώ τελικά περαιτέρω μέτρα μείωσης θα περιλαμβάνουν διαχείριση και ανταλλαγή αέριων ρύπων, στο πλαίσιο του ευρωπαϊκού συστήματος εμπορίας των δικαιωμάτων εκπομπής αέριων ρύπων.

Δεδομένου όμως ότι οι ναυτιλιακές εταιρείες δεν δημοσιεύουν στοιχεία σχετικά με τις αέριες εκπομπές των πλοίων τους αλλά ούτε και για την κατανάλωση καυσίμων τους, αναγκαζόμαστε να εφαρμόσουμε διάφορες μεθόδους υπολογισμού των αέριων εκπομπών, όπου σε ερευνητικό επίπεδο έχει πάρα πολύ μεγάλη σημασία να εφαρμόσουμε την πλέον αξιόπιστη και ακριβή μέθοδο, ανάλογα με τα διαθέσιμα δεδομένα. Ένας από τους σημαντικότερους στόχους της εργασίας μας είναι να εφαρμόσουμε μια τέτοια μέθοδο υπολογισμού και να αποδείξουμε με πραγματικά στοιχεία την αξιοπιστία και την ακρίβεια της.

Στην παρούσα Δ.Δ. αναλύθηκαν οι διαθέσιμες επιλογές για όλες τις παραμέτρους που συμμετέχουν στις διάφορες μεθοδολογίες υπολογισμού, επιλέχθηκαν οι ορθότερες και αναλύθηκαν τέσσερα σενάρια υπολογισμού. Το προτεινόμενο βασικό σενάριο βασίζεται σε λεπτομερή εκτίμηση της παραμέτρου της ειδικής κατανάλωσης καυσίμου SFOC μέσω ανάλυσης παλινδρόμησης (regression analysis) καθώς και της ισχύος των κινητήρων των πλοίων σύμφωνα με τον κατασκευαστή.

Ως μελέτη περίπτωσης εξετάσαμε τις αέριες εκπομπές (CO_2, SO_X, NO_X, $PM_{2.5}$ και PM_{10}) από όλα τα πλοία επιβατών (ακτοπλοΐα και κρουαζιέρα) στα δύο βασικά λιμάνια της Κρήτης (Σούδα και Ηράκλειο) σε μία περίοδο πέντε ετών, από το 2017 έως και το τελευταίο έτος αναφοράς 2021. Για κάθε ερευνητή που ασχολείται με τον υπολογισμό των αέριων εκπομπών στη ναυτιλία, σχεδόν πάντα τίθεται το ερώτημα σχετικά με την ακρίβεια των αποτελεσμάτων και συγκεκριμένων παραμέτρων-παραγόντων που περιλαμβάνονται στους υπολογισμούς. Δεδομένου ότι η πραγματική κατανάλωση καυσίμου και οι αέριες εκπομπές δεν ήταν διαθέσιμα πριν από μερικά χρόνια, η βάση δεδομένων EMSA/MRV-THETIS

που έχει υλοποιηθεί ως αποτέλεσμα του κανονισμού EU-MRV 757/2015, είναι ένα πολύ χρήσιμο εργαλείο για την δημοσιοποίηση της πραγματικής κατανάλωσης καυσίμου και εκπομπών CO_2 από όλα τα πλοία που προσεγγίζουν Ευρωπαϊκούς λιμένες. Ένας από τους σημαντικότερους στόχους ήταν να αντιπαραβάλουμε τα αποτελέσματα των υπολογισμών με πραγματικά στοιχεία από τη βάση δεδομένων EMSA/MRV-THETIS ώστε να διαπιστώσουμε την αξιοπιστία και την ακρίβεια της προτεινόμενης μεθοδολογίας. Από αυτές τις συγκρίσεις οδηγούμαστε στο συμπέρασμα ότι τα αποτελέσματα της προτεινόμενης μεθοδολογίας στο βασικό σενάριο, είναι αυτά που βρίσκονται πολύ κοντά (6-12%) στα δημοσιευμένα από το EU MRV.

Έχοντας ως βάση την ακρίβεια των υπολογισμένων αέριων εκπομπών, ολοκληρώνουμε τη μελέτη μας υπολογίζοντας τα εξωτερικά κόστη αυτών. Τα κόστη αυτά καλύπτουν επιπτώσεις στην υγεία των ανθρώπων, ζημιές υλικών και κτιρίων, ζημιές στη βιοποικιλότητα και απώλειες καλλιεργειών που προκαλούνται από τους αέριους ρύπους. Επίσης, σύμφωνα με την πολιτική «ο ρυπαίνων πληρώνει» που διαφαίνεται ότι είναι η σταδιακή προσέγγιση της ΕΕ προς τη δέσμευση μείωσης των ναυτιλιακών εκπομπών αερίων του θερμοκηπίου καταλαβαίνουμε ότι η επερχόμενη πολιτική της ΕΕ για τον ναυτιλιακό τομέα, είναι το EU ETS.

Όπως είδαμε ως αποτέλεσμα των υπολογισμών, τα εξωτερικά κόστη είναι ένα σημαντικό ποσοστό των εσόδων των ναυτιλιακών εταιρειών (αποτελούν περίπου το 25-35% κατά τα τελευταία έτη από το 2019 και μετά) που σημαίνει ότι αν κληθούν να πληρώσουν οι εταιρείες, τότε θα υπάρξει σημαντική απώλεια των εσόδων τους, με επικρατέστερο σενάριο να μην μπορούν να απορροφήσουν αυτό το κόστος και να το μετακυλήσουν στο εισιτήριο κάθε κατηγορίας επιβάτη / οχήματος / φορτηγού. Με αυτό ως στόχο έγινε μια ανάλυση και προσδιορισμός αυτού του επιπρόσθετου κόστους το οποίο το ονομάσαμε “Externalities Surcharge” και δείχνει την επιβάρυνση στα εισιτήρια, που θα προκύψει σε περίπτωση που κληθούν οι ναυτιλιακές εταιρείας να πληρώσουν τις αέριες εκπομπές που προκαλούν κατά την προσέγγιση των πλοίων τους στους λιμένες της Κρήτης.

SYNOPSIS & THESIS STRUCTURE

Shipping is an important and growing source of gaseous pollutants, which have an impact on climate change, but also have extremely adverse effects on both ecosystems and the health and quality of life of people. Carbon dioxide (CO_2) is considered to have a significant contribution to the phenomenon of climate change, while particulate matter (PM), nitrogen oxides (NO_X) and sulfur oxides (SO_X) have significant effects on public health. Studies have been carried out by the International Maritime Organization (IMO) which conclude that without restrictive actions, these emissions are expected to more than double by 2050, as shipping remains the only mode of transport (passengers and cargo) that does not has been incorporated into the pan-European obligation to reduce greenhouse gas emissions.

The EU recognizing this potential problem, even relatively late, since June 2013 has set out a three-step strategy for the gradual integration of maritime transport into European greenhouse gas reduction policy. As a first step, vessels approaching or departing from EU ports should monitor, calculate and report to the EU, CO_2 emissions starting from 2018 (EU MRV Regulation 757/2015). At a later stage, we believe that targets are set to reduce these gaseous emissions, and eventually further reduction measures will include the management and exchange of gaseous pollutants, under the European emissions trading scheme.

In this context, ports are hubs of great importance, providing a connection between land and sea, acting as gateways, enhancing trade and global communication in general. As we can understand, the environmental impact of ports (in the form of gaseous pollutants) on the atmosphere and human health (due to their proximity to densely populated areas) is extremely important.

However, since the shipping companies do not publish data on the air emissions of their ships nor on their fuel consumption (which with appropriate emission factors we could calculate the air emissions) we are forced to apply different methodologies to estimate the air emissions, while in research level it is very important to apply the most reliable and accurate method, depending on the available data, geographic area and ships type. One of the most important goals of our work is to apply such a calculation method and to prove with actual (reported) data its reliability and accuracy.

For the calculation of fuel consumption and energy, a bottom-up methodology has been followed which uses specific parameters that play an important role in the accurate calculation of air emissions. These are:

- Engine load factor (LF)
- Specific Fuel Consumption (SFOC)
- Emission factors (EF)

In current study the available options and alternatives for these parameters were analyzed, the most accurate were selected and four calculation scenarios were analyzed. The basic scenario is based on a detailed assessment of the SFOC through regression analysis applied to the technical characteristics of fuel consumption of the engines (main and auxiliary) as well as their power according to the manufacturer.

In addition to the above parameters, one of the most critical factors for accurately estimating gaseous emissions is engine power. Usually for most ships the engine power is not known and only the IMO number, the size of the vessel and the gross tonnage (GT) are widely available, so in this case, the estimation of the installed engine power can be done following a standard methodology given in the literature based on GT of vessel, with reference to 2010 passenger vessels world fleet ($Power_{ME} = 9.55078 \cdot GT^{0.7570}$) or 2006 Mediterranean Sea fleet ($Power_{ME} = 42.966 \cdot GT^{0.6035}$). The above applies to the main engines, while the installed power of the auxiliary engines is calculated from the average ratio of Auxiliary Machines / Main Engines for passenger ships: 0.16 and 0.27 for the world and Mediterranean fleets, respectively. The alternative scenarios that we examined beyond the basic one, calculate the SFOC by applying specific factors (adjustment factors) that refer to the literature and the installed power of the machines according to the above standard methodologies that have been mentioned.

As a case study we examined the air emissions (CO_2, SO_X, NO_X, $PM_{2.5}$ and PM_{10}) from all passenger ships (passenger ferries and cruise ships) in the two main ports of Crete (Souda and Heraklion) over a period of five years, from 2017 to the last reference year 2021. For the purposes of this study, a detailed technical inventory was created containing all the required technical details for 10 passenger ships (from three different shipping companies) operating daily year-round and 88 different cruise ships (which approached both ports mainly during the summer season). All data on ship arrivals and the duration of port approaches were collected and validated by the port authorities as well as by the Hellenic Ports Association, the most reliable cruise portal. In addition, in order to confirm the above data and to determine the required duration of each operating phase, an extensive search has been carried out in the relevant AIS database for the itineraries in study.

For any researcher involved in the calculation of air emissions in shipping, the question is almost always asked about the accuracy of the results and specific parameters-factors included in the calculations. As actual fuel consumption and emissions were not publicly available a few years ago, the EMSA / MRV-THETIS database implemented as a result of EU-MRV Regulation 757/2015 is a very useful tool for publicizing actual fuel consumption and CO_2 emissions from all ships approaching European ports. One of the most important objectives of our study was to compare the results of the calculations with reported data from the EMSA / MRV-THETIS database in order to verify the reliability and accuracy of the proposed methodology.

The structure of the text is developed in four chapters. In the first chapter we talked about the main gaseous pollutants from shipping, we pointed out their effects; we saw the IMO forecasts on CO_2 emissions by 2050 and the effects of climate change. We also reported the policies implemented for the protection of the environment in the field of shipping and the benefits of these policies for human health and the mitigation of climate change.

In the second chapter we analyzed the EU MRV regulation. EU publishes an annual report on CO_2 emissions and other relevant information from shipping in order to inform the public. In addition to the EU's MRV system, which focuses on CO_2 emissions from shipping in the EU region, there is also the IMO system which covers emissions from shipping worldwide, but these results are not made public or have yet to be decided if, how and when the two systems will converge. Both systems have the overall goal of mitigating climate change, as the result of both are annual reports reporting CO_2 emissions per ship (EU MRV) or total fuel consumption (IMO DCS). The logical consequence would be that, given the experience and results of these systems, the IMO and the EU would be able to decide further on setting targets for greenhouse gas emission levels from international shipping.

In the third chapter we analyzed in detail the parameters that take part in the calculations of air emissions in shipping, according to the existing methodologies and the four scenarios we described above for the case study of the ports of Crete for the last five years. The results of the calculations are the fuel and energy consumption for each sector (passenger ferries and cruise ships) and the air emissions of CO_2, NO_X, SO_X, $PM_{2.5}$ and PM_{10}. This chapter makes very important comparisons between the results from the different scenarios and the reported data as derived from the latest published EU MRV report on our study vessels. From these comparisons we lead with relative certainty to the conclusion that the proposed methodology we described in the basic scenario is very close (6-12%) to the reported data from EU MRV.

In the fourth chapter we complete our study by calculating the external costs of shipping air emissions for our case study. The general definition of external costs is interpreted as the cost of the effects resulting from the activities (social or economic) of one group of people to another group of people. In order to assess the costs and benefits of shipping to society, it is necessary to take into account all costs, including the external cost of gas emissions, in this case the cost of the impact of gas emissions on local port communities. These costs cover health impacts, damage to materials and buildings, damage to biodiversity and crop losses caused by gaseous pollutants. According to the "polluter pays" policy, which seems to be the EU's gradual approach to reducing GHG maritime emissions, we understand that the EU's forthcoming maritime policy is the EU ETS. In our case study we have calculated CO_2 emissions and its market value seems to be a good indicator for calculating the external cost of CO_2 emissions. We could see this as a variant of the avoidance cost approach, but it is understandable that additional policy intervention is needed to force shipping companies to switch to different forms of fuel and energy in general.

As we saw from the results in the last chapter, external costs are a significant percentage of the revenue of shipping companies (about 25-35% from 2019 onwards) which means that if shipping companies were called to pay, then there will be a significant revenue loss with the prevailing scenario this cost to not absorb by the shipping companies. Most probably the shipping companies will pass this cost on to the ticket fare of each transportation category (clients). As a final result of this chapter, an analysis and determination of this surcharge was made for each transportation category (passengers, vehicles, cargo vehicles).

ΕΚΤΕΤΑΜΕΝΗ ΠΕΡΙΛΗΨΗ & ΔΟΜΗ ΤΗΣ ΕΡΓΑΣΙΑΣ

Η ναυτιλία αποτελεί μια σημαντική και αναπτυσσόμενη πηγή αέριων ρύπων, οι οποίοι επιδρούν στην κλιματική αλλαγή, αλλά έχουν και εξαιρετικά δυσμενείς επιπτώσεις τόσο στα οικοσυστήματα όσο και στην υγεία και την ποιότητα ζωής των πολιτών. Το διοξείδιο του άνθρακα (CO_2) θεωρείται ότι έχει σημαντική συνεισφορά στο φαινόμενο της κλιματικής αλλαγής, ενώ τα αιωρούμενα σωματίδια (PM), τα οξείδια αζώτου (NO_X) και θείου (SO_X) έχουν σημαντικές επιπτώσεις για τη δημόσια υγεία. Έχουν εκπονηθεί μελέτες από τον Διεθνή Ναυτιλιακό Οργανισμό (International Maritime Organization-IMO) που καταλήγουν στο συμπέρασμα, ότι χωρίς περιοριστικές δράσεις, οι εκπομπές αυτές αναμένεται να υπερδιπλασιαστούν μέχρι το 2050, καθώς η ναυτιλία παραμένει ο μόνος τρόπος μεταφοράς (επιβατών και φορτίων) που δεν έχει ενσωματωθεί στην πανευρωπαϊκή υποχρέωση μείωσης εκπομπών αερίων του θερμοκηπίου.

Η Ε.Ε. αναγνωρίζοντας αυτό το δυνητικό πρόβλημα, έστω και σχετικά καθυστερημένα, από τον Ιούνιο του 2013 έχει καθορίσει μια στρατηγική τριών βημάτων για τη σταδιακή ενσωμάτωση των θαλάσσιων μεταφορών στην ευρωπαϊκή πολιτική για τη μείωση των εκπομπών αερίων του θερμοκηπίου. Ως πρώτο βήμα, οι πλοιοκτήτες πλοίων που προσεγγίζουν ή αναχωρούν από λιμάνια της Ε.Ε. θα πρέπει να παρακολουθούν, να υπολογίζουν και να αναφέρουν στην Ε.Ε. τις αέριες εκπομπές διοξειδίου του άνθρακα (CO_2) για κάθε έτος, ξεκινώντας από το 2018 (EU MRV). Σε επόμενο στάδιο εκτιμούμε ότι αναμένεται να τεθούν στόχοι μείωσης αυτών των αέριων εκπομπών, ενώ τελικά περαιτέρω μέτρα μείωσης θα περιλαμβάνουν διαχείριση και ανταλλαγή αέριων ρύπων, στο πλαίσιο του ευρωπαϊκού συστήματος εμπορίας των δικαιωμάτων εκπομπής αέριων ρύπων.

Μέσα σε αυτό το πλαίσιο, τα λιμάνια αποτελούν κόμβους μεγάλης σημασίας, παρέχοντας σύνδεση ανάμεσα στην ξηρά και στη θάλασσα, λειτουργώντας ως πύλες διασύνδεσης, ενισχύοντας το εμπόριο και εν γένει την παγκόσμια επικοινωνία. Όπως μπορούμε να κατανοήσουμε, οι περιβαλλοντικές επιπτώσεις των λιμανιών (με τη μορφή αέριων ρύπων) στην ατμόσφαιρα και στην ανθρώπινη υγεία (λόγω της εγγύτητάς τους σε πυκνοκατοικημένες περιοχές) είναι εξαιρετικά σημαντικές.

Δεδομένου όμως ότι οι ναυτιλιακές εταιρείες δεν δημοσιεύουν στοιχεία σχετικά με τις αέριες εκπομπές των πλοίων τους αλλά ούτε και για την κατανάλωση καυσίμων τους (όπου με κατάλληλους συντελεστές θα μπορούσαμε να υπολογίσουμε τις αέριες εκπομπές) αναγκαζόμαστε να εφαρμόσουμε διάφορες μεθόδους υπολογισμού των αέριων εκπομπών, όπου σε ερευνητικό επίπεδο έχει πάρα πολύ μεγάλη σημασία να εφαρμόσουμε την πλέον αξιόπιστη και ακριβή μέθοδο, ανάλογα με τα διαθέσιμα δεδομένα. Ένας από τους σημαντικότερους στόχους της εργασίας μας είναι να εφαρμόσουμε μια τέτοια μέθοδο υπολογισμού και να αποδείξουμε με πραγματικά στοιχεία την αξιοπιστία και την ακρίβεια της.

Για τον υπολογισμό της κατανάλωσης καυσίμου και ενέργειας έχει ακολουθηθεί μια μεθοδολογία από κάτω προς τα πάνω (bottom-up) η οποία χρησιμοποιεί συγκεκριμένες παραμέτρους οι οποίες διαδραματίζουν σημαντικό ρόλο στον ακριβή υπολογισμό των αέριων εκπομπών. Αυτές είναι :

- Συντελεστής φορτίου κινητήρα (LF)
- Ειδική κατανάλωση καυσίμου (SFOC)
- Συντελεστές εκπομπών (EF)

Στην παρούσα εργασία αναλύθηκαν οι διαθέσιμες επιλογές για αυτές τις παραμέτρους, επιλέχθηκαν οι ορθότερες και αναλύθηκαν τέσσερα σενάρια υπολογισμού. Το βασικό σενάριο βασίζεται σε λεπτομερή εκτίμηση του SFOC μέσω ανάλυσης παλινδρόμησης (regression analysis) που εφαρμόστηκε στα τεχνικά χαρακτηριστικά κατανάλωσης καυσίμου των κινητήρων (κύριων και βοηθητικών) καθώς και της ισχύος τους σύμφωνα με τον κατασκευαστή.

Πέρα από τους παραπάνω παραμέτρους, ένας από τους πιο κρίσιμους παράγοντες για την ακριβή εκτίμηση των αέριων εκπομπών είναι η ισχύς του κινητήρα. Συνήθως για τα περισσότερα πλοία η ισχύ των κινητήρων δεν είναι γνωστή και μόνο ο αριθμός IMO, το μέγεθος του σκάφους και η ολική χωρητικότητα (GT) είναι ευρέως διαθέσιμα, οπότε σε αυτή την περίπτωση, η εκτίμηση της εγκατεστημένης ισχύος του κινητήρα μπορεί να πραγματοποιηθεί με βάση τυπική μεθοδολογία που δίδεται στη βιβλιογραφία με βάση την ολική χωρητικότητα του, με αναφορά στον παγκόσμιο στόλο επιβατηγών πλοίων του 2010 ($Power_{ME} = 9.55078 \cdot GT^{0.7570}$) ή στον στόλο της Μεσογείου 2006 ($Power_{ME} = 42.966 \cdot GT^{0.6035}$). Το παραπάνω ισχύει για τις κύριες μηχανές, ενώ η εγκατεστημένη ισχύ των βοηθητικών μηχανών υπολογίζεται από τη μέση αναλογία Βοηθητικών Μηχανών / Κύριων Μηχανών για επιβατηγά πλοία: 0,16 και 0,27 για τους στόλους του κόσμου και της Μεσογείου, αντίστοιχα. Οι εναλλακτικές προσεγγίσεις (σενάρια) που εξετάσαμε πέρα από το βασικό, υπολογίζουν την SFOC με εφαρμογή συγκεκριμένων συντελεστών (adjustment factors) που αναφέρονται στη βιβλιογραφία και την εγκατεστημένη ισχύ των μηχανών σύμφωνα με τις ανωτέρω τυπικές μεθοδολογίες που αναφέρθηκαν.

Ως μελέτη περίπτωσης εξετάσαμε τις αέριες εκπομπές (CO_2, SO_X, NO_X, $PM_{2.5}$ και PM_{10}) από όλα τα πλοία επιβατών (ακτοπλοΐα και κρουαζιέρα) στα δύο βασικά λιμάνια της Κρήτης (Σούδα και Ηράκλειο) σε μία περίοδο πέντε ετών, από το 2017 έως και το τελευταίο έτος αναφοράς 2021. Για τις ανάγκες της παρούσας μελέτης δημιουργήθηκε ένας αναλυτικός τεχνικός κατάλογος που περιέχει όλες τις απαιτούμενες τεχνικές λεπτομέρειες για 10 επιβατηγά πλοία (από τρείς διαφορετικές ναυτιλιακές εταιρείες) που πραγματοποιούν καθημερινά δρομολόγια όλο το χρόνο και 88 διαφορετικά κρουαζιερόπλοια (τα οποία προσέγγισαν και τα δύο λιμάνια κυρίως κατά την καλοκαιρινή περίοδο). Όλα τα δεδομένα σχετικά με τις αφίξεις πλοίων και τη διάρκεια των λιμενικών προσεγγίσεων συλλέχθηκαν και επικυρώθηκαν από τις λιμενικές αρχές καθώς και από την Ελληνική Ένωση Λιμένων, την πλέον αξιόπιστη διαδικτυακή πύλη κρουαζιέρας. Επιπρόσθετα, για την επιβεβαίωση των παραπάνω δεδομένων και τον προσδιορισμό της απαιτούμενης διάρκειας κάθε φάσης λειτουργίας έχει πραγματοποιηθεί εκτενής αναζήτηση στις σχετικές βάσεις δεδομένων AIS για τα δρομολόγια της μελέτης μας.

Για κάθε ερευνητή που ασχολείται με τον υπολογισμό των αέριων εκπομπών στη ναυτιλία, σχεδόν πάντα τίθεται το ερώτημα σχετικά με την ακρίβεια των αποτελεσμάτων και συγκεκριμένων παραμέτρων-παραγόντων που περιλαμβάνονται στους υπολογισμούς. Δεδομένου ότι η πραγματική κατανάλωση καυσίμου και οι αέριες εκπομπές δεν ήταν διαθέσιμα πριν από μερικά χρόνια, η βάση δεδομένων EMSA/MRV-THETIS που έχει υλοποιηθεί ως αποτέλεσμα του κανονισμού EU-MRV 757/2015, είναι ένα πολύ χρήσιμο εργαλείο για την δημοσιοποίηση της πραγματικής κατανάλωσης καυσίμου και εκπομπών CO_2 από όλα τα πλοία που προσεγγίζουν Ευρωπαϊκούς λιμένες. Ένας από τους σημαντικότερους στόχους ήταν να αντιπαραβάλουμε τα αποτελέσματα των υπολογισμών με πραγματικά στοιχεία από τη βάση δεδομένων EMSA/MRV-THETIS ώστε να διαπιστώσουμε την αξιοπιστία και την ακρίβεια της προτεινόμενης μεθοδολογίας.

Η διάρθρωση του κειμένου αναπτύσσεται σε τέσσερα κεφάλαια. Στο πρώτο κεφάλαιο αναφερθήκαμε στους κυριότερους αέριους ρύπους από τη ναυτιλία, επισημάναμε τις επιπτώσεις τους, είδαμε τις προβλέψεις του IMO σχετικά τις εκπομπές CO_2 μέχρι το 2050 και τις επιπτώσεις της κλιματικής αλλαγής. Επίσης είδαμε τις εφαρμοζόμενες πολιτικές για την προστασία του περιβάλλοντος στον τομέα της ναυτιλίας και τα οφέλη των πολιτικών αυτών για την υγεία των ανθρώπων και τον μετριασμό της κλιματικής αλλαγής.

Στο δεύτερο κεφάλαιο αναλύσαμε τον κανονισμό EU MRV. Η Ε.Ε. δημοσιεύει ετησίως έκθεση για τις εκπομπές CO_2 και άλλες σχετικές πληροφορίες από τη ναυτιλία με στόχο την ενημέρωση του κοινού και τη δυνατότητα αξιολόγησης των εκπομπών CO_2 και της ενεργειακής απόδοσης των θαλάσσιων μεταφορών. Εκτός από το σύστημα MRV της ΕΕ, το οποίο έχει επικεντρωθεί στις εκπομπές CO_2 από τη ναυτιλία στην περιοχή της ΕΕ, υπάρχει και το σύστημα του IMO το οποίο καλύπτει τις εκπομπές από τη ναυτιλία παγκοσμίως, χωρίς όμως να δημοσιοποιούνται τα αποτελέσματα αυτά και ούτε να έχει αποφασιστεί ακόμη, εάν, πώς και πότε θα συγκλίνουν τα δύο σχήματα. Και τα δύο συστήματα έχουν ως γενικό στόχο τον μετριασμό της κλιματικής αλλαγής, καθώς το αποτέλεσμα και των δύο είναι ετήσιες εκθέσεις που θα αναφέρουν τις εκπομπές CO_2 ανά πλοίο (EU MRV) ή τη συνολική κατανάλωση καυσίμου (IMO DCS). Η λογική συνέπεια θα ήταν ότι λαμβάνοντας υπόψη την εμπειρία και τα αποτελέσματα που προκύπτουν από τα συστήματα αυτά, ο IMO και η ΕΕ θα μπορέσουν να αποφασίσουν περαιτέρω για τον καθορισμό στόχων σε σχέση με τα επίπεδα εκπομπών αερίων του θερμοκηπίου από τη διεθνή ναυτιλία.

Στο τρίτο κεφάλαιο αναλύσαμε αναλυτικά τις παραμέτρους που λαμβάνουν μέρος στους υπολογισμούς των αερίων εκπομπών από την ναυτιλία, σύμφωνα με τις υπάρχουσες μεθοδολογίες και τα τέσσερα σενάρια που περιγράψαμε παραπάνω για τη μελέτη περίπτωσης των λιμένων της Κρήτης για τα πέντε τελευταία έτη. Τα αποτελέσματα των υπολογισμών είναι η κατανάλωση καυσίμου και ενέργειας για κάθε κλάδο (ακτοπλοΐα, κρουαζιέρα) και οι αέριες εκπομπές CO_2, NO_X, SO_X, $PM_{2.5}$ και PM_{10}. Σε αυτό το κεφάλαιο γίνονται πολύ σημαντικές συγκρίσεις μεταξύ των αποτελεσμάτων από τα διαφορετικά σενάρια και των δεδομένων όπως απορρέουν από την τελευταία δημοσιευμένη έκθεση του EU MRV για πλοία της μελέτης μας. Από αυτές τις συγκρίσεις οδηγούμαστε στο συμπέρασμα ότι τα αποτελέσματα που προκύπτουν με εφαρμογή της προτεινόμενης μεθοδολογίας που περιγράψαμε στο βασικό σενάριο είναι αυτά που βρίσκονται πολύ κοντά (6-12%) στα δημοσιευμένα από το EU MRV.

Στο τέταρτο και τελευταίο κεφάλαιο, έχοντας ως βάση την ακρίβεια των υπολογισμένων αέριων εκπομπών, ολοκληρώνουμε τη μελέτη μας υπολογίζοντας τα εξωτερικά κόστη αυτών. Ως γενικός ορισμός του εξωτερικού κόστους ερμηνεύεται το κόστος των επιπτώσεων που προκύπτουν από τις δραστηριότητες (κοινωνικές ή οικονομικές) μιας ομάδας ανθρώπων σε μια άλλη ομάδα ανθρώπων. Προκειμένου να αξιολογηθεί το κόστος και τα οφέλη της ναυτιλίας στην κοινωνία, είναι απαραίτητο να ληφθούν υπόψη όλα τα κόστη, συμπεριλαμβανομένου του εξωτερικού κόστους των αέριων εκπομπών, εν προκειμένω του κόστους των επιπτώσεων των αέριων εκπομπών στις τοπικές κοινωνίες των λιμένων. Τα κόστη αυτά καλύπτουν επιπτώσεις στην υγεία, ζημιές υλικών και κτιρίων, ζημιές στη βιοποικιλότητα και απώλειες καλλιεργειών που προκαλούνται από τους αέριους ρύπους. Σύμφωνα με την πολιτική «ο ρυπαίνων πληρώνει» που διαφαίνεται ότι είναι η σταδιακή προσέγγιση της ΕΕ προς τη δέσμευση μείωσης των ναυτιλιακών εκπομπών αερίων του θερμοκηπίου καταλαβαίνουμε ότι η επερχόμενη πολιτική της ΕΕ για τον ναυτιλιακό τομέα, είναι το EU ETS. Στη μελέτη περίπτωση μας έχουμε υπολογίσει τις εκπομπές CO_2 και η χρηματιστηριακή αξία του, φαίνεται να είναι ένας καλός δείκτης για τον υπολογισμό του εξωτερικού κόστους των εκπομπών CO_2. Θα μπορούσαμε να το θεωρήσουμε ως παραλλαγή της προσέγγισης του κόστους αποφυγής, αλλά είναι κατανοητό ότι απαιτείται πρόσθετη πολιτική παρέμβαση για να αναγκαστούν οι ναυτιλιακές εταιρείες να στραφούν σε διαφορετικές μορφές καυσίμων και ενέργειας γενικότερα.

Όπως είδαμε στο τελευταίο κεφάλαιο, τα εξωτερικά κόστη είναι ένα σημαντικό ποσοστό των εσόδων των ναυτιλιακών εταιρειών (αποτελούν περίπου το 25-35% κατά τα τελευταία έτη από το 2019 και μετά) που σημαίνει ότι αν κληθούν να πληρώσουν οι εταιρείες, τότε θα υπάρξει σημαντική απώλεια των εσόδων τους, με επικρατέστερο σενάριο να μην μπορούν να απορροφήσουν αυτό το κόστος και να το μετακυλήσουν στο εισιτήριο κάθε κατηγορίας επιβαινόντων. Ως τελικό αποτέλεσμα αυτού του κεφαλαίου έγινε μια ανάλυση και προσδιορισμός αυτού του επιπρόσθετου κόστους σε κάθε κατηγορία επιβαίνοντα (επιβάτες, οχήματα, φορτηγά επαγγελματικής χρήσης).

PUBLICATIONS UNDER THIS PhD STUDY

The following originated during the research on the topics of this PhD study:

International peer reviewed journals

- Doundoulakis, E. & Papaefthimiou, S. (2022) "**Comparative analysis of fuel consumption and CO_2 emission estimation based on ships activity and reported fuel consumption: the case of short sea shipping in Crete**", Greenhouse Gases: Science and Technology – ***Accepted 19/7/2022***
- Doundoulakis, E., Papaefthimiou, S. & Sitzimis, I. (2022) "**Environmental impact assessment of passenger ferries and cruise vessels: the case study of Crete**", European Transport\Trasporti Europei. http://dx.doi.org/10.48295/ET.2022.87.2
- Doundoulakis, E. & Papaefthimiou, S. (2022) "**Estimation of externalities of major ports of Crete: Analytical methodological framework**", Climate Journal 10(7), 100. https://doi.org/10.3390/cli10070100
- Doundoulakis, E. & Papaefthimiou, S. (2021) "**A comparative methodological approach for the calculation of ships air emissions and fuel-energy consumption in two major Greek ports**" *Maritime Policy & Management*, 1–20. https://doi.org/10.1080/03088839.2021.1946610

International Conference

- Doundoulakis, E. & Papaefthimiou, S. (2021) "**Comparative analysis between different approaches for calculating on-board passenger ship's emissions and fuel-energy consumption based on operational data**", *6th HAEE Energy Transition Symposium (International Conference presentation) Sep 30, 2021.*
- Doundoulakis, E. & Sitzimis, I. (2021) "**Environmental impact of new Directives, Regulations and Covid-19 restrictions in the shipping sector: the case study of passenger ferries and cruise vessels in the region of Crete**", *6th HAEE Energy Transition Symposium (International Conference presentation) Sep 30, 2021.*

Book Chapter

- Doundoulakis E. & Papaefthimiou S. (2020) "**Ancillary Benefits of Climate Policies in the Shipping Sector**" In: Buchholz W., Markandya A., Rübbelke D., Vögele S. (eds) Ancillary Benefits of Climate Policy. Springer Climate. Springer, Cham. https://doi.org/10.1007/978-3-030-30978-7_15

CHAPTER 1: AIR EMISSIONS FROM SHIPPING

1.1 Introduction

In modern times, the effects of global climate change are constantly increasing and already have observable consequences on the environment. Many people have in mind that climate change and global warming are synonyms. This is not correct, as the term "climate change" is used to describe the complex changes that are now affecting our planet's weather and climate systems, which include not only rising average temperatures but also extreme weather events which occur in areas where no such climatic behavior has occurred so far.

The Intergovernmental Panel on Climate Change (IPCC), is the United Nations body for assessing the science related to climate change, forecasts temperature rise for decades to come, largely due to greenhouse gas (GHG) emissions produced by human activities. This is one of the main global challenges that humanity will have to face urgently and adopt measures in the way to mitigate the effects of climate change. Four impacts are considered as more prominent and worth emphasizing (Doundoulakis & Papaefthimiou, 2019):

- **Rising temperatures.** While temperature rises around the globe, longer heat waves and longer periods of drought with higher frequency and intensity are expected globally, affecting wildlife populations and habitats.
- **Extreme weather effects** (increased number of tornadoes, hurricanes and floods).
- **Bad air quality** (in addition to gas emissions resulting from combustion of fossil fuels, climate change related processes, e.g. more wildfires due to longer-lasting dry seasons burdens the air quality of the atmosphere).
- **Vector-borne diseases** (variable climatic conditions e.g. higher temperature and humidity in more areas compared to the past, allows some insects benefiting under these conditions to expand their population thus spreading out diseases).

Greenhouse gas (GHG) emissions can come from a range of sources (non-human and human activities) and climate change mitigation can be applied across all sectors of human activities (since we cannot control non-human activities) by limiting or preventing GHG emissions. These include energy production, transport of people and goods, buildings construction and operation, all kinds of industry, waste management, agriculture, forestry and land management in general. Shipping belongs to the transport sector though emissions from international shipping cannot be attributed to any particular national economy, due to its global nature and complex operation.

1.2 Maritime transportation

Shipping is the most efficient sector of mass transport and cities have traditionally developed themselves around ports embracing their activities which usually take place close to densely populated regions thus making ports' air emissions one of the main sources of urban air pollution. One of the main challenges for ports in their relation with the local communities is to ensure that their activities (including cruise and ferry operations) remain as environmentally sustainable as possible. In terms of emitted 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% (Fourth IMO GHG Study, 2020). 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, 2021; Fourth IMO GHG Study, 2020).

On the other hand, the potential impact of emitted air pollutants to human health, has been emphasized in reports issued by the European Environment Agency and the World Health Organization in a regularly basis, while 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 air quality issues constantly being in its highest priorities, since more than 90% of European ports are urban and air quality as a result of port activities is a key factor for public acceptance (Darbra, Wooldridge, & Puig, 2020).

The land intensive character of modern ports is characterized by a continuous search for reducing costs, resulting in economies of scale, larger terminal facilities and increasing ship sizes. In many cases new terminals are built further away from city centers or freight ports are relocated on new port sites, with less space constraints (Merk, 2013). Nowadays cruise ships and passenger ferries are often the only large scale port activities that have remained close to the city, thus allowing an interaction between the port and the close living citizens. Before COVID-19 pandemic, in all regions ports have developed strong interest in expanding their cruise related activities. Predictions indicated that 32 million passengers were expected globally in 2020, while almost 30 million passengers were assigned to 2019. Local communities at visiting ports destinations around the world received significant economic benefits from cruise passengers: before boarding $376 spent in port cities and during the cruise spent $101 at each visiting port (Cruise Lines International Association, 2020).

COVID-19 spread has had devastating impacts on the cruise industry as between mid-March and September 2020, a loss of about 50% compared to previous years' economic figures was recorded: $77 billion in global economic activity, 518,000 jobs, $23 billion in wages (Cruise Lines International Association, 2021). An important aspect is that in most cases both cruise and ferries' activities are typically seasonal with high peaks and the induced economic benefits are transferred to another location/attraction. At the same time, their proximity to densely populated residential areas has obliged hosting ports to strengthen their efforts towards the reduction of environmental impacts due to the cruise and ferry activities (ESPO, 2016).

An important parameter regarding the anticipated health effects of air pollution in ports is the population density of the adjacent residential areas. In terms of European ports operating both freight and cruise/ferries, Piraeus has the highest population density (it is one of the most populated areas in Greece, with a population of 163,688 for an area of 11.2 km^2, i.e. population density of 14,615 residents per km^2) (Hellenic Statistical Authority, 2022). 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).

In order to mitigate air emissions, cruise industry has invested $23.5 billion on new energy efficient technologies and collaborations with local communities and governments in significant destinations. The most important proposed technical interventions are (Cruise Lines International Association, 2020, 2021; IMO, 2019; Winkel, Weddige, Johnsen, Hoen, & Papaefthimiou, 2016):

i. use of Liquefied Natural Gas (LNG) as main propulsion fuel in 44% of new build ships;
ii. extended use of Exhaust Gas Cleaning Systems (ECGS) as 68% of international fleet currently employs EGCS, while 75% of non-LNG new-builds will have EGCS;
iii. use of Advanced Wastewater Treatment Systems in all new ship builds;
iv. 88% of new ship builds will be designed to host or support Shore-Side Power;
v. Other areas (battery propelled vessels, advanced recycling practices, reduced plastic use, energy-efficient lighting, solar energy, and fuel cell).

The potential of shore side electrification of ships at berth (in economic and environmental terms) has been analyzed and specific key policy actions for implementation in European ports were recommended. It was estimated that if all seagoing vessels in European ports used shore side electricity by year 2020, they would consume 3342 GWh annually which corresponds to almost 620,000 tons of fuel consumption at berth. About 40% of this consumption is made from cruise vessels at berth, while docked they need really large amounts of fuel and energy to provide power for leisure and "hoteling" facilities, taking on-board (Winkel et al., 2016).

Ships produce a wide range of emissions causing different health and environmental issues. Key compounds that are emitted are carbon dioxide (CO_2), nitrogen oxides (NO_X), sulphur oxides (SO_X), particulate matter (PM), ozone-depleting substances (ODSs) and volatile organic compounds (VOCs). In the following, each of these air emissions is briefly explained along with the environmental and health issues they can cause (Fourth IMO GHG Study, 2020; GEF-UNDP-IMO, 2018) :

1.2.1 Carbon Dioxide (CO_2)

CO_2 is a heavy, colorless and odorless gas that is naturally present in the Earth's atmosphere. It is produced by natural processes, such as by respiration or the decomposition of organic substances, but also by human activities, primarily the combustion of fossil fuels. CO_2 is the principal GHG and traps heat in the atmosphere, thus contributing to the greenhouse effect, commonly known as global warming or climate change.

1.2.2 Nitrogen Oxides (NO_X)

NO_X refers to a mixture of gases that are composed of nitrogen and oxygen, such as nitric oxide (NO) and nitrogen dioxide (NO_2). They are formed when oxygen and nitrogen react under high pressure or at high temperatures, such as in engines. NO_X contributes to acid deposition which can lead to adverse effects on aquatic ecosystems in rivers and lakes and damage to forests, crops and other vegetation. Furthermore, NO_X emissions can cause eutrophication and thus reduce water quality with subsequent impacts including decreased biodiversity, changes in species composition and dominance, and toxicity effects (EEA, 2020).

1.2.3 Sulphur Oxides (SO_X)

SO_X are compounds of sulphur and oxygen molecules; sulphur dioxide (SO_2) is the predominant form found in the lower atmosphere. Because petroleum-derived fuels contain sulphur (to a greater or lesser extent) their combustion results in the formation of SO_X. Exposure to SO_X has been associated with reduced lung function, increased incidence of respiratory symptoms and diseases and premature mortality. With regards to adverse environmental effects, SO_X emissions can damage vegetation and cause acid rain (WORLD-BANK, 1998).

1.2.4 Particulate Matter (PM)

PM refers to a mixture of solid particles and liquid droplets found in the air. The formation of PM depends on the efficiency and completeness of the combustion process, the amount of lubricating oil used and the amount of hydrocarbons, ash and sulphur in the fuel. The link with sulphur is why PM and SOx emissions are often grouped together. PM, especially finer particles, can enter the respiratory system and cause breathing problems, irritation of the lung capillaries, deficiencies in lung function and initiate or worsen heart diseases. In addition, PM arising from incomplete combustion of fossil fuel or biomass primarily consists of black carbon (BC), a short-lived climate change agent. The climate change impact of BC is second only to CO_2 (surpassing that of CH_4, CFCs, N_2O, or tropospheric ozone) and that its impact is slightly more than half that of CO_2 (UNEP.org, 2022).

1.2.5 Ozone-Depleting Substances (ODSs)

ODSs are man-made substances that damage the stratospheric ozone layer. The ozone layer in the stratosphere absorbs a portion of the radiation from the sun, preventing it from reaching the planet’s surface. Most importantly, it absorbs the portion of UV light called UVB which has been linked to many harmful effects, including skin cancers, cataracts, and harm to some crops and marine life (EPA.gov, 2022). Usually in the form of chlorofluorocarbons (CFCs), ODSs are used in refrigeration systems on board ships, normally for the refrigeration of cargo, provisions and air conditioning systems (Third IMO GHG Study, 2014).

1.2.6 Volatile Organic Compounds (VOCs)

VOCs are a large group of carbon-based chemicals that easily evaporate at ambient temperature and can react to form ground-level ozone. They are usually divided into non-methane VOCs (NMVOC) and methane (CH_4). They are formed when crude oil evaporates which can occur during loading, storage and transportation of crude oil on ships. Methane emissions are associated with LNG-powered vessels. They can occur as a result of: tank venting, fugitive leaks (pipework, flanges etc.) and methane slip during combustion through incomplete combustion of intake gas and gas remaining in crevices in the combustion chamber and in sections of the gas intake ports. Methane is a potent GHG with a global warming potential 21 times greater than CO_2, thus significantly contributing to climate change (Third IMO GHG Study, 2014).

1.3 Emission projections 2018 – 2050

Emissions projections from IMO shows increasing trends from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios (see Figure 1). Emissions could be higher (lower) than projected when economic growth rates are higher (lower) than assumed or when the reduction in GHG emissions from land-based sectors is less (more) than would be required to limit the global temperature increase to well below 2 degrees centigrade.

Although we haven't projected until this point the results of our study, it is clear that the impact of Covid-19 on air emissions for years 2020 and 2021 will be lower. Depending on the recovery trajectory, emissions over the next decades may be a few percent lower than projected, at most.

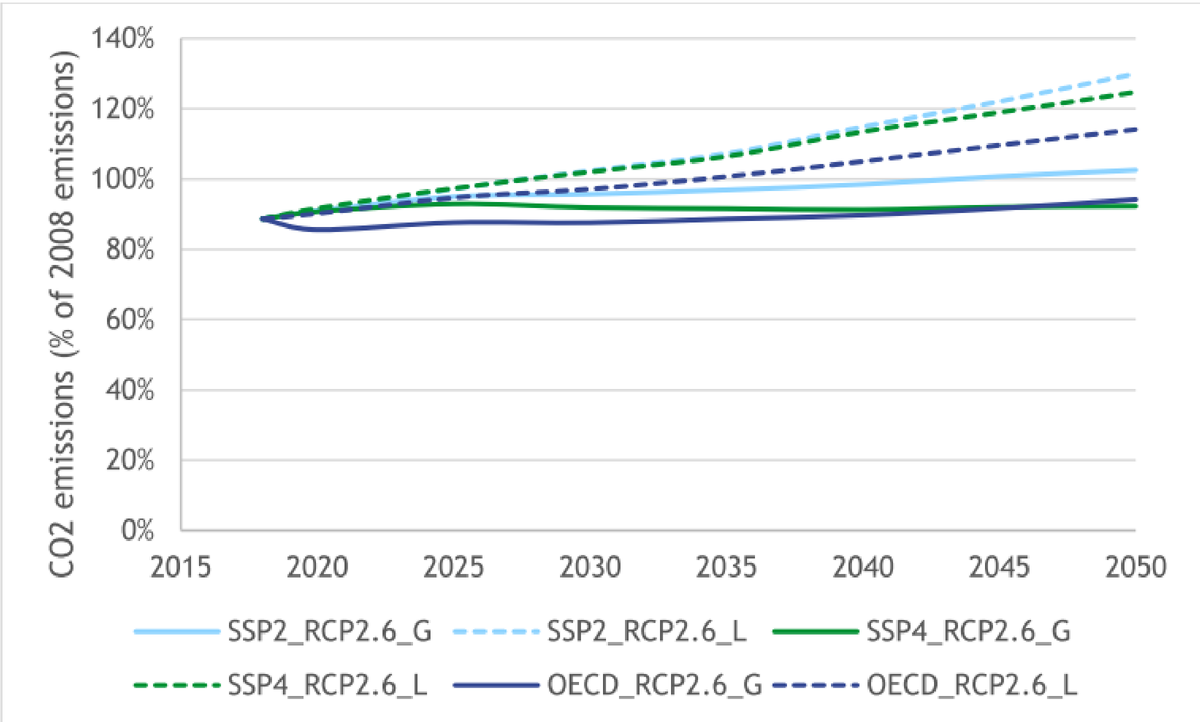


Figure 1: Projections of maritime ship emissions as a percentage of 2008 emission (source IMO)

1.4 Policy measures towards environmental protection within the shipping sector

IMO has been energetically pursuing the limitation and reduction of GHG emissions from international shipping, in recognition of the magnitude of the climate change challenge and the intense focus on this topic. 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, 2021; Fourth IMO GHG Study, 2020).

In terms of emitted 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% 2008 (Fourth IMO GHG Study, 2020).

IMO has addressed ship pollution under the MARPOL convention and required a gradual decrease of air emissions (NO_X, SO_X and Particulate Matters) originating from consumption of maritime fuel oil. In addition, major energy efficiency improvements for vessels have been proposed, through the application of the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). Also Emission Control Areas (ECAs) were firstly introduced including European sea areas, North American area and the US Caribbean Sea (see Figure 2).

Figure 2: Map illustrating the four emission control areas (ECAs) (source IMO)

Concerns about the impact of maritime transport on air quality were expressed through the Strategy for Sustainable Development, published on the EU White Paper on Transport Policy (EC, 2011). As a consequence EU actually adopted the enforcement of IMO MARPOL Annex VI sulphur cap to all European seas by establishing the EU Regulation 2016/802 for sulphur content in marine fuels and setting the same sulphur cap as IMO (0.5%). The Regulation also provides that during port stays, all ships should consume low sulphur marine fuel with 0.1% sulphur content if stays longer than two hours or a shore-side electricity connection.

The implemented timeline was that since January 2015 marine fuel for all ship operations in ECAs, must have 0.1% sulphur content while the sulphur limit for all other areas is 0.5% due to IMO regulations framework, initiated from January 2020 (see Figure 3). 2020 was a milestone year for the target of reducing air emissions from shipping due of the implementation of above Directives and Regulations and as we will see later in the results, there was a significant reduction of gaseous pollutants of SO_X and PM's due to this. Also Climate Change in the Baltic sea 2021 Fact Sheet, published by Helsinki

Commission (HELCOM, 2021) reported the impact of the implementation of ECA 0.1% SO_X limit for ships in this area and concluded that measures to reduce air emissions from ships can be effective and as a case study since the limit has been introduced, the air quality in the Baltics has improved by 70%.

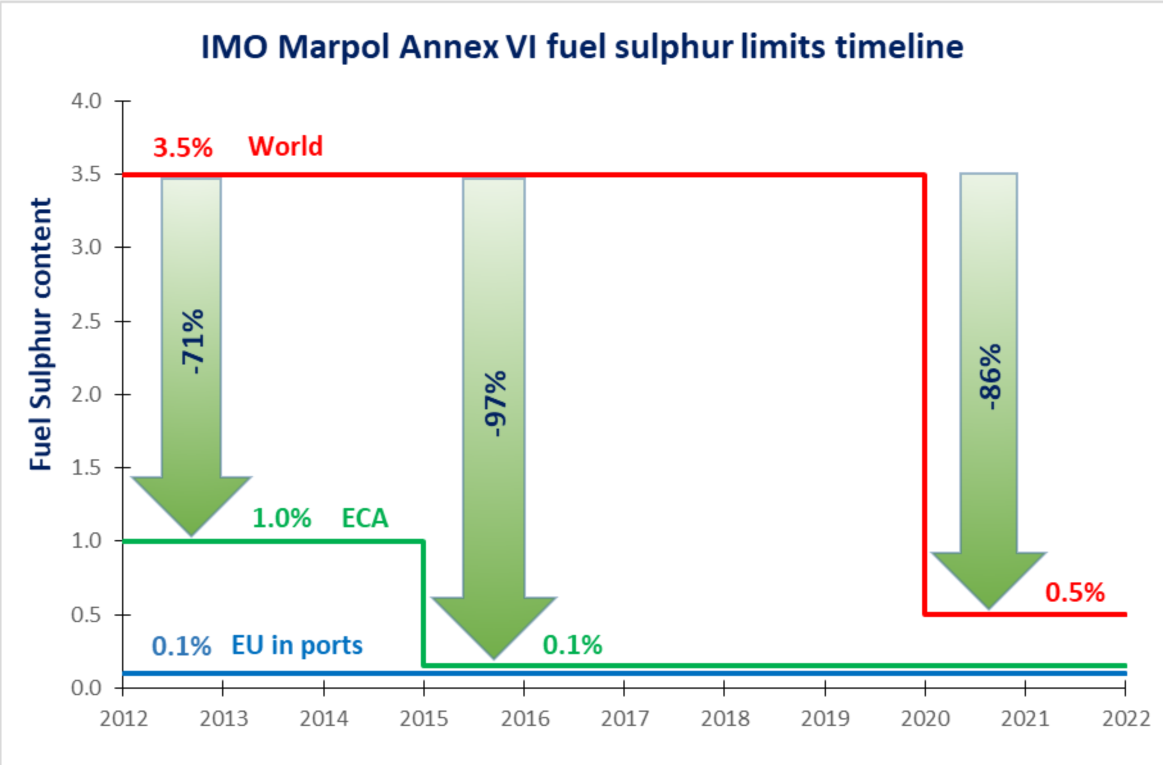


Figure 3: IMO Marpol Annex VI fuel sulphur limits timeline

Due to the latest ESPO Environmental report (ESPO, 2021) air quality has been the highest environmental priority for ports every year continuously since 2013 and is concerned as the main parameter towards public acceptance of port activities which mainly take place very close to populated port cities. As shipping is the main activity of ports it's obvious that this is the major source of air emissions in ports area.

An alternative way to comply with fuel sulphur standards is by removing sulfur dioxide from the air emissions instead of using lower sulfur fuels which are more expensive. This can be done by the use of exhaust gas cleaning systems (EGCSs also known as scrubbers) attached on the exhaust of the ships since IMO accepts this as an equivalent compliance option. Ships with scrubbers can continue to use cheaper high-sulfur heavy fuel oil (HFO) while scrubbers 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 scrubbers can be estimated for ships. In this report ICCT compiled 8 different studies containing 23 representative samples providing information on scrubbers air emissions and finally they presented that for a ship using HFO 2.60% (HFO global average as of 2019) the relative emissions reduction by using scrubbers in the ship's exhaust are:

-98% for SO_X, -79% for PM (10 or 2.5), no change for NO_X and +2% for CO_2. It is obvious that there is a significant reduction of SO_X and PM air emissions by using scrubber and small increase for CO_2 (Comer, Georgeff, & Osipova, 2020).

It is clear from the above that both EU and IMO have the will to implement policies to reduce emissions from ships and especially the air emissions of SO_X and PM, since this is the result of consuming fuel with lower sulphur or by the use of scrubbers. CO_2 emissions depend on fuel consumption and as a result of this two similar data collection schemes have been implemented:

- EU MRV implemented in accordance with the regulation 2015/757 (Council of the European Union, 2015) collecting fuel consumption and CO_2 emissions (data collection started 1 January 2018)
- IMO DCS collecting fuel consumption (data collection started 1 January 2019)

The above data collection schemes are mandatory for the shipping companies to follow their data reporting requirements and intend to be the first steps in a process to collect, analyze and report emissions data related to the maritime sector. These first steps are towards the action to cut emissions by understanding the emitted quantities and where. Through EU MRV a large amount of CO_2 emission data and other relevant information are publically available every year and an annual report is published, providing a comprehensive and granular understanding of CO_2 emissions for ships covered by the Regulation, providing also analysis on the characteristics and energy efficiency of ships, adding value and helping identify the various factors influencing CO_2 emissions.

1.5 Ancillary benefits of climate policies in the shipping sector

The policy measures towards climate and environmental protection within the shipping sector and the development of the existing regulation of various institutions are in a manner of continuous contribution to global efforts, to limit and reduce GHG emissions, with ultimate goal the climate change mitigation that comes from shipping sector. Climate change is already negatively impacting our health and if permitted to continue unabated, it will exacerbate direct and indirect health impacts to varying degrees across populations. Reduction of annual premature mortality and morbidity, in populations worldwide, is one of the objectives of IMO global compliance with 2020 marine fuel sulphur standards. There are significant benefits from consumption of cleaner marine fuels, especially in trading routes and ports close to densely populated areas. Low sulphur marine fuels, still account annually for ~250k deaths and ~6.4M childhood asthma cases, so additional reductions beyond 2020 standards may prove beneficial (Third IMO GHG Study, 2014)

The use of cleaner fuels in marine sector and the reduction of sulphur based emissions, may offer collateral health and climate benefits that merit quantification. For example, 2020 compliant marine fuels may enable or be accompanied with additional $PM_{2.5}$ emissions reductions, such as organic carbon and black carbon particles. Moreover, many control technologies for harmful particulates and ozone precursor emissions, perform better under low-sulphur combustion conditions. International policy making efforts jointly pursuing air pollution health benefits and climate targets may increase the urgency for continued progress to control and mitigate GHG.

1.6 Health impacts of Climate change and health co-benefits of mitigation measures

Accessibility to energy has been fundamental for human development and progress, but the combustion of fossil fuels, contributes to climate change, resulting in direct and indirect health impacts. While the attribution of these impacts on human health is challenging, researchers utilize more sophisticated scientific methods and long-term datasets, which are able to quantify and attribute in a better and more accurate way, specific health burdens to climate (Ebi, Ogden, Semenza, & Woodward, 2017; WHO, 2014). The Intergovernmental Panel on Climate Change (IPCC) classifies the health impacts of climate change into three categories: direct impacts, ecosystem-mediated (indirect) impacts, and human institution-mediated impacts (see Table 1) (Smith et al., 2015).

Table 1: An overview of health impacts of climate change

Classification	Potential Impacts - Increased morbidity and mortality from :
Direct	Increased exposure to extreme weather conditions; Hurricanes, storms, floods; heatwaves, UV radiation.
Ecosystem-mediated	Increased exposure to vector-borne and other infectious diseases; food and water borne infections; air pollution and lung diseases.
Human institution-mediated	Poor nutrition; occupational health; mental health; violence and conflict.

Projections of bad air quality, as a result of climate change, point out increasing premature deaths, due to ozone and especially Particulate Matter in coming years (Silva et al., 2017). As a consequence to these events, there are estimations for substantial external economic costs, attributable to climate change and air pollution, which point out that global annual Gross Domestic Product (GDP) could be impacted by up to 3.3% by 2060, while labor productivity constitutes one area that will be most significantly impacted. Additional analysis by the Organization for Economic Cooperation and Development (OECD) estimates, that, the economic consequences of outdoor air pollution will result in health care costs of US$176 billion and 3.7 billion lost working days annually by 2060 (OECD, 2016b; Workman, Blashki, Bowen, Karoly, & Wiseman, 2018).

Realizing the size of current and projected health impacts, researchers highlight the potential health co-benefits that result from ambitious mitigation efforts. The term "co-benefits" refers to multiple benefits in different fields resulting from specific actions, strategies or policies. Co-beneficial approaches to climate change mitigation, are those that also promote positive outcomes in other areas, such as concerns relating to: the environment (e.g. air quality management, health, agriculture, forestry, and biodiversity), energy (e.g. renewable energy, alternative fuels, and energy efficiency) and economics (e.g. long-term economic sustainability, industrial competitiveness, income distribution).

To determine the potential health co-benefits from domestic and global action, new more complex modeling techniques have been created and utilized by researchers and organizations. The findings are consistent; despite the heterogeneity of study methods, prospective health co-benefits studies consistently conclude, that the implementation of ambitious mitigation measures, can reap significant health benefits for local populations, and partially, if not completely, offset resulting implementation costs. A strong effect of health co-benefits, is their immediacy and specifically, health benefits associated with reduced air pollution, can materialize promptly after mitigation measures are implemented (see Table 2) (Remais et al., 2014; Workman et al., 2018).

Table 2: Examples of potential health co-benefits from mitigation activities relating to the energy and transport sectors, including the anticipated time lag for the realization of health co-benefits

Mitigation activity	Potential health co-benefits	Anticipated time lags
Reductions in fossil fuel use Improvements in fuel economy; incentivize electric vehicle use; tighten vehicle emission standards	Reductions in sudden cardiac death risk; acute respiratory infections; chronic obstructive pulmonary disease exacerbations	Days to weeks; weeks and months; weeks and months
Increases in accessibility to active modes of transport, including walking and cycling	Reductions in type 2 diabetes; depression; breast and colon cancer incidence	Years for all potential health co-benefits identified

EU has a defined policy development process for climate change and supporting governance structures in place, to develop evidence-based integrated policies, with opportunities for input from diverse stakeholders. Specifically, impact assessments developed for climate change mitigation policies, are explicit in their consideration of health and other impacts, and are a good example of procedures and tools that can support the incorporation of multiple considerations, into the development of a cross-sectoral policy issue.

Despite a robust policy development process, health co-benefits ultimately play a limited role in the development of climate change mitigation policies. In spite of the EU's commitment to the equal consideration of economic, social and environmental impacts, the realpolitik, considers economic costs and energy supply security issues, as particularly influential in final climate change mitigation policies. In reality, the Commission's role in this issue requires balancing the provision of cost-effective and evidence-based policy options, with politically palatable policy choices for the Member States with their own national interests and diverse stakeholder groups to assuage (A. Workman, G. Blashki, K. Bowen, D. Karoly, 2018).

1.7 Case for equity between Paris Climate agreement's co-benefits and adaptation

Whilst significant co-benefits have been associated with energy and transportation, adaptation offers ancillary benefits for emission reduction through land and forest conservation, which merit to be described as co-benefits, because they are enhanced with biodiversity management, nutrient recycling and water purification as part of the indicators.

Although adaptation policy goals do not always have measurable indicators compared to mitigation, its impacts extend beyond human development issues (e.g. land area loss, people displacement, ecosystem loss or change, economic value loss, infrastructure loss, cultural heritage loss, etc.) when viewed from the UN Sustainable Development Goals (SDGs) perspective as outlined in the Article 8 of the Paris Climate Agreement (Dovie, 2019). Mitigation co-benefits clearly aligns to:

(i) SDG 7 on affordable and clean energy,
(ii) SDG 9 on industry, innovation and infrastructure,
(iii) SGD 12 on responsible consumption and production, and
(iv) SDG 13, yet intersect with adaptation on the climate action

The SDGs are a call for action by all countries (poor, rich or with middle-income) to promote prosperity while protecting the planet. They recognize that ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs including education, health, social protection, and job opportunities, while tackling climate change and environmental protection.

Emphasizing mitigation (e.g. renewable energy, energy efficiency, sustainable transportation, cleaner fuels) should not diminish adaptation but rather enhance it (e.g. forest protection, land use changes, Infrastructure and green building design) which is comparable to co-benefits (e.g. green infrastructure, distributed energy, water and energy conservation, low-input agriculture) (Dovie, 2019).

We can discern, that there is need for new forms of multi-level governance of the climate policy schemes, including financing mechanisms and response measures, for enhanced adaptation to effectively protect the integrity of emission reduction, hence the Nationally Determined Contributions, that Paris Agreement requests from each country to clarify and communicate their post-2020 climate actions. Nowadays, we can utilize further expansions and compilations of potential co-benefits and we are able to suggest the categorization as depicted in Table 3 (Mayrhofer & Gupta, 2016).

Table 3: Co-benefits categorization of climate change policy.

Category	Co-benefit
Climate-related	▪ Reduce GHG emissions ▪ Enhance resilience to climate change
Economic	▪ Enhance energy security ▪ Trigger private investment ▪ Improve economic performance ▪ Generate employment ▪ Stimulate technological change ▪ Contribute to fiscal sustainability
Environmental	▪ Protect environmental resources ▪ Protect biodiversity ▪ Support ecosystem services ▪ Improve soil quality ▪ Reduce air pollution
Social	▪ Enhance energy access ▪ Reduce poverty incidence and inequality ▪ Contribute to food and water security ▪ Improve health

	▪ Reduce stressors
Political & institutional	▪ Contribute to political stability ▪ Improve democratic quality of governance ▪ Contribute to interregional collaboration

In order to have sufficiently positive impacts, climate policies need to look beyond climate impacts. There are significant negative impacts and limited time available, to address the alarming pace of observed global warming. The social and economic co-benefits of climate change mitigation, offer an important opportunity to mobilize a strategic and interest-oriented approach, to support effective and timely climate actions. Interest-oriented co-benefits of climate change mitigation, represent positive net effects of policies and actions, beyond those directly related to climate change and global warming processes (such as greenhouse gas emission reduction) that pertain to the following five key attributes (Table 4) (Mayrhofer & Gupta, 2016).

Table 4: Key attributes of co-benefits of climate change mitigation.

Interest oriented	Benefit can be defined in view of specific interests/interest groups
Identifiable	Benefit can be distinctly described, delimited from other factors, measured, and evaluated
Timely	Benefit unfolds in a timeframe crucial for the addressed interest group (usually less than 10 years)
Attributable	Benefit can be connected to a specific intervention and allocated to a specific interest group and reconstructed by members of this group
Opportunity oriented	Benefit can be defined through a resulting opportunity or profit, and not merely through avoided burdens, risks, or losses

1.8 Guidelines for mobilizing the interest-oriented co-benefits of climate change mitigation

The global transformation toward green technologies, renewable resource energy or cleaner fuels, seems to be irreversible in the long term, given its many advantages and additionally competitive outlook. In contrast, current investments in heavy fossil fuel-based energy scheme are still present and consists a serious threat for the climate of our planet. For this reason, IMO decided to apply a new regulation for the maritime sector to control and set, lower sulphur limit content of marine fuels.

The interest-oriented co-benefits of climate change mitigation act as important players towards enhanced transformation and additionally promote long-lasting political deadlocks, in order to prevent environmentally harmful path dependencies. We can mobilize these co-benefits, by expanding the view of traditional climate policy evaluation by specifically addressing the net effects of climate policy measures and actions. Also, explicit strategic use of the multiple-benefits approach to climate policy must be promoted.

While at present there is no standard practice for climate change attribution for health outcomes, from the literature, our empirical study, and various case studies, we can conclude that a proportion of the current burden of climate-sensitive health outcomes can be attributed to climate change. Extreme weather effects, undoubtedly increasing the probability to observe more deaths, during heatwaves or floods, which are attributable to climate change and estimate the exact proportion using different approaches.

A conservative and defensible approach would be by attributing deaths above a threshold, related to the degree to which climate change increased ambient temperature over recent decades. Also, sensitivity analyses and assumptions of the linearity between mortality and temperature, could be used to provide an uncertainty range around the estimated impact (Ebi et al., 2017).

As climate change unfolds, climate sensitive health outcomes will continue to emerge. We must urgently gain a better understanding of the distribution of climate change burden on human health, by achieving more knowledge about the factors that contribute and affect our health, due to climate. Greater knowledge sharing between different science sectors, reliable long-run datasets, refinement of analytic techniques for detection and attribution, will all be important and help policy makers to adjust climate change policy and achieve multiple targeted benefits.

1.9 An overview of wider impacts

The realization of the potential multiple impacts of climate change to our planet and our civilization, will lead to a strong engagement, towards mitigation and adaptation actions. Possible behavioral changes, including sensitivity to environment, decreased air pollution, recycling, employment of renewable resources and sustainable agriculture practices, are some of the actions that can be developed. An overview of the wider key impacts associated with these actions is provided below:

- Significant health benefits through decreased air pollution, has associated multiple economic benefits, by reduction in health care costs and increase of the size of the workforce, as more working-age people are in good health.
- Reduced air pollution and reduced noise as a consequence of alternatively fueled vehicles (ships, trucks, buses, cars) provide health and wellbeing benefits. However, one of the most significant potential wider benefits, comes from a reduced demand for fossil fuels thus increasing energy security.
- Energy efficiency improvements in constructions (vehicles, ships, buildings) provide reduced exposure to cold or hot living environments and increased income, due to lower energy bills. Energy efficiency can provide significant health and wellbeing, energy security by reduced fuel dependence and affordable living benefits.
- Measures towards sustainable agriculture and environmentally friendly farming practices, protect the environment and natural resources. Reduced nitrogen runoff or less fertilizers or pesticides use is a key outcome and has benefits for water quality, biodiversity and human health.
- Education and behavior change are closely linked and should complement any technical measures.

However, there are barriers that prevent the implementation of these actions or minimize the wider benefits that can be gained. Some actions are needed to overcome these barriers:

- Clear messages that translate targets into local actions, accompanied by comprehensive and consistent performance monitoring across policies and sectors. By effective communication across various levels of government and relevant stakeholders the most effective policies can be applied and people engagement can be increased.
- Lack of "political appetite and willingness" may occur due to restricted time (i.e. four-year) governmental changes. Thus the precariousness of political actions, combined with the potential costs (economic and/or social) of climate change policies, can lead to a lack of long-term thinking and probably inaction. This barrier can be overcome through reliable political will, awareness raising among the public and global funding for implementation of climate change actions.
- Climate change is a complex global issue, which is hard to understand by individuals who don't actually comprehend the impact that they can exhibit and are reluctant to change their beliefs which are rooted in experiences, knowledge and tradition. This barrier can be overcome by educating communities, about all the benefits they spring up from climate change policies. For some, the health of their children or the quality of life is a priority, whilst for others this may be house prices or noise reduction.
- Recognition of the barriers and specific conditions for each geographic area, as these affect the magnitude of wider impacts that can be experienced, will contribute to maximized efficiency. To overcome these barriers, targeted actions are required, climate change policy and action needs to be embedded into wider governmental strategies, as a way of bringing together community, environmental and economic goals.

CHAPTER 2: THE EU MRV REGULATION

2.1 Introduction

The EU MRV regulation 2015/757 for maritime transport applies to ships above 5,000 gross tonnage (G.T.) and refers to CO_2 emissions released during their voyages, excluding warships, naval auxiliaries, fish-catching or fish-processing ships and government ships used for non-commercial purposes. EU MRV applies for all ships, regardless of their flag, for voyages:

- intra-EU
- from the last non-EU port to the first EU port of call (incoming voyages)
- from an EU port to the next non-EU port of call (outgoing voyages)

Ship operators must follow specific monitoring plans, to monitor data on per-voyage and annual basis. The monitoring plan, emission reports and the issuance documents of compliance, will be accredited by third party verifiers. It's mandatory that verifiers shall be independent of the company or operator of the ship concerned and be accredited by a national accreditation body, according to European Commission (EC) regulation No.765/2008 (European Commission, 2012).

2.2 Monitoring

The actual monitoring of the maritime emissions started in January 2018. Ship owners and operators, will not get confirmation of compliance, until the first annual report has been satisfactorily verified by their chosen verifier, by the end of April 2019. Based on the monitoring plan, for each ship arriving in, or departing from, and for each voyage to or from a port under a Member State's jurisdiction, companies shall monitor the following parameters (European Commission, 2012):

- port of departure including the date/hour of departure
- port of arrival including the date/hour of arrival
- for each type of fuel, the amount consumed in total
- emission factor and quantity of CO_2 emitted
- distance travelled and time spent at sea
- cargo carried, transport work.

Reporting on a per-voyage basis is not needed, if both of the below criteria apply during the reporting period:

1) all of the ship's voyages, either start from or end at a port of EU region and
2) according to its schedule, the ship performs more than 300 voyages.

In this case, a summarized yearly reporting per-ship is needed. Based on the monitoring plan, for each ship and for each calendar year, companies shall monitor the following parameters:

- amount and emission factor for each type of fuel consumed in total
- total aggregated CO_2 emitted:
    a. within the scope of the Regulation
    b. from all voyages between ports under a Member State's jurisdiction
    c. from all voyages which departed from ports or arrived at a port under a Member State's jurisdiction
    d. which occurred within ports under a Member State's jurisdiction at berth

- total distance travelled, total time spent at sea
- total transport work
- average energy efficiency.

To calculate CO_2 emissions, the following formula is typically applied:

$$CO_2 \text{ emissions} = \text{Fuel consumption} \times CO_2 \text{ emission factor}$$

The fuel consumption includes fuel consumed by main engines, auxiliary engines, gas turbines, boilers and inert gas generators. Ships are using different types of engines, which are burning different types of fossil fuels. Fuel consumption at berth, shall be calculated for each voyage, using one or a combination of the following methods:

(i) Bunker Fuel Delivery Note (BDN) and periodic stocktaking of fuel tanks
(ii) Bunker fuel tank monitoring on board
(iii) Flow meters for applicable combustion processes, or
(iv) Direct CO_2 emissions measurements.

The company must define in the monitoring plan, which of the above mentioned methods will be used, to calculate fuel consumption for each ship under its responsibility and ensure that once the method has been chosen, it is consistently applied.

For emission factors, default values are used unless the operator decides to use data from the Bunker Fuel Delivery Note (BDN). The BDN is part of the existing legislative requirements for ships, to monitor the total amount of fuel bunkered and used for demonstrating compliance with applicable regulations of sulphur emissions. A BDN contains information of the total quantity of fuel bunkered in metric tons and density at 15°C, as well as sulphur content. The default values for emission factors, are based on the latest available values from Annex VI of the Intergovernmental Panel for Climate Change report (European Commission, 2003).

2.3 Reporting

From 2019, by 30 April of each year, companies will have to submit to the EC and to the relevant authorities, an emissions report regarding CO_2 emissions and other relevant information for the entire reporting period, for each ship under their responsibility, which has been accordingly verified. Maritime companies must include in their emissions report the following information:

(a) data identifying the ship and the company, including:
  (i) name of the ship, IMO identification number, port of registry or home port, ice class of the ship, if included in the monitoring plan,
  (ii) technical efficiency of the ship: Energy Efficiency Design Index (EEDI) or the Estimated Index Value (EIV) in accordance with IMO Resolution MEPC.215 (63),
  (iii) name, address and principal place of business of the ship-owner or the managing company, telephone and e-mail details of a contact person
(b) the identity of the verifier that assessed the emissions report
(c) information on the monitoring method used and the related level of uncertainty

(d) annual monitoring of the parameters in accordance with the Regulation.

2.4 Verification and accreditation

In the case that the verifier's assessment identifies non-conformities with the requirements of the regulation, the company revises its monitoring plan accordingly and submits the revised plan, for a final assessment by the verifier, before the reporting period starts. In particular, the verifier assesses whether the CO_2 emissions and other relevant information included in the emissions report, have been determined in accordance with the regulation and the monitoring plan. When the verification assessment concludes with reasonable assurance from the verifier that the emissions report is free from misstatements, the verifier issues a verification report, stating that the emissions report has been verified as satisfactory. The verification report specifies all issues relevant to the work carried out by the verifier.

In the case that verification assessment concludes that the emissions report includes misstatements or non-conformities with the requirements of the regulation, the verifier informs the company thereof in a timely manner. The company then corrects the misstatements or non-conformities, so as to enable the verification process to be completed in time and submits to the verifier the revised emissions report and any other necessary information, to correct the non-conformities identified. The verifier states whether the initial misstatements or non-conformities have been corrected by the company. If the misstatements or non-conformities, are not corrected and, individually or combined, lead to material misstatements, the verifier issues a verification report stating that the emissions report does not comply with the regulation (European Commission, 2012).

2.5 Publication of information and report

By 30 June each year, European Commission will make publicly available the information on CO_2 emissions reported. 2019 is the first year that Commission initiated this process and the following information are publicly available:

(a) identity of the ship (name, IMO identification number and port of registry or home port)
(b) technical efficiency of the ship (EEDI or EIV, where applicable)
(c) annual CO_2 emissions
(d) annual total fuel consumption for voyages
(e) annual average fuel consumption and CO_2 emissions per distance travelled of voyages
(f) annual average fuel consumption and CO_2 emissions per distance travelled and cargo carried on voyages
(g) annual total time spent at sea in voyages
(h) method applied for monitoring
(i) date of issue and the expiry date of the document of compliance
(j) identity of the verifier that assessed the emissions report
(k) any other information monitored and reported on a voluntary basis.

The Commission publish an annual report on CO_2 emissions and other relevant information from maritime transport, including aggregated results, aiming at informing the public and allowing for an assessment of CO_2 emissions and energy efficiency of maritime transport, per size, type of ships, activity, etc (Dnv.com, 2022).

2.6 EU MRV against IMO DCS

Whilst the EU scheme has focused on CO_2 emissions from shipping in the EU area, the IMO scheme covers emissions from shipping globally. It should be noted that it is not yet decided, if, how and when, the two schemes will converge. Both schemes have overall as objective to mitigate climate change. The outcome of both schemes will be annual reports stating CO_2 emissions per vessel (EU MRV) or aggregated fuel consumption (IMO DCS). The logical consequence would be that considering the experience from EU MRV and IMO DCS schemes, IMO and EU, will further decide on setting targets with respect to GHG emission levels from international shipping. Table 5, depicts an overview of the requirements from the two schemes, in terms of scope and reporting.

Table 5: Comparison of EU MRV and IMO DCS (IMO MEPC-72, 2018)

	EU MRV	IMO DCS
Applicability:		
	Ships > 5,000 GT calling any EU ports.	Ships ≥ 5000 GT trading globally.
First reporting period:		
	▪ 2018 (01/01 – 31/12) ▪ Reporting to verifier by end of Jan 2019	▪ 2019 (1 Jan - 31 Dec) ▪ Reporting to verifier by end of March 2020
Monitoring plan:		
	▪ Separate document describing the methodology for data collection and reporting. ▪ Pre-defined format published by the European Commission (EC). ▪ Subject to verification by an independent and accredited verifier. ▪ The deadline for submission of monitoring plan was 31 Aug 2017.	▪ Data collection and reporting methodology shall be described as Part II in an integrated part of the Ship Energy Efficiency Management Plan (SEEMP). ▪ Conformation of compliance by Flag/Recognized Organization (RO). ▪ Deadline for submission of SEEMP Part II was 31 Dec 2018.
Reporting details:		
	▪ Amount and emission factor for each type of fuel consumed in total ▪ Total CO2 emitted and additionally differentiated to aggregated CO2 emitted (trips to and from EU ports, trips between EU ports, at berth) ▪ Total transport work (time at sea and in port, cargo carried)	▪ Period of calendar year for which the data is submitted ▪ Distance travelled ▪ Amount of each type of fuel consumed in total ▪ Hours underway under own propulsion

	▪ Average energy efficiency	▪ DWT to be used as cargo proxy
Reporting to:		
	European Commission: ▪ Company reports annual emissions to the EMSA data base ("Thetis MRV"). ▪ Annual report to be verified by an accredited verifier	Flag state: ▪ Annual emission report to be verified by Flag Admin. ▪ Flag State or RO reports to IMO data base
Disclosure:		
	EC will make data publicly available	Individual ship data will be kept confidential

In November 2017, EU decided that international shipping will not be incorporated into the EU Emissions Trading System (ETS) as part of the wider overhaul it is undertaking due to the existing ETS for CO_2 emissions. This decision was a result of intensive negotiations, between EU Member States, the European Parliament, the European Commission and shipping stakeholders.

In conjunction with the European Community Ship-owners Associations (ECSA), International Chamber of Shipping (ICS) has consistently argued that the application of a regional EU ETS to all ships calling at EU ports regardless of flag would have been completely inappropriate and would have led to serious market distortion. Many ships would have simply diverted to non-EU ports (including potentially a post-Brexit United Kingdom) in order to minimize cost exposure to the EU system. Additionally, as happened several years ago when the EU tried unsuccessfully to impose ETS on international aviation, the unilateral application to shipping could generate trade disputes with China and other Asian nations.

This EU decision does not remove the pressure from IMO. Notwithstanding the industry's doubts about the real CO_2 reductions that can be delivered via Market Based Measures (MBM), the only appropriate forum to have this debate, is IMO. The terms of the EU political agreement, are that continued exclusion from some form of regional MBM, may be dependent on IMO adopting some kind of alternative measure by 2023, which is understood to mean, that the EU believes there should indeed be a global MBM.

Moreover, the EC will be required to make an annual report to the European Parliament and EU Member States, on progress being made by IMO. In effect, this could mean that if at any time, the EC deems progress insufficient, it may seek to justify the need, to continue working on unilateral measures. Nevertheless, the EU decision in 2017 seems to represent a recognition, that IMO is the best forum in which to have the debate about the appropriateness or otherwise of applying an MBM to shipping.

In November 2017, ICS and ECSA submitted detailed comments to an EC consultation, on the possible alignment of its MRV Regulation with the global CO_2 Data Collection System (IMO DCS) which is up and running through 2019. The EU had previously underlined its willingness to consider this alignment, in order to help persuade non-EU governments to agree to the establishment of the IMO DCS.

The IMO DCS adopted in 2016 and was viewed as an acceptable compromise between IMO Member States, which are interested to collect reliable information about fuel consumption (and calculate CO_2

emissions) in order to adjust future IMO work and those Member States that wish to collect some more detailed information about transport work and fuel efficiency of ships. The necessary support for this IMO compromise, was given with the understanding that the DCS should be simple for the ships and primarily be based on fuel consumption and most importantly, data relating to fuel consumption under the IMO system, will remain anonymous. The purpose of the IMO DCS, is to inform future policy making, rather than to penalize or reward individual ships or ship owners.

The EU MRV Regulation was adopted in 2015 and in addition to the submission of data by ships on fuel consumption some international shipping stakeholders believe that includes controversial provisions for the transport work, using different metrics to those currently agreed by IMO. Moreover, the verification and certification method that has been developed by the EU seems to be complex. The greatest concern about the EU MRV regulation is that the EC will annually publish commercially sensitive information, along with ship name and company identifiers. This is with the intention of facilitating comparison of the supposed operational efficiency of individual ships. In general, the EU regulation contains many of the elements, which most IMO Member States chose to reject when adopting the global IMO DCS. From this fact, we can clearly understand the major competition concerns and possible reactions, of ship-owners, in view of the publically publication of emission report.

CHAPTER 3: METHODOLOGIES FOR THE CALCULATION OF AIR EMISSIONS IN SHIPPING

3.1 Introduction

Maritime passenger vessels are categorized in two main categories: ferries and cruise ships. Cruise vessels have annually scheduled routes depending on country, region or touristic importance and as we can understand can vary highly between years, while ferries routes are characterized according to fixed time schedules. The major part of maritime transportation passengers (excluding cruise) in the European Union (EU) is carried out between ports located in the same country (74 % in 2020), pointing by this way the significant role of national ferry sector (Eurostat, 2021). Generally, each continent with populated or touristic islands has frequent ferry connection between islands and large volume of freight and passengers. Due to Eurostat, this applies to Italy and Greece which classifies them as the two leading maritime transportation passenger countries and some other Mediterranean countries follow, like Spain, Portugal Croatia and Malta.

ESPO's latest environmental report (ESPO, 2021) shows that ports constantly focus on green environmental priorities. Since 2013, air quality has been the top environmental priority for ports, whereas climate change is the second priority for the last two years. Additionally energy efficiency is ranked as third priority. Air pollution in port areas is caused mainly from ships during navigating in the port, maneuvering and at berth. Related land traffic within the port area and industrial port activities that can be often found are also burden air quality. Air quality is not only a ranking of ESPO or an environmental concern but it's very important to safeguard and protect the health of the citizens, working people around the port and visitors, since the majority of European ports are located near densely populated city areas.

Typical example is Piraeus port which 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, 2022). 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).

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. 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).

The fuel and energy consumption of ships during their stay in ports are quite significant, while the creation of accurate ships emissions inventories is a case specific, rigorous and time-consuming process that entails precise application of a selected methodology and detailed screening of several technical parameters and processes. Typically, these studies are based on empirical or, in the best cases, operational data from ships or shipping companies and the accuracy of the presented results is in many cases quite ambiguous. A recent study presented a comparative analysis of reports and academic papers published in EU and USA regarding the calculation of ship emissions (Moreno-Gutiérrez et al., 2019). The fuel consumption was evaluated based on factors derived from four different methodologies and finally the use of STEAM (Ship Traffic Emission Assessment Model) was recommended (Jalkanen et al., 2012). Authors use a parabolic second degree polynomial to estimate Specific Fuel Oil Consumption (SFOC) and point out that there are two factors that play a significant role for the best possible accuracy for the quantification of fuel/energy consumption and air emissions in shipping: the engine's SFOC and the load factor of Main (ME) and Auxiliary Engines (AE). Thus, since many papers presenting inventories of ships' air emissions do not contain details on the performed calculations and the identification of SFOC values at specific engine loads (we assume that the parabolic relationship between SFOC and engine load is not actually taken into account), there are several misconceptions that need further clarification regarding the completeness and accuracy of ships air emissions calculations. Typically emissions inventories are created based on emission factors which due to lack of technical data, are largely based on the professional or empirical assessments of the researchers. These factors estimate air emissions in conjunction with energy or fuel consumption and vary depending on the pollutant, engine type, type of fuel and operating phase. Thus technical proposals that will allow for more precise SFOC estimations are necessary for accurate bottom-up approaches.

One of the scopes of current study is to focus on the main technical discrepancies (i.e. engine load, SFOC, emissions factors) of the existing methodological approaches for calculating ships' on-board emissions and propose a framework that will allow various stakeholders to conduct accurate air emissions calculations based on ships' operational data. The calculation of fuel/energy consumption and air emissions (CO_2, SO_X, NO_X, $PM_{2.5}$, PM_{10}) will be presented, for a 5 year period (2017-2021) in the two major ports of Crete island in Greece (i.e. Souda and Heraklion), for both cruise vessels and passenger ferries. A detailed technical inventory has been created containing all technical details for 10 passenger ferries (owned by three different shipping companies) operating every day following various itineraries all year around and 88 different cruise vessels (which approached both ports mainly during the summer period). 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.

Regarding the studied ports, Heraklion (with population of 151,324 people) is the largest city and the administrative capital of Crete and the fifth largest city in Greece, while Souda is the commercial port of Chania city (the second largest in Crete with population of 80,224 people). Both ports are arrival points for ferries to/from mainland Greece via Piraeus port and constitute significant Mediterranean destinations for cruise vessels.

3.2 Methodologies for the estimation of air emissions due to shipping

Depending on the availability of data and technical parameters there are various studies regarding the existing methodologies for estimating ship’s air emissions with many different case studies (Doundoulakis & Papaefthimiou, 2021; Maragkogianni, 2017; Maragkogianni & Papaefthimiou, 2015; Moreno-Gutiérrez et al., 2015, 2019; Papaefthimiou, Sitzimis, & Andriosopoulos, 2017; Perdiguero & Sanz, 2020; Trozzi & Lauretis, 2019). The criteria for the selection of the appropriate methodology vary depending mostly on the availability of relevant data and technical parameters. A top-down approach is based on fuel consumption reports and is typically used when there isn’t available information about the ship's detailed activity and/or status on various operational phases. On the other hand, a bottom-up approach 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.
Regarding air emissions calculation, the Environmental European Agency’s 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 candidates (called Tiers). Tier 1 and 2 use fuel sales reports 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. Tier 3 methodology can be more accurate and is recommended when technical parameters (e.g. engine power and technology, total power installed, fuel type) and detailed data regarding individual ships movements are available. The total emissions (E_{Trip}) for a trip are calculated as the sum of emissions for the different operational phases, i.e. hoteling (or at berth), maneuvering and cruising), as follows (Trozzi & Lauretis, 2019):

$$E_{Trip} = E_{Hoteling} + E_{Maneuvering} + E_{Cruising} \quad (1)$$

For the estimation of air emissions, the energy and/or fuel consumption of the studied ships needs to be calculated in conjunction with specific emission factors depending on the air pollutant, engine, duty cycle and type of fuel. If SFOC is available, it doesn’t matter if emissions factors are energy-based (g pollutant/kWh) since it’s possible to convert energy-based emissions factors to fuel-based emissions factors (g pollutant/g fuel consumed) by dividing them by SFOC (Third IMO GHG Study, 2014). An engine's fuel consumption is calculated by combining two terms: the energy demand (in kWh) and the SFOC (in units of fuel mass per unit of energy). The energy depends on the maximum continuous rated power (MCR) of the engine (in kW), the load factor of the selected operational phase (hoteling, maneuvering and cruising) and the duration of operation. The total air emissions for a trip (E_{Trip}) are estimated through the following equation:

$$E_{Trip,e,i} = \sum_{p} \left(MCR_e \cdot LF_e \cdot T_p \cdot SFOC_e \cdot EF_i \right) \quad (2)$$

where: e = the specific engine for which the calculations are made, i = type of air emission (CO_2, NO_x, SO_X, PM_{10}), MCR = maximum continuous rated power (kW), LF = engine Load Factor, T = duration of the operational phase p (h), SFOC = Specific Fuel Oil Consumption of engine (g/kWh), EF = emission factor (g pollutant/g fuel).

In this study 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.

3.2.1 Determination of engine Load Factor

The determination of the load factor for vessels ME and AE engines, during their activities in ports involves serious uncertainties. Research efforts (De Meyer, Maes, & Volckaert, 2008) propose load factors for cruise and passenger ship engines during maneuvering and anchorage, which are significantly higher compared to other values prepared by ENTEC on behalf of the UK Government (ENTEC, 2002). In previous studies authors have acknowledged the significant effect of local climate conditions on auxiliary power demand and tried to use more realistic engine load factors especially for cruise vessels approaching Greek ports (Maragkogianni, 2017; Maragkogianni & Papaefthimiou, 2015; Papaefthimiou, Maragkogianni, & Andriosopoulos, 2016; Tzannatos, 2010). It was found that passenger ferries and cruise vessels demand high power from auxiliary engines to operate and provide electricity for hoteling services, as well as support for other ship's operational systems. Also due to variation in weather conditions between seasons there is different demand of power for summer (where temperatures are higher and the capacity of passengers is increased) and the rest year. For the calculations thereafter the engine load factors for the mooring and maneuvering phases in port are depicted in Table 6 (Doundoulakis & Papaefthimiou, 2021; Maragkogianni & Papaefthimiou, 2015; Tzannatos, 2010).

Table 6: Load factors for ME and AE engines.

	Cruise ships				Passenger ships			
	Summer*		Rest of the year		Summer*		Rest of the year	
	ME	AE	ME	AE	ME	AE	ME	AE
Maneuvering	0.20	0.75	0.20	0.60	0.20	0.75	0.20	0.60
At berth	0	0.60	0	0.40	0	0.45**	0	0.30***

* In Mediterranean region June, July and August is characterized as summer period

****** 0.70 for 50% and 0.20 for the rest 50% of the duration while at berth phase

******* 0.40 for 50% and 0.20 for the rest 50% of the duration while at berth phase

For normal cruising speed, the load factor of the propulsion system for the main engines is typically between 0.8-0.85, depicting the most efficient operation range for the engine. For lower speed (e.g. navigating in the port) the determination of the load factor for the propulsion system is based on the theoretical fact that the propulsion engine’s load is equal to (Styhre, Winnes, Black, Lee, & Le-Griffin, 2017):

$$LF = (\text{Actual speed} / \text{Max speed})^3 \quad (3)$$

The load factor for the auxiliary engines varies, depends on the operational phase (Table 6) and the type of engines. The exact values of load factors for both main and auxiliary engines introduce uncertainty in the creation of emissions inventories, mainly due to different auxiliary engines size and model (i.e. kW, SFOC).

3.2.2 Determination of Emission Factors

Due to the fact that typically main and auxiliary engines operate under partial load, correction factors for the emission factors are introduced. An extensive work regarding these issues has been conducted elsewhere (ENTEC, 2002). Based on this report, the emission factors for the main engines when the ship is in normal cruise mode (operating at about 0.8 - 0.85 MCR) were obtained by measuring and averaging all emissions in 0.7 - 1 MCR engine load range, while for auxiliary engines were obtained in 0.4 – 0.8 MCR engine load range. In addition, the average emission factors for the main engines when operating at low loads (<0.4 MCR) were evaluated based on the IVL/Lloyds database and the methodology approach is based on adaptation of the ME emission factors during the normal cruising phase (as we described earlier, derived from constant state engine loads with MCR 0.7 - 1) by multiplying them with 0.8 for NO_X, 3 for HC and 3 for PM_{10}. At these low engine's loads, SFOC (and thereby air emissions i.e. SO_X and CO_2 emissions) has been assumed to increase by 10%. It is clear that this approach introduces significant uncertainty and needs further investigation by future studies and research. It is thus evident that emission factors are dependent on the engines' load and its variability, but furthermore on the sulfur content and the type of fuel consumed by each engine. It is worth noting that the emission factors during maneuvering and/or at berth, involves increased uncertainty compared to the corresponding values during the normal cruising phase mainly for two reasons:

1. Typically main engines start when they are cold and this causes significantly different emissions in quantity and quality (especially for HC and PM_{10}) compared to operating the engines when they are not cold.
2. The engine load is not constant during maneuvering thus increasing emissions variability.

All these parameters should be taken into account for the accurate estimation of the emission factors. Occasionally correction factors (FCF) are used to adjust emission factors for used fuel type (as fuel composition changes from year to year):

$$EF_{actual}\left(g_{pollutant}/g_{fuel}\right) = EF_{baseline}\left(g_{pollutant}/g_{fuel}\right) \cdot FCF \quad (4)$$

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; Third IMO GHG Study, 2014):

$$CO_2\left(g/_{kWh}\right) = (3.114 \text{ or } 3.206) \cdot SFOC\left(g_{fuel}/_{kWh}\right) \quad (5)$$

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

$$NO_x\left(g/_{kWh}\right) = 45 \cdot n^{-0.20} \quad \text{(6a) IMO Tier I}$$

$$NO_x\left(g/_{kWh}\right) = 44 \cdot n^{-0.23} \quad \text{(6b) IMO Tier II}$$

$$NO_x\left(g/_{kWh}\right) = 9 \cdot n^{-0.20} \quad \text{(6c) IMO Tier III}$$

with n being the engine revolution speed.

$$SO_x\ (g/_{kWh}) = SFOC\ (g_{fuel}/_{kWh}) \cdot 2 \cdot 0.97753 \cdot (\%\ Fuel\ Sulfur) \tag{7}$$

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.

$$PM_{10,HFO}\ (g/_{kWh}) = 1.35 + SFOC\ (g_{fuel}/_{kWh}) \cdot 7 \cdot 0.02247 \cdot (\%\ Fuel\ Sulfur - 0.0246) \tag{8a}$$

$$PM_{10,MGO}\ (g/_{kWh}) = 0.23 + SFOC\ (g_{fuel}/_{kWh}) \cdot 7 \cdot 0.02247 \cdot (\%\ Fuel\ Sulfur - 0.0024) \tag{8b}$$

It is well understood from the above equations that:

i. CO_2 emissions depend exclusively on the fuel type, as depicted by equation (5),
ii. NO_x emissions depend exclusively on engine rev. speed (n), as depicted by equations (6a), (6b) and (6c),
iii. SO_x and PM_{10} emissions depend solely on the fuel type and particularly on its sulphur content, as depicted by equations (7), (8a) and (8b).

3.2.3 Determination of engine power

One of the most crucial factors for the accurate estimation of air emissions in a bottom-up methodology is the engine power. Typically for most ships the detailed power per engine is not known and only the IMO number, size of the vessel and gross tonnage (GT) are widely available. Due to the lack of relevant data in many cases engine power estimations are carried out based on average GT power. Thus, in literature there is a typical methodology to estimate the installed main engine power based on GT (Trozzi & Lauretis, 2019), with reference to 2010 passenger vessels world fleet ($Power_{ME} = 9.55078 \cdot GT^{0.7570}$) or 2006 Mediterranean Sea fleet ($Power_{ME} = 42.966 \cdot GT^{0.6035}$). The installed auxiliary engine power is estimated from an average ratio of Auxiliary Engines / Main Engines for passenger vessels: 0.16 and 0.27 for the world and Mediterranean Sea fleets, respectively (Trozzi & Lauretis, 2019).

In the case of ships employing diesel-electric engines, all the required power for the regular ship's operation (including propulsion) results from main engines (which operate to generate electricity while electric motors are used for propulsion). Diesel electric power generation scheme allows the most flexible and efficient utilization of the fuel and thus it is usually implemented in most of the large scale newly built vessels which have extensive power demand. For diesel-electric engines, various studies use the average ratio of 0.278 for Auxiliary Engines / Main Engines for passenger vessels to estimate the AE power (Moreno-Gutiérrez et al., 2015, 2019; Tzannatos, 2010).

For the current study the technical characteristics of all ships approaching the two ports under study, i.e. type or model of main and auxiliary engines, were available from the DNV GL database (vesselregister.dnvgl.com, 2022). Since now, DNV GL is the only major international accredited registrar and classification society that provides free public access to basic ships' data (IMO number, year of build, flag, vessel length, width, draught, propulsion system, engines model). For those vessels that data were not available through the DNV GL database, all necessary info were acquired from IHS Sea-Web (SeaWeb, 2022). The current study will focus on the calculation of air emissions (CO_2, SO_x, NO_x, PM_{10})

from the 10 passenger ferries and 88 different cruise vessels that operated in total in the studied ports for five years period (2017-2021). 7 passenger ferries and 34 cruise vessels used conventional propulsion, while 3 ferries and 54 cruisers had diesel-electric engines. The necessary technical details for the 98 vessels were retrieved, thus providing a detailed inventory for 41 different engine models mainly extracted from relevant technical datasheets and manufacturers' websites.

The average gross tonnage (GT) based on real data for the ships in the studied ports has been used as input for the estimation of ME and AE via both the abovementioned methodologies (i.e. $Power_{ME} = 9.55078 \cdot GT^{0.7570}$ or $Power_{ME} = 42.966 \cdot GT^{0.6035}$), and the calculated engine data are depicted on Table 7. These data refer only to vessels with conventional propulsion and separate ME–AE engines, since for diesel-electric vessels AE power must be estimated using a ratio of total power.

Table 7: Comparison between different engines power estimation approaches.

		Average technical characteristics of ships in studied ports								
Vessels		Based on real technical data			Based on $ME = 9.55078*GT^{0.7570}$			Based on $ME = 42.966*GT^{0.6035}$		
Type	Number	ME (kW)	AE (kW)	AE/ME ratio	ME (kW)	AE (kW)	AE/ME ratio	ME (kW)	AE (kW)	AE/ME ratio
Cruise ships	34	28,096	18,956	0.675	14,128 (-49.7%)	2,260 (-88.1%)	0.16	11,579 (-58.8%)	3,126 (-83.5%)	0.27
Passenger ferries	7	28,935	4,369	0.151	16,715 (-42.2%)	2,674 (-38.8%)	0.16	15,379 (-46.8%)	4,152 (-0.05%)	0.27

The comparison of the calculated engines' values clearly shows that using the two methodologies (based on average GT power), leads in all cases in underestimation of the engine power values and the observed differences between the real technical data are extremely high (reaching deviations of more than 58% and 88% for ME and AE respectively). Thus we can infer that the estimation of the main engine power as a function of GT (for both methodologies) is not a reliable approach.

3.2.4 Determination of SFOC values

Over the years, ship engines have evolved due to the application of modern electromechanical technologies. However, it is not possible to operate with maximum fuel economy across the full range of engine loads. For this reason, engines are adjusted according to their operational status (i.e. the type of routes and the typical engine load they employ) in order to optimize their performance within a specified load range, thus achieving fuel economy and less air emissions (for the specified operational thresholds). Usually the "optimal" range of engine load is at 0.75 - 0.85 of their nominal engine power and the operation outside this range leads to higher SFOC, fuel consumption per unit of power (gr / kWh). In relatively new engine technologies, the on board engineer can electronically adjust in advance the optimal range of engine load, but older engines require mechanical settings that demand actions from the engine manufacturer (e.g. valve timing, fuel injection mode, etc) (MAN Diesel &Turbo, 2019).

One important parameter for diesel engines is SFOC, which shows the amount of fuel needed for the production of 1 kWh of energy. This parameter varies over the lifetime of the engine, while increments in SFOC may occur between service intervals and they can be attributed to various factors: dirty intake air filters, partly blocked turbocharger and/or charged air coolers, dirty nozzle rings, worn injection pump elements and injection nozzles, etc. Additionally other factors can cause continuous variations in SFOC, for example differences in fuel quality (e.g. fuel water content, low fuel heat value, fuel sulphur content and fuel ash content). Typically, a regular periodic engine service according to manufacturer's instructions, can decrease, or in the best case, eliminate these increments (Lundh, Garcia-Gabin, Tervo, & Lindkvist, 2016; MAN Diesel &Turbo, 2019) and since maritime companies have a big concern about the reduction of fuel consumption, this is a major assumption that we made in our study (all engines follow a regular periodic service according to manufacturer's instructions). Moreover, large ships like cruise vessels or big passenger ferries have a set of engines with identical or in many cases with different power capacity and varying number of operating hours, thus in most cases the operator's selection on which engine(s) will operate may lead to optimal performance and fuel consumption.

The instantaneous fuel consumption of the engine is calculated by the product of instant SFOC value (gr/kWh) with the instant power of the engine (kW), thus resulting in a relatively linear relationship between fuel consumption and instantaneous engine power. It is well understood that not all engines have the same SFOC as they differ both in size (kW power), revolution speed, manufacture year and technology used. For a complete study for a ship, all engines (ME and AE) should be modeled separately to accurately calculate fuel consumption and finally air emissions. However, in practice this is not so simple, as the engine manufacturers do not publicize all required data.

The major engine manufacturers for each new engine model launched in the market, usually provide in public the technical specifications including the SFOC, but only at representative engine load levels (e.g. 0.5, 0.75, 0.85, 1), while in most cases SFOC values are given for only one or two engine load values. Thus in general SFOC data are not publically available from maritime companies. In our case, it is necessary to estimate the SFOC values in all needed engine loads and then proceed to calculate fuel consumption and total air emissions as described in paragraph 3.2.

Indicatively, Table 8 depicts SFOC values of three of the most commonly used engines both in passenger ferries and cruise vessels of our study, as provided from the manufacturers technical datasheet (Caterpillar Marine Power Systems, 2008; MAN, 2019; Wartsila 38 Project, 2008). In the case that SFOC values are known for at least more than three different engine load levels, we can employ a regression analysis via a second degree regression polynomial (via a typical statistical software package, i.e. Minitab, SPSS or even Excel) in order to determine the whole SFOC *vs* engine load curve. These polynomials have been used in the literature and have the form (Jalkanen et al., 2012; Lundh et al., 2016; Third IMO GHG Study, 2014):

$$SFOC = a \cdot L^2 + b \cdot L + c \tag{9}$$

where L is the engine load (values ranging from 0 to 1), while the coefficients a, b and c, depend on the respective engine.

Table 8: SFOC values for major manufacturers' typical engines.

Engine	SFOC (gr/kWh)

load	Wartsila 12V38	Caterpillar MAK 9M43C	MAN 8L48/60B
0.50	185	185	-
0.75	179	178	-
0.85	178	176	182
1	182	177	186

The curve provided from the regression analysis allows the calculation of the consumption at every level of the engine load. For the two engines with four SFOC values available, i.e. Wartsila 12V38 and Caterpillar MAK 9M43C, the polynomials derived from the regression analysis are: SFOC = 217.4 - 95.64·L + 59.59·L^2 and SFOC = 220.2 - 97.32·L + 53.95·L^2, respectively. For the third engine (i.e. MAN 8L48/60B) that not enough SFOC values are available, we used the second degree SFOC polynomial (eq.10a, 10b), described in STEAM2 model (Jalkanen et al., 2012). The STEAM and the updated STEAM2 models assume a parabolic function for all engines, derived after a regression analysis of the comprehensive SFOC measurement data taken from major engine manufactures (Wartsila, MAN, Caterpillar).

$$SFOC_{relative} = 0.455 \cdot L^2 - 0.71 \cdot L + 1.28 \quad (10a)$$

The typical engine consumption, SFOC, is calculated by multiplying $SFOC_{relative}$ (for the specific load level we are interested) with the specific engine base consumption ($SFOC_{base}$). That is:

$$SFOC = SFOC_{relative} \cdot SFOC_{base} \quad (10b)$$

The $SFOC_{base}$ is the lowest SFOC value (normally this is observed at 0.75-0.85 load range) and for MAN 8L48/60B as we see from Table 3 the lowest value is 182 gr/kWh. Thus from equations 10a and 10b we can calculate SFOC for the missing load levels, i.e. for 0.5 and 0.75 the SFOC is 189.1 gr/kWh and 182.6 gr/kWh respectively. Due to literature the abovementioned process is the most reliable (Jalkanen et al., 2012; Moreno-Gutiérrez et al., 2019; Third IMO GHG Study, 2014) to calculate missing SFOC values when experimental data are not available. After the additional SFOC data calculation for MAN 8L48/60B, we can proceed to the regression analysis, which gives the following polynomial: SFOC = 232.96 - 129.22·L + 82.81·L^2. The abovementioned process has been followed for all 41 engines, as in the best case 4 or 3 SFOC values were provided by the manufacturers (i.e. for 11 and 6 engines respectively), while in most cases less than 2 SFOC values were available.

Figure 4 represents the calculated (lines) and real values (markers) of SFOC *vs* the engine load for the three engines depicted in Table 8. We can easily infer that there are differences in consumption at each engine load level, and the dependence between SFOC and engine load is not linear but almost parabolic. The minimum fuel consumption is for engine load of 0.8 to 0.85, which corresponds to the optimal working conditions in terms of consumption and efficiency. On the other hand, it is evident that the use of the regression analysis provides an accurate estimation of SFOC for the whole range of engine load.

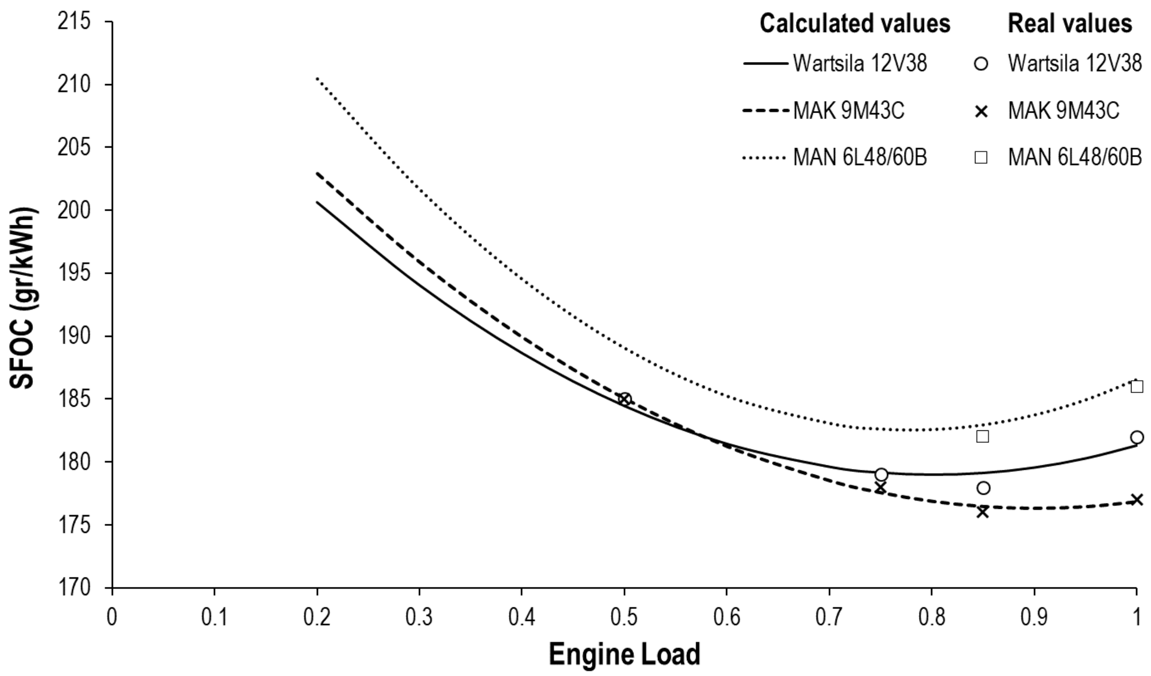


Figure 4: Typical SFOC curves for Wartsila, Caterpillar MAK and MAN engines.

As already mentioned the calculation of air emissions from ships largely depends on the employed emission factors, which typically due to lack of data are based on the professional or empirical assessment of the researcher. In order to emphasize the importance of the current study and validate the role of accurate SFOC values in the calculated air emissions we have calculated the fuel consumption and CO_2 emissions for a typical hoteling phase of a Wartsila 12V38 engine using SFOC values based on the regression analysis and on conventional methods widely used in the literature.

Wartsila 12V38 is a 4-stroke diesel engine, turbocharged and intercooled with direct injection of fuel, 8700 kW nominal power and 600 rpm nominal speed, and it has been designed to be used as a main propulsion and/or auxiliary engine (Wartsila 38 Project, 2008), while its SFOC (as described earlier) is given by the regression equation $217.4 - 95.64 \cdot L + 59.59 \cdot L^2$. As presented in Table 6 the load factor during the hoteling phase varies from 0.3 to 0.6, depending on the type of vessel (i.e. cruise or passenger ferry) and the season (i.e. summer or rest of year).

Apart from the use of the regression analysis as described above, SFOC values at various engine load levels are calculated in the literature either by using adjustment factors (Faber, Freund, Kopke, & Nelissen, 2010; Styhre et al., 2017) or based on scientific reports of IMO (Third IMO GHG Study, 2014) and/or ENTEC UK (ENTEC, 2002). Based on the former methodology for 4-stroke engines and for engine load greater than 0.5 MCR the recommended SFOC is the nominal, while for engine load less than 0.25 MCR or 0.25 – 0.50 MCR, the recommended SFOC is 1.7 times and 1.15 times the nominal value respectively. The creation of emissions inventories via the use of emission factors reported by either the IMO and/or ENTEC is common in the literature, but the provided emission factors from both reports are based on SFOC value equal to 227 gr/kWh at 0.75 engine load. In Table 9 we present the manufacturer's SFOC values, those calculated via the regression analysis, the IMO-ENTEC studies and the application of the adjustment factors.

As we can see the application of the adjustments factors on the manufacturer's SFOC value (column 5) results to differences ranging from -1.6% to 54.2%. For engine load levels more than 0.5 the two methodologies provide similar values but for lower engine load levels the application of adjustment factors increases the SFOC values. On the other hand, the application of adjustment factors on the IMO/ENTEC SFOC value (column 6) provides significantly increased SFOC values with differences ranging from 22.7% to 92.3%. From this analysis it is evident that in both cases of application of adjustment factors, the SFOC values especially during the "hoteling" phase are systematically overestimated compared to the values provided by the regression analysis methodology.

Table 9: Comparison of SFOC values for engine Wartsila 12V38 estimated with different methodologies.

		SFOC (gr/kWh)					Difference	
	Engine load	Manufacturers' values	Regression analysis (3)	IMO/ENTEC (4)	Adjustment factors on manufacturers' values (5)	Adjustment factors on IMO/ENTEC (6)	(5) *vs* (3)	(6) *vs* (3)
	0.20	-	200.7	-	(182 × 1.7) = 309.4	(227 × 1.7) = 385.9	+54.2%	+92.3%
Hoteling phase	0.30	-	194.1	-	(182 × 1.15) = 209.3	(227 × 1.15) = 261.1	+7.8%	+34.5%
Hoteling phase	0.40	-	188.7	-	(182 × 1.15) = 209.3	(227 × 1.15) = 261.1	+10.9%	+38.4%
Hoteling phase	0.45	-	186.4	-	(182 × 1.15) = 209.3	(227 × 1.15) = 261.1	+12.3%	+40.1%
Hoteling phase	0.50	185.0	185.0	-	182.0	227.0	-1.6%	+22.7%
Hoteling phase	0.60	-	181.5	-	182.0	227.0	+0.3%	+25.1%
	0.75	179.0	179.0	227.0	182.0	227.0	+1.7%	+26.8%
	0.85	178.0	178.0	-	182.0	227.0	+2.2%	+27.5%
	1.00	182.0	182.0	-	182.0	227.0	0%	+24.7%

The importance of the above findings is obvious when it comes to the quantification of air emissions. In Table 10 we present the results for total fuel consumption and CO_2 emissions for a Wartsila 12V38 engine for 10 hours operation at hoteling phase (almost average duration for the ships of our study).

In the parentheses we present the additional amounts compared to the values derived when the SFOC with regression analysis is used. It is evident that the employment of low accuracy SFOC values results to the calculation of significantly increased fuel consumption and air emissions.

Table 10: Total fuel consumption and CO_2 emissions for a Wartsila 12V38 engine during 10h operation at hoteling phase.

Vessel-Season	Engine Load	SFOC with regression analysis	SFOC with adjustment factors on manufacturers' values	SFOC with adjustment factors on IMO/ENTEC

		Fuel (t)	CO_2 (t)	Fuel (t)	CO_2 (t)	Fuel (t)	CO_2 (t)
Passenger Ferry (Summer)	0.30	5.066	16.242	5.463 (+0.397)	17.514 (+1.272)	6.815 (+1.749)	21.848 (+5.606)
Passenger Ferry (Rest of the year)	0.45	7.298	23.396	8.194 (+0.897)	26.270 (+2.874)	10.222 (+2.925)	32.772 (+9.376)
Cruise ship (Summer)	0.60	9.474	30.375	9.500 (+0.026)	30.458 (+0.084)	11.849 (+2.375)	37.989 (+7.615)
Cruise ship (Rest of the year)	0.40	6.567	21.053	7.284 (+0.717)	23.351 (+2.298)	9.086 (+2.520)	29.131 (+8.078)

3.3 Case study results

The calculation of fuel/energy consumption and air emissions (CO_2, SO_X, NO_X, PM_{10}) for passenger ferries and cruise vessels was carried out for the two major ports of Crete island in Greece, i.e. Souda and Heraklion (see Figure 5), for a 5 years period (2017-2021). An important part of the current study is to present a comparative analysis between different approaches for calculating on-board ship's emissions and fuel consumption based on operational data and to make clear the differences and accuracy of each method. A bottom-up calculation methodology has been employed for each ship, based on equation (2), mainly depending on data for engine power and load factor, operating phase duration, SFOC and emission factor for each gas emission. One of the main parameters that vary is SFOC, and we have analyzed in previous paragraphs the different approaches for its estimation, i.e. based on regression analysis or via the application of specific adjustment factors.

Engine power can be determined accurately from the manufacturer technical datasheets, or if not available it is estimated via expressions for the average 2010 World fleet or the 2006 Mediterranean Sea fleet. The duration of the operational phases for both passenger ferries and cruise ships was based on a thorough study of the itineraries.

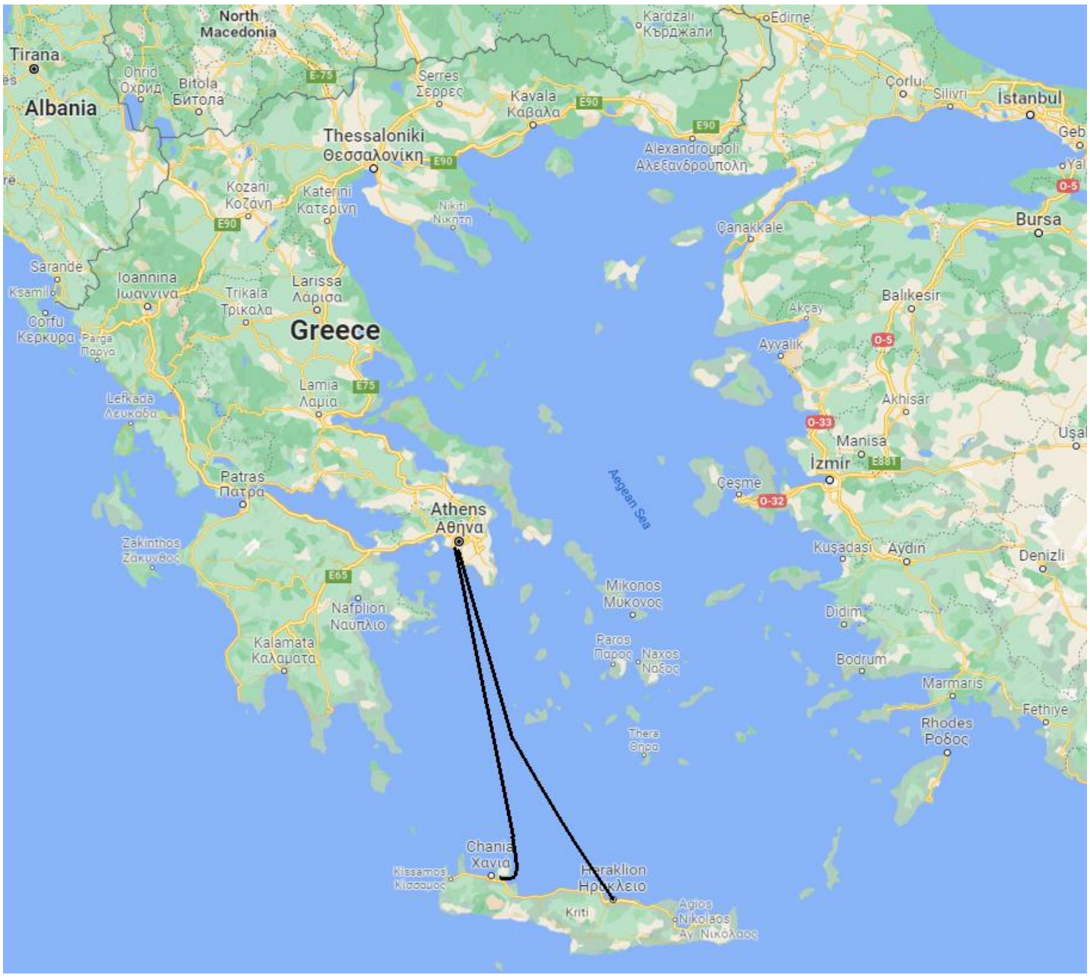


Figure 5: Map of Greece – Ships route from Piraeus to two major Crete ports (Souda and Heraklion)

Based on the variations in engine power and SFOC estimation methodology, four basic scenarios (1A, 1B, 2A and 2B) have been studied and compared as presented in Table 11. The SFOC base value is taken from the manufacturer technical datasheet for scenario 1B, while for 2A and 2B from the IMO GHG Study (Third IMO GHG Study, 2014).

Table 11: Alternative scenarios based on engines power and SFOC estimation methodology

	SFOC based on regression analysis	SFOC based on adjustment factors
Manufacturer's technical datasheet	1A	1B
Average 2010 world fleet $ME = 9.55078*GT^{0.7570}$, AE/ME=0.16		2A
2006 Mediterranean sea fleet $ME = 42.966*GT^{0.6035}$, AE/ME=0.27		2B

3.3.1 Ship calls at the studied ports

Passenger ferries (10 different ships, owned by three different shipping companies) are operating on daily routes all year around between the two studied ports and the port of Piraeus in mainland Greece, while cruise ships (88 different vessels) sail mainly during the summer period in both ports. All data regarding ships arrivals and duration of port calls were collected and validated from Port authorities and a web based cruise portal (Hellenic Ports Association, 2022). To confirm the above data and determine the required duration of each operating phase we conducted an extensive search in the related AIS databases for the itineraries of our study.

As resulted from the available data for the last pre-Covid era (year 2019), the 10 major Mediterranean cruise ports hosted a total of about 18.5 million cruise passenger movements. While this is a 9.23% increase compared to its last year (2018) as an example Barcelona reaches an all-time record as a major Mediterranean cruise port for second consecutive year, hosting more than 3 million cruise passenger movements (MedCruise, 2019). Cruise industry was expected to have continuously increased trend 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 with revenues nearly zero for months.

As depicted in Table 12 and presented in Figure 6, the ports under study reported significant decreased cruise ship calls during the last two Covid-19 years 2020, 2021 (2020 comparing to 2019: -90.7% for Heraklion and -100% for Souda and 2021 comparing to 2019: -43.1% for Heraklion and -52.7% for Souda) and this affected to fuel and energy consumption also (as it is obvious from the data in table 12).

Table 12: Cruise and passenger ferries fuel & Energy consumption (Souda and Heraklion ports)

Year	Sector	Port	Ship calls	Port stay Duration (h)	Fuel (t)	Energy (kWh)
2017	Cruise	Souda	89	9:58:58	1,239.250	6,616,670.7
		Heraklion	129	8:03:15	1,594.064	8,445,920.1
	Passenger ferries	Souda	382	12:32:59	3,163.416	15,232,445.3
		Heraklion	690	14:20:08	11,785.039	61,426,194.3
2018	Cruise	Souda	80	10:13:18	1,431.407	7,478,354.7
		Heraklion	188	9:09:47	2,557.107	13,300,590.1
	Passenger Ferries	Souda	536	13:21:59	3,725.798	18,218,715.2
		Heraklion	731	12:32:55	11,671.577	60,686,025.0
2019	Cruise	Souda	148	9:06:41	1,877.984	9,813,756.1
		Heraklion	204	10:26:12	2,619.560	13,675,825.8
	Passenger ferries	Souda	709	9:06:13	7,628.536	38,208,089.7
		Heraklion	745	10:05:39	11,318.339	58,434,802.8
2020	Cruise	Souda	0	-	-	-
		Heraklion	19	15:06:19	470.068	2,533,515.7
	Passenger ferries	Souda	677	9:38:15	6,896.137	35,118,325.9
		Heraklion	722	10:49:42	11,882.128	61,726,969.4

2021	Cruise	Souda	70	10:25:43	1,080.044	5,673,167.6
		Heraklion	116	15:13:57	2,291.526	12,427,257.7
	Passenger ferries	Souda	683	10:52:27	7,804.122	40,001,254.7
		Heraklion	707	11:47:12	12,237.923	63,667,330.9

Although the assumption that passenger ferries' ship calls would decrease due to Covid-19 as happened with cruise sector seemed reasonable, finally the observed reduction is not so significant (2020 comparing to 2019: -3.1% for Heraklion and -4.5% for Souda and 2021 comparing to 2019: -5.1% for Heraklion and -3.7% for Souda). Table 13 depicts the variation of relevant data comparing to 2019 (passengers, vehicles and freight cargo vehicles). It is evident that even if the trend of all transportation types units (passengers, vehicles, cargo) from 2017 to 2019 is increased, in 2020 there is a significant decrease especially to passengers (around 50% for both ports) and vehicles (-39.6% for Souda and -37.9% for Heraklion), due to Covid-19 applied travel restrictions and the insecurity of people to move freely.

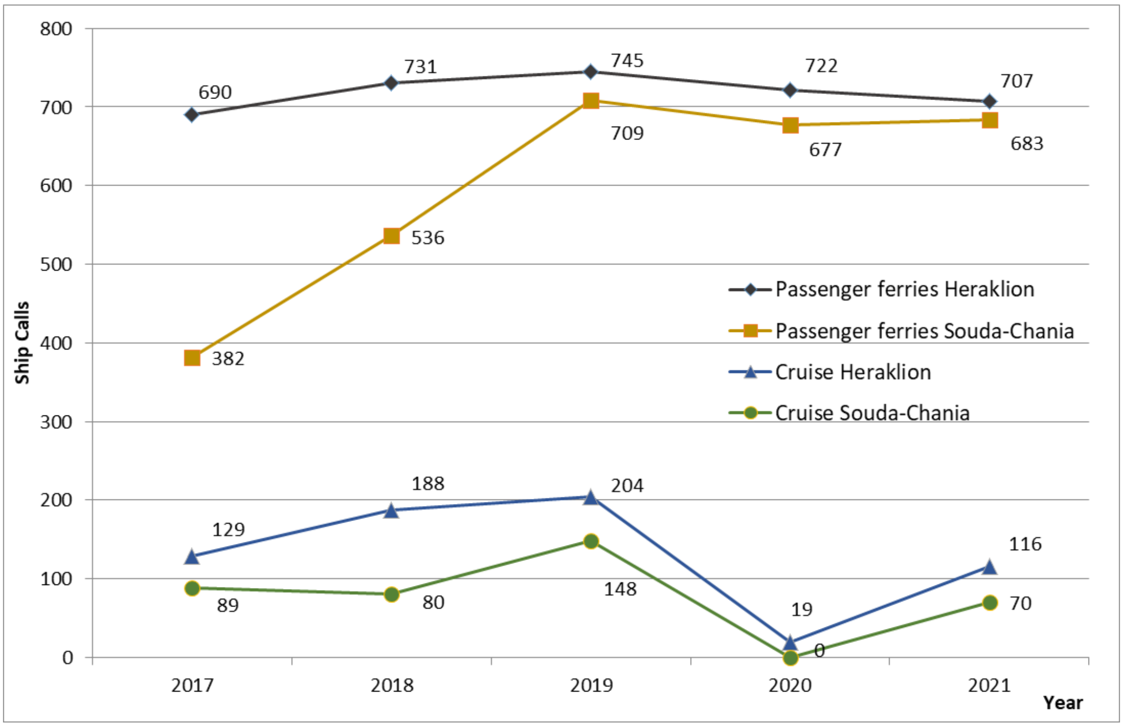


Figure 6: Annual ship calls for ports Souda and Heraklion (years 2017-2021)

Even 2021 was not a recovery year since significant reduction occurred: passengers -41.9% for Souda and -43.4% for Heraklion, vehicles: -16.2% for Souda and -17.3% for Heraklion. After 2019, cargo vehicles had a decrease also, but not so large (2020: -12.8% for Souda and -5.7% for Heraklion, 2021: -1.3% for Souda and +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.

Table 13: Passenger ferries data difference comparing to 2019

	Souda						Heraklion					
Year	Passengers		Vehicles		Cargo		Passengers		Vehicles		Cargo	
2017	379,553		60,457		26,530		523,448		77,637		59,804	
2018	439,043	+15.7	69,287	+14.6	30,067	+13.3	500,163	-4.4	76,490	-1.5	59,138	-1.1
2019	**463,669**	**+5.6**	**78,669**	**+13.5**	**33,431**	**+11.2**	**550,590**	**+10.1**	**86,530**	**+13.1**	**57,607**	**-2.6**
2020	224,707	-51.5	47,503	-39.6	29,150	-12.8	271,103	-50.8	53,744	-37.9	54,309	-5.7
2021	269,259	-41.9	65,922	-16.2	33,009	-1.3	311,596	-43.4	71,591	-17.3	62,237	+8.0

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.

3.3.2 Results for the basic scenario

The basic scenario that will be used for comparison with all other cases is 1A, with the SFOC being calculated based on manufacturer's technical datasheet and regression analysis to fit all engine load levels. The calculations for both main and auxiliary engines of fuel/energy consumption and air emissions were performed for every ship call of each passenger ferry and cruise vessel approaching the two studied ports. The fuel consumption for cruise ships and passenger ferries are summarized and presented for each port per year in Figure 7, while in Table 14 the annual fuel and energy consumption data (split for ME and AE) are depicted.

Table 14: Total annual fuel and energy consumption for passenger ferries and cruise ships

			Main Engines (ME)		Auxiliary Engines (AE)		Total (ME+AE)	
Year	Sector	Port	Fuel (t)	Energy (kWh)	Fuel (t)	Energy (kWh)	Fuel (t)	Energy (kWh)
2017	Cruise	Souda	80.620	387,139.5	1,158.630	6,229,531.2	1,239.250	6,616,670.7
		Heraklion	109.081	543,035.9	1,484.982	7,902,884.3	1,594.063	8,445,920.2
	Passenger ferries	Souda	778.721	3,602,467.5	2,384.695	11,629,977.8	3,163.416	15,232,445.3
		Heraklion	1,177.750	5,701,667.8	10,607.289	55,724,526.5	11,785.039	61,426,194.3
2018	Cruise	Souda	87.319	409,068.8	1,344.088	7,069,285.9	1,431.407	7,478,354.7
		Heraklion	148.673	724,724.6	2,408.434	12,575,865.5	2,557.107	13,300,590.1
	Passenger Ferries	Souda	1,160.621	5,504,666.7	2,565.176	12,714,048.5	3,725.797	18,218,715.2
		Heraklion	1,754.589	8,526,966.6	9,916.989	52,159,058.4	11,671.578	60,686,025.0
2019	Cruise	Souda	169.348	777,669.3	1,708.636	9,036,086.8	1,877.984	9,813,756.1
		Heraklion	149.805	733,528.5	2,469.755	12,942,297.4	2,619.560	13,675,825.9
	Passenger ferries	Souda	1,747.410	8,362,197.1	5,881.127	29,845,892.6	7,628.537	38,208,089.7
		Heraklion	2,733.563	13,356,848.3	8,584.776	45,077,954.5	11,318.339	58,434,802.8

2020	Cruise	Souda	-	-	-	-	-	-
		Heraklion	19.603	100,322.7	450.465	2,433,192.9	470.068	2,533,515.6
	Passenger ferries	Souda	1,535.285	7,519,517.7	5,360.853	27,598,808.2	6,896.138	35,118,325.9
		Heraklion	2,411.153	11,779,995.9	9,470.975	49,946,973.5	11,882.128	61,726,969.4
2021	Cruise	Souda	93.704	389,026.1	986.339	5,284,141.5	1,080.043	5,673,167.6
		Heraklion	107.294	543,043.6	2,184.232	11,884,214.1	2,291.526	12,427,257.7
	Passenger ferries	Souda	1,495.250	7,359,168.8	6,308.871	32,642,085.9	7,804.121	40,001,254.7
		Heraklion	2,344.681	11,458,172.1	9,893.243	52,209,158.9	12,237.924	63,667,331.0

We observe that there is a big difference in fuel consumption for AE compared to ME for both types of ships during their stay in ports. This is perfectly normal, as the auxiliary engines of ships operate continuously during mooring and maneuvering and at a relatively high load, while on the other hand main engines operate for significantly less time during the maneuvering phase and at a lower rate and engine load.

The most fuel/energy consuming sector per ship call differs for the two ports (Table 15): the passenger ferries dominate in terms of fuel/energy consumption in Heraklion (until 2019) while for Souda cruise ships prevail for all years. For years 2020 and 2021 Heraklion cruise has a significant increase on average fuel and energy consumption in port and as we observe to our dataset (table 12, column 5) this is due to longer average duration of stay at port for the cruise vessels. Longer stay means more fuel/energy consumption at port.

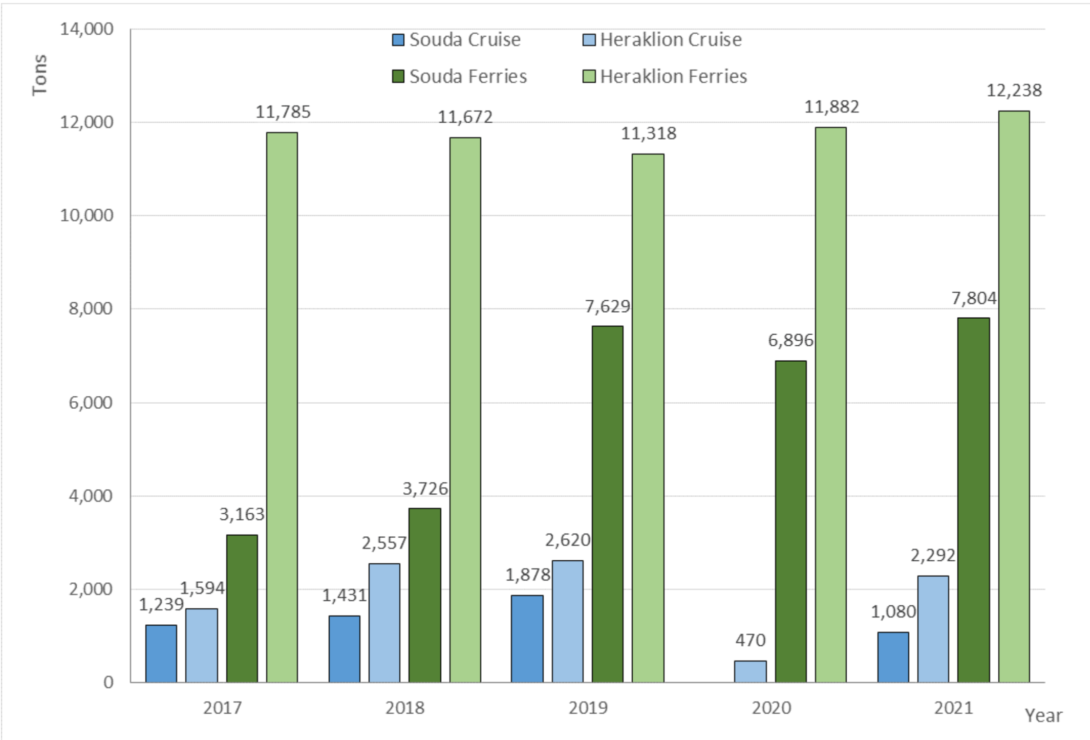


Figure 7: Annual fuel consumption for passenger ferries and cruise ships (2017-2021)

Table 15: Fuel & Energy consumption per ship call for passenger ferries and cruise ships

Year	Sector	Port	Fuel per ship call (t)	Energy per ship call (kWh)
2017	Cruise	Souda	13.924	74,344.6
		Heraklion	12.357	65,472.2
	Passenger ferries	Souda	8.281	39,875.5
		Heraklion	17.080	89,023.5
2018	Cruise	Souda	17.893	93,479.4
		Heraklion	13.602	70,747.8
	Passenger Ferries	Souda	6.951	33,990.1
		Heraklion	15.967	83,017.8
2019	Cruise	Souda	12.689	66,309.2
		Heraklion	12.841	67,038.4
	Passenger ferries	Souda	10.760	53,890.1
		Heraklion	15.192	78,436.0
2020	Cruise	Souda	-	-
		Heraklion	24.740	133,342.9
	Passenger ferries	Souda	10.186	51,873.5
		Heraklion	16.457	85,494.4
2021	Cruise	Souda	15.429	81,045.3
		Heraklion	19.755	107,131.5
	Passenger ferries	Souda	11.426	58,567.0
		Heraklion	17.310	90,052.8

The detailed quantities for air emissions have been calculated for all ship calls in both ports during five years period 2017-2021, and in all cases as depicted in table 16, CO_2 emissions are the vast majority of all other gas emissions in study. Actually they account for about 97-98% in terms of total air emissions every year.

Table 16: Air emissions for Souda and Heraklion port (years 2017-2021)

Year	Sector	Port	Ship calls	CO_2 (t)	SO_X (t)	NO_X (t)	$PM_{2.5}$ (t)	PM_{10} (t)
2017	Cruise	Souda	89	3,965.619	20.029	71.376	3.873	0.337
		Heraklion	129	5,100.533	21.942	99.770	4.446	0.387
	Passenger ferries	Souda	382	10,070.270	30.501	185.018	5.833	0.507
		Heraklion	690	37,674.482	284.899	670.167	50.652	4.405
2018	Cruise	Souda	80	4,581.057	19.504	80.448	3.763	0.327
		Heraklion	188	8,184.408	25.472	161.019	5.775	0.502
	Passenger ferries	Souda	536	11,838.131	52.079	215.637	9.413	0.819
		Heraklion	731	37,257.655	287.396	661.509	50.700	4.409
2019	Cruise	Souda	148	6,005.236	29.397	112.526	5.460	0.475
		Heraklion	204	8,384.526	26.239	157.995	5.603	0.487
	Passenger ferries	Souda	709	24,296.325	155.804	427.945	27.509	2.392
		Heraklion	745	36,035.107	275.153	637.946	48.201	4.191
20	Cruise	Souda	0	-	-	-	-	-

		Heraklion	19	1,493.066	0.478	13.085	0.509	0.044
	Passenger ferries	Souda	677	21,967.771	14.162	391.039	9.591	0.834
		Heraklion	722	37,872.275	18.993	671.593	16.522	1.437
2021	Cruise	Souda	70	3,430.522	1.098	40.197	1.215	0.106
		Heraklion	116	7,278.528	2.350	95.801	2.700	0.235
	Passenger ferries	Souda	683	24,882.451	14.847	444.048	10.908	0.949
		Heraklion	707	39,019.071	17.709	692.375	16.718	1.454

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 separately. The detailed annual CO_2 air emissions quantities during five years period 2017-2021 are graphically presented in figure 8.

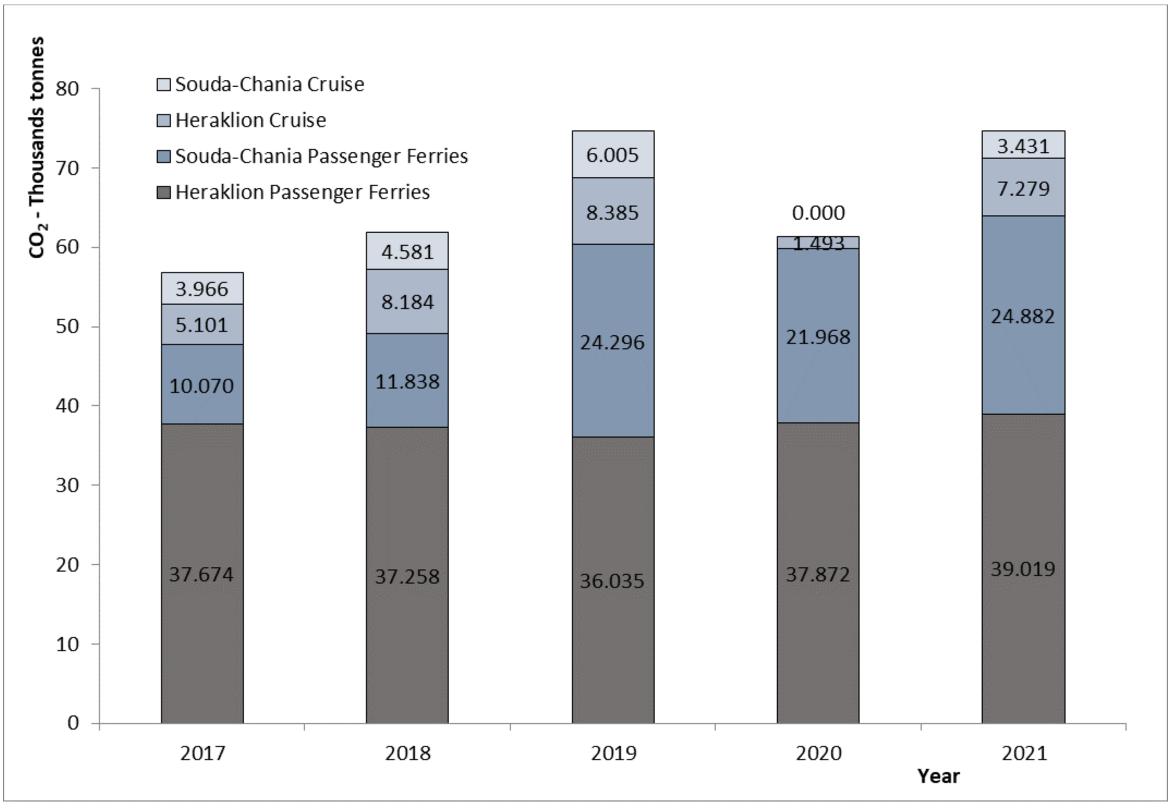


Figure 8: Annual CO_2 emissions for Souda and Heraklion ports

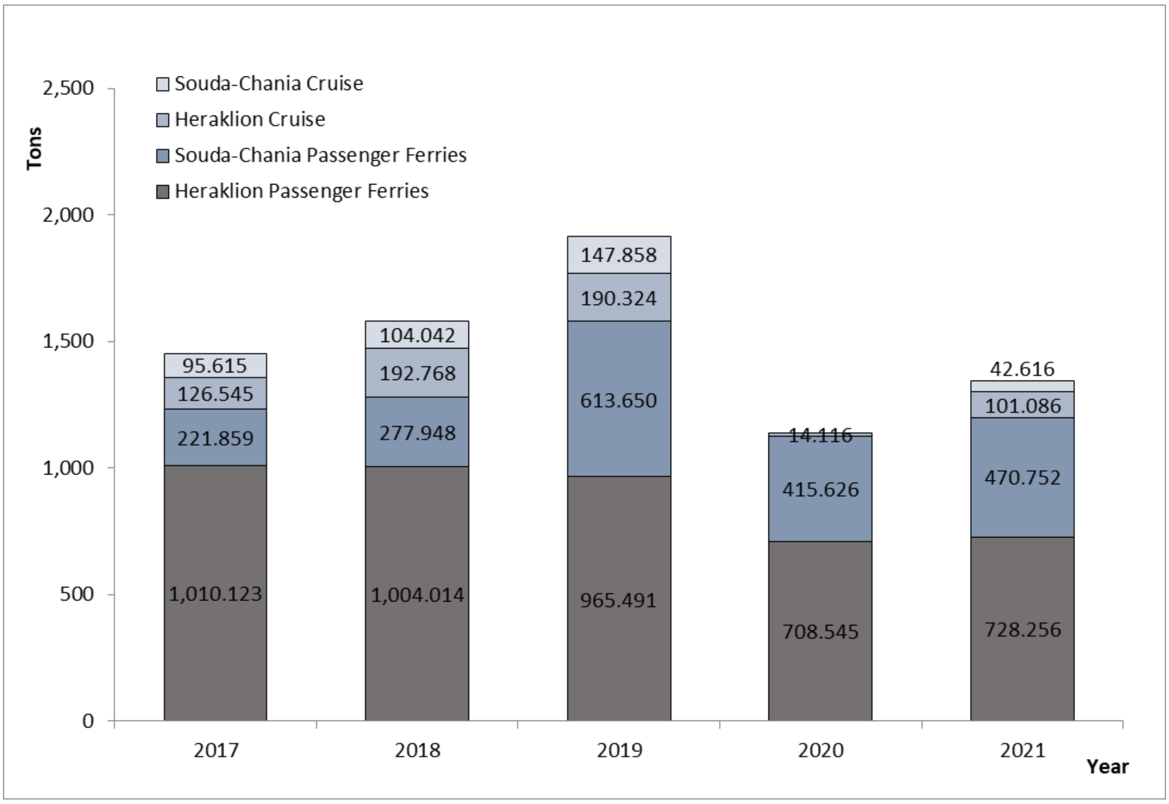


Figure 9: Annual gaseous pollutants (NO_X, SO_X, PM's) for Souda and Heraklion ports

Gaseous pollutants SO_X, NO_X, $PM_{2.5}$ and PM_{10} are also depicted in Table 16. The detailed annual summary of gaseous pollutants quantities during five years period 2017-2021 are graphically presented in figure 9. We observe that the most polluting sector in quantity terms is the passenger ferries in Heraklion followed by passenger ferries in Souda. Cruise ships sector at Heraklion port is at the third place while at last is cruise at Souda port. In figure 8 we observe similar status for CO_2 emissions also.

Figure 10 presents the quantity of air pollutants (NO_X, SO_X, $PM_{2.5}$, and PM_{10}) for the five years in study for both sectors (ferries, cruise). As we see NO_X emissions are the majority of all other gaseous pollutants in study We also notice a significant reduction for SO_X and PM's for the last two years (2020-2021) and this is due to new regulations initiated from 2020 (scrubbers, 0.5% S fuel).

An important finding is that the most air emission sector per ship call differs for the two ports (Table 17): the passenger ferries dominate in terms of air emissions in Heraklion (until 2019) while for Souda cruise ships prevail for all years. For years 2020 and 2021 Heraklion cruise has a significant increase on air emissions per ship call in port and as we observe to our dataset (Table 12, column 5) this is due to longer average duration of stay at port for the cruise vessels. Longer stay means more fuel/energy consumption and air emissions at port.

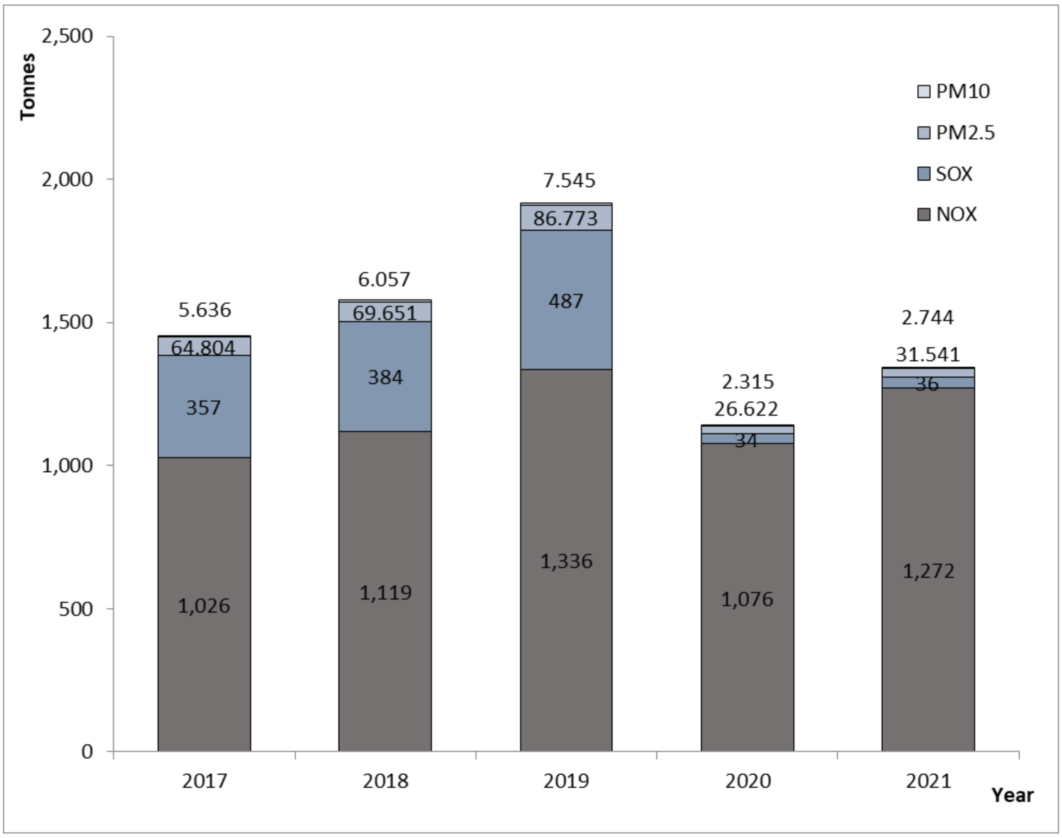


Figure 10: Air pollutants quantity for Souda and Heraklion ports

Table 17: Air emissions per ship call for passenger ferries and cruise ships

Port	Year	Sector	CO2 per ship call (t)	Air pollutants per ship call (t)
Souda	2017	Cruise	**44.558**	**1.074**
		Passenger ferries	26.362	0.581
	2018	Cruise	**57.263**	**1.301**
		Passenger Ferries	22.086	0.519
	2019	Cruise	**40.576**	**0.999**
		Passenger ferries	34.268	0.866
	2020	Cruise	-	-
		Passenger ferries	32.449	0.614
	2021	Cruise	**49.007**	0.609
		Passenger ferries	36.431	**0.689**
Heraklion	2017	Cruise	39.539	0.981
		Passenger ferries	**54.601**	**1.464**
	2018	Cruise	43.534	1.025
		Passenger Ferries	**50.968**	**1.373**
	2019	Cruise	41.101	0.933
		Passenger ferries	**48.369**	**1.296**
	2020	Cruise	**78.582**	0.743

	Passenger ferries	52.455	**0.981**
2021	Cruise	**62.746**	0.871
	Passenger ferries	55.190	**1.030**

3.3.3 Results for the alternative scenarios

The four scenarios presented in Table 11, were selected in order to validate the effect of different SFOC estimations on the estimation of fuel/energy consumption and air emissions. Scenario 1A depicts SFOC values based on engine's manufacturer's technical data estimated via regression analysis, while SFOC was calculated through adjustment factors applied on engine's data (scenario 1B) and ME power estimated through ship's GT using data based either on average World fleet (scenario 2A) or Mediterranean sea fleet (scenario 2B). In order to perform a reliable comparison between the three alternative approaches (1B, 2A and 2B) and the basic scenario (1A), we have calculated for both passenger ferries and cruise ships the 5-year average and the total values for fuel/energy consumption and air emissions for ME and AE per approach for the studied ports. These results are presented in Table 17a and Table 17b, while in Figures 10, 11a and 11b the total fuel/energy consumption and air emissions are depicted respectively. We can observe the following regarding the comparison of the results from the four different approaches 1A, 1B, 2A and 2B.

Table 17a: Fuel and energy consumption per ship call and scenario for years 2017-2021

		Souda port				Heraklion port			
		Passenger ferries		Cruise ships		Passenger ferries		Cruise ships	
Scenario		Fuel (t)	Energy (kWh)	Fuel (t)	Energy (kWh)	Fuel (t)	Energy (kWh)	Fuel (t)	Energy (kWh)
1A	ME	2.249	10,829.6	1.114	5,072.1	2.899	14,137.3	0.815	4,031.5
	AE	7.533	38,309.6	13.431	71,367.0	13.484	70,964.6	13.716	72,772.0
	Total	**9.782**	**49,139.2**	**14.545**	**76,439.1**	**16.383**	**85,101.9**	**14.531**	**76,803.5**
1B	ME	3.415	10,829.6	1.667	5,072.1	4.488	14,137.3	1.225	4,031.5
	AE	8.096	38,309.6	13.990	71,367.0	13.754	70,964.6	14.357	72,772.0
	Total	**11.511**	**49,139.2**	**15.657**	**76,439.1**	**18.242**	**85,101.9**	**15.582**	**76,803.5**
2A	ME	2.518	7,755.7	2.394	7,432.0	2.376	7,485.3	2.174	6,497.3
	AE	4.457	20,864.0	12.243	59,950.4	5.338	24,649.3	13.572	63,996.3
	Total	**6.975**	**28,619.7**	**14.637**	**67,382.4**	**7.714**	**32,134.6**	**15.746**	**70,493.6**
2B	ME	2.055	6,305.1	2.048	6,348.7	2.227	7,015.8	1.938	5,762.0
	AE	6.169	28,771.7	13.679	66,945.7	7.773	35,987.7	14.740	69,621.2
	Total	**8.224**	**35,076.8**	**15.727**	**73,294.4**	**10.000**	**43,003.5**	**16.678**	**75,383.2**

Table 17b: Total Fuel and energy consumption per scenario for years 2017-2021

		Souda port				Heraklion port			
		Passenger ferries		Cruise ships		Passenger ferries		Cruise ships	
Scenario		Fuel (t)	Energy (kWh)	Fuel (t)	Energy (kWh)	Fuel (t)	Energy (kWh)	Fuel (t)	Energy (kWh)
1A	ME	6,717.287	32,348,017.8	430.991	1,962,903.7	10,421.735	50,823,650.8	534.456	2,644,655.3
	AE	22,500.722	114,430,813.0	5,197.694	27,619,045.4	48,473.271	255,117,671.8	8,997.868	47,738,454.2
	Total	**29,218.009**	**146,778,830.8**	**5,628.685**	**29,581,949.1**	**58,895.006**	**305,941,322.6**	**9,532.324**	**50,383,109.5**
1B	ME	10,201.137	32,348,017.8	645.150	1,962,903.7	16,133.342	50,823,650.8	803.639	2,644,655.3
	AE	24,183.013	114,430,813.0	5,413.966	27,619,045.4	49,447.030	255,117,671.8	9,418.475	47,738,454.2
	Total	**34,384.150**	**146,778,830.8**	**6,059.116**	**29,581,949.1**	**65,580.372**	**305,941,322.6**	**10,222.114**	**50,383,109.5**
2A	ME	7,520.520	23,166,338.8	926.564	2,876,170.5	8,542.101	26,909,614.3	1,426.052	4,262,198.5
	AE	13,314.254	62,320,726.4	4,738.158	23,200,806.0	19,191.156	88,614,092.1	8,902.918	41,981,547.1
	Total	**20,834.774**	**85,487,065.2**	**5,664.722**	**26,076,976.5**	**27,733.257**	**115,523,706.4**	**10,328.970**	**46,243,745.6**
2B	ME	6,136.890	18,833,393.0	792.626	2,456,954.8	8,005.049	25,221,964.2	1,271.207	3,779,874.8
	AE	18,428.181	85,941,125.0	5,293.671	25,907,995.5	27,943.456	129,375,924.5	9,669.265	45,671,511.6
	Total	**24,565.071**	**104,774,518.0**	**6,086.297**	**28,364,950.3**	**35,948.505**	**154,597,888.7**	**10,940.472**	**49,451,386.4**

Scenario 1B vs 1A: Comparing the basic scenario approach 1A and the alternative approach 1B, we see that the values of average energy consumption are identical for all sectors and ports. This was expected since all data for energy consumption calculation (as described in paragraph 3.2) depend on the MCR of the engine, the load factor of the selected operational phase (hoteling, maneuvering and cruising) and its duration, which are equal for both approaches. The use of approach 1B provides higher fuel consumption values for both ME & AE, with significant difference for ME while for AE the values seem to be similar. In terms of the air emissions, the use of approach 1B seems to provide slightly higher air emissions values in total. We observe similar air emissions for both scenarios, except for the CO_2 which is slightly higher for 1B. NO_X and energy consumption values are identical for both scenarios, as the emission factor depends exclusively on engine rev. speed (n), as depicted by equations (6a), (6b) and (6c) at paragraph 3.2.2 which is the same for the two scenarios.

Scenario 2A vs 1A: In contrast with the results from the previous comparison we observe that total fuel and energy consumption (for ME and AE) is significantly lower for the scenario 2A compared to 1A for all sectors and ports. We observe a big difference for total fuel and energy consumption for passenger ferries for both ports, while total fuel consumption for cruise ships at Souda port seems to be similar between the two approaches and fuel consumption for cruise ships at Heraklion port seems to be close to 1A approach. As a result, we clearly understand that approach 2A underestimates both fuel and energy consumption (Figure 10) and thus these results to significantly reduced air emissions (which is proved from the results of Figures 11a and 11b).

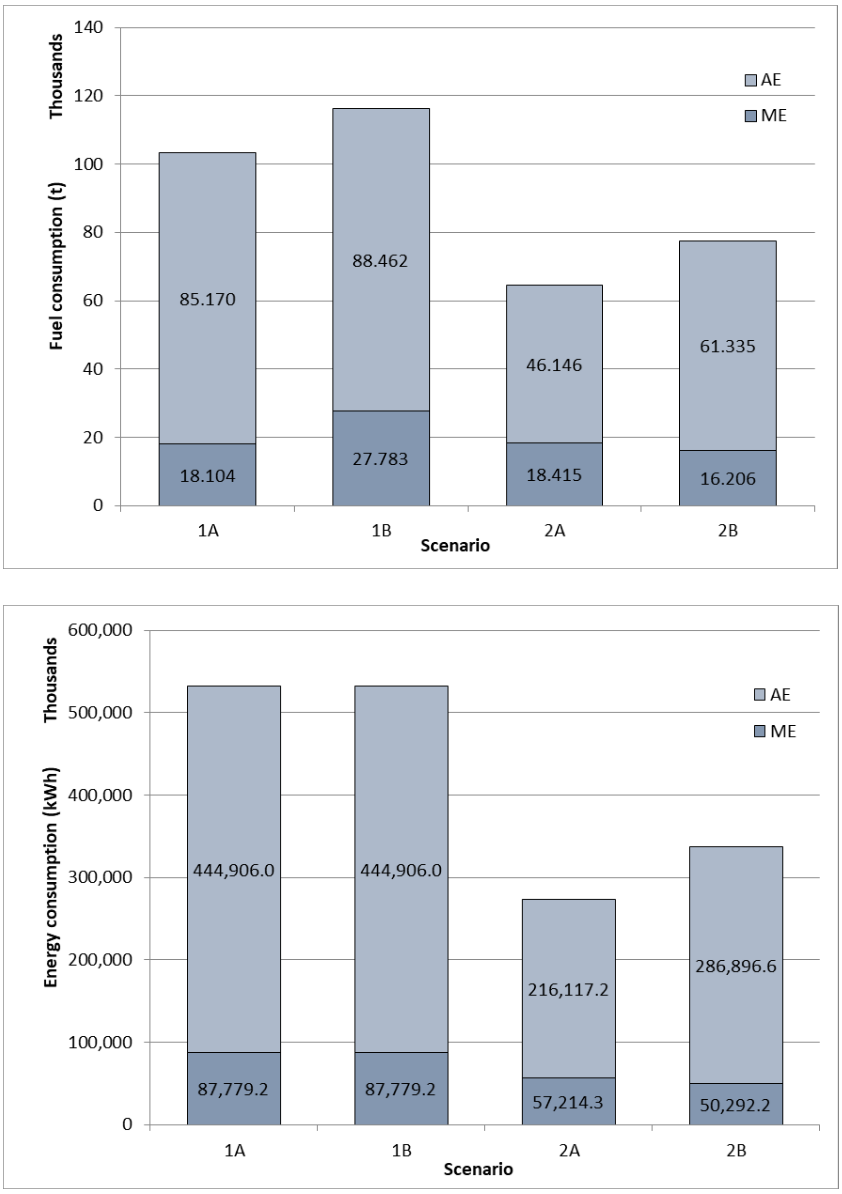


Figure 10: Total fuel and energy consumption for Souda and Heraklion ports (years 2017-2021)

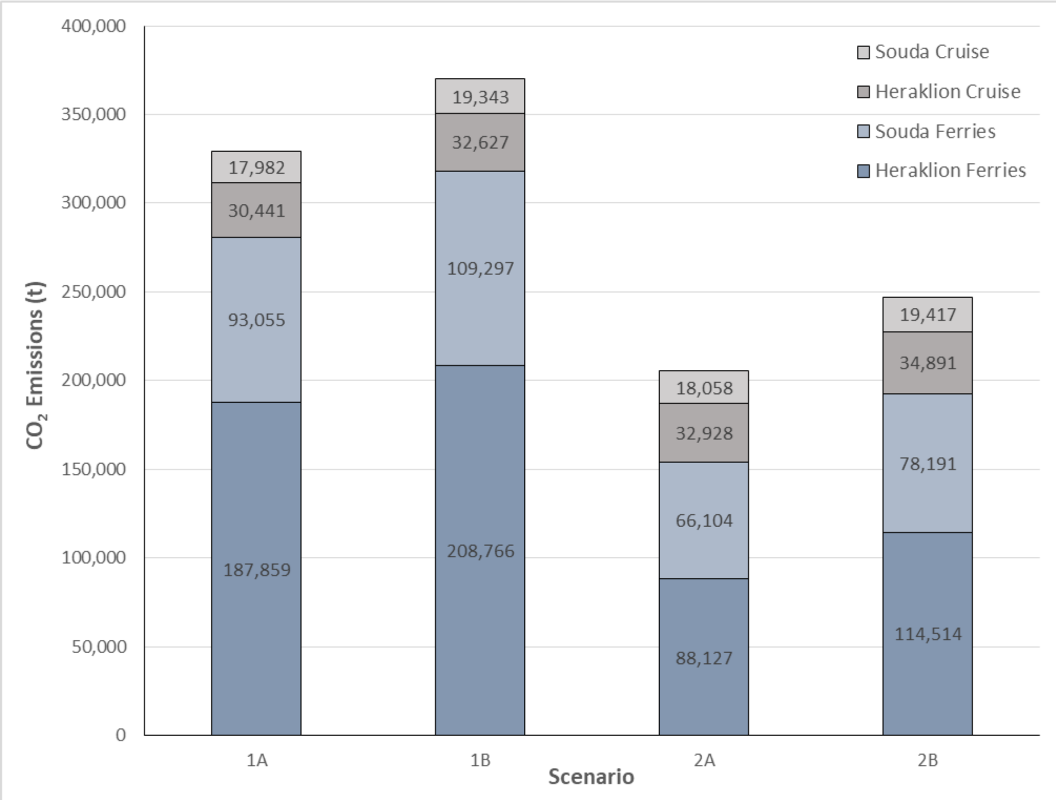


Figure 11a: Total CO_2 emissions for 5 years period (2017-2021).

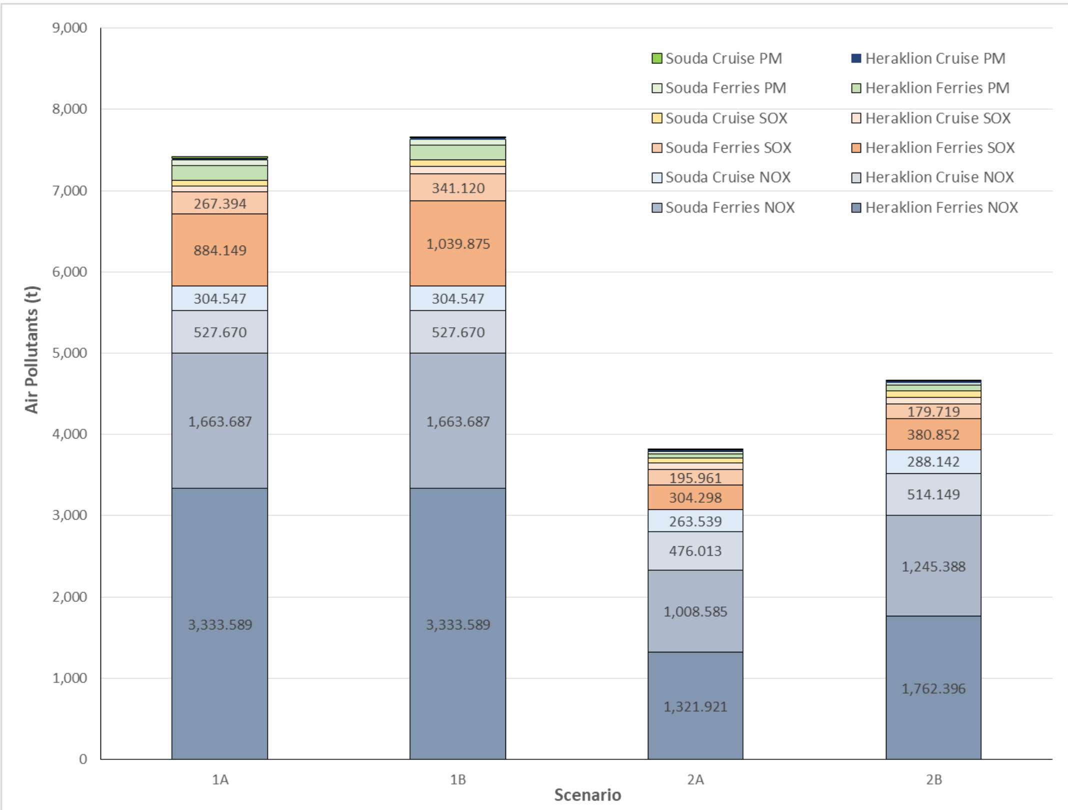


Figure 11b: Total air pollutants (NO_X, SO_X, PM) for 5 years period (2017-2021)

Scenario 2B vs 1A: The use of scenario 2B results to lower fuel/energy consumption and air emissions in almost all cases compared to approach 1A (except from cruise ships ME fuel consumption at Souda port). For the cruise sector we observe similar fuel consumption for both scenarios at both ports: using 2B results to slightly lower fuel consumption for Heraklion port and slightly higher for Souda. Regarding the energy consumption, approach 2B also leads to significant underestimation in all cases. As a result we can conclude that approach 2B also underestimates both fuel and energy consumption and thus this reflects to an underestimation of air emissions.

Due to the lack of publically available SFOC data, the application of various methodologies provides results with significant differences. SFOC is considered as one of the most significant factor for the precise calculation of fuel consumption, and consequently for the accurate estimation of air emissions.

The above mentioned methodologies aim for the estimation of air emissions from ships in ports based on specific technical data. It is clear that no data based on real time air pollution monitoring from either ports or ships are available in large scale nowadays. We can assume that online air pollution monitoring through marine emissions monitoring systems, might be widely used in the near future. The new era of shipping needs to demonstrate environmental responsibility as charterers and the public, demand high standards of performance and reliability. The only robust and reliable method for the authorities to monitor and control the air pollutants from ships and investigate non-compliance and possible violation of the emissions regulations is the installation of onboard Marine Emissions Monitoring Systems.

3.4 Discussion on case study's results

In this chapter we presented in detail all the main parameters, i.e. engine load, SFOC, emissions factors, included in existing methodologies for calculating ships' on-board emissions and emphasized on the importance of having accurate SFOC values especially for low engine load levels. The proposed technical approach to define SFOC via publically available operational data was compared to typical methodologies (i.e. application of adjustment factors either on manufacturers' values or on IMO/ENTEC data) and the results indicated that the application of adjustment factors leads to systematically overestimated SFOC values especially during the "hoteling" phase. The importance of these findings was validated via a bottom-up methodology employed for the quantification of fuel/energy consumption and air emissions (CO_2, SO_X, NO_X, $PM_{2.5}$ and PM_{10}) in two major ports (Souda and Heraklion) of Crete island in Greece for passenger ferries and cruise ships for five years period (2017-2021) for both main and auxiliary engines of all vessels.

A detailed comparative analysis has been performed between different approaches for calculating on-board ship's emissions and fuel/energy consumption, mainly focusing on the effect of SFOC and engine power in the obtained results. The most accurate estimations were performed when SFOC was calculated based on a regression analysis on widely available engines' technical data, and this was considered as the basic scenario for comparison to alternative approaches. The use of SFOC values calculated through adjustment factors applied on engines' data resulted in average energy consumption identical for all sectors and ports, while in terms of air emissions it provided slightly higher values in total. On the other hand, when the SFOC values were calculated through adjustment factors and the

ME power was estimated via ship's GT (using data based either on average World fleet or Mediterranean sea fleet), both fuel and energy consumption were underestimated thus leading to a significant underestimation of air emissions. The basic scenario reflects a complete methodological framework that various stakeholders can follow to conduct air emissions calculations based on ships' operational data.

Regarding the comparison between passenger ferries or cruise vessels for the studied ports, in terms of air emissions the results from the current study clearly show that the most polluting sector differs for the two ports: passenger ferries dominate in Heraklion (until 2019) while for Souda cruise ships prevail for all years. For years 2020 and 2021 Heraklion cruise has a significant increase on air emissions per ship call in port and as we observe to our dataset (table 12, column 5) this is due to longer average duration of stay at port for the cruise vessels. Longer stay means more fuel/energy consumption and air emissions at port.

3.5 Reported fuel consumption vs Estimated Fuel consumption and CO_2 emissions.

For any researcher involved in the calculation of air emissions in shipping, there is almost always the question regarding the accuracy of the results following a bottom-up methodological approach and specific determination of parameters-factors that are included in the calculations. Since actual fuel consumption and air emissions were not publically available before some years, EMSA/MRV-THETIS Database (EMSA, 2022) is a very useful tool to provide actual (as reported from ship-owners) fuel consumption and CO_2 emissions from ships.

In our current case study a bottom-up methodology was followed to calculate the fuel/energy consumption and air emissions (including CO_2 emissions) of passenger ships for five year period (2017-2021). An important detail on the above methodology is the accuracy of the specific approach that we believe we have achieved. The main objective of this paragraph is to perform a comparative analysis between fuel consumption and CO_2 emissions estimation (from the above mentioned results) and actual fuel consumption.

Since detailed actual fuel consumption for ships is not publically available, as actual we assume the data from the EMSA/MRV-THETIS database (EMSA, 2022) which provides annual reporting of fuel consumption and CO_2 emissions. For reliable results we studied vessels that operated throughout one year between ports under the EU MRV regulation. After studying the itineraries for passenger ferries and cruise vessels for Souda and Heraklion for the most recent available data (2020) the presented results hereafter focus on 5 passenger ferries which operated from Souda to Piraeus and Heraklion to Piraeus. These ships do not use scrubbers and they consume fuel with 0.5% Sulphur content for ME and 0.1% for AE. Table 18a depicts the vessels that meet the above criteria and additionally their MRV operational data that are available from EMSA/THETIS-MRV Database. The ships were using two different monitoring methods of fuel consumption, which correspond to:

A. Bunker Fuel Delivery Note (BDN) and periodic stocktaking of fuel tanks and
B. Bunker fuel tank monitoring on board

To fully understand the type and size of ships in study, table 18b depicts some more technical parameters (length, width, GT, ME power, AE power, and percentage of each engine type to total).

During cruising (between ports) all engines (ME and AE) are operating in a relatively high rate (0.85 for ME, 0.75 for AE at summer period (Jun-Jul-Aug) 0.60 for AE for all other months). This is reflected in fuel consumption and CO_2 emissions and as it is normal, there is a big difference in the quantity of CO_2 emissions occurred within ports and between ports.

This is depicted in Table 19 and represented in Figure 13 where we can observe that CO_2 emissions between ports are more than 70% to total and depending on each ship is from 72.14% to 93.67%. Thus it is critical to estimate as accurately as possible the fuel consumption and CO_2 emission especially during the normal cruise operational phase, since this phase is a large part of the total.

Table 18a: MRV data of passenger ferries exclusively operated during 2020 between major Crete ports and Piraeus port

IMO Number	Ship Name	Monitoring method	Time spent at sea annually (h)	Total fuel consumption (t)	CO_2 emissions occurred within ports (t)	CO_2 emissions between ports (t)	Total CO_2 emissions (t)
7814046	F/B KRITI I	A	781.48	2652.90	2319.86	6007.84	8327.70
7814058	F/B KRITI II	A	2739.52	9482.68	3854.53	25778.13	29634.66
7907673	F/B EL.VENIZELOS	A	1210.72	3485.59	2251.85	8674.30	10926.18
8616336	F/B BLUE HORIZON	B	1960.00	5354.22	1963.00	14788.00	16751.00
9035876	F/B BLUE GALAXY	B	2651.38	9214.79	1819.31	26929.39	28748.70

Source EMSA/THETIS-MRV Database (EMSA, 2022)

Table 18b: Technical characteristics of passenger ferries in study

IMO Number	Ship Name	Length (m)	Width (m)	Gross Tonnage	Main Engines power (kW)	Main Engines %	Auxiliary Engines power (kW)	Auxiliary Engines %	Total power (kW)
7814046	F/B KRITI I	192.0	29.4	27239	24,800	85.5	4,200	14.5	29,000
7814058	F/B KRITI II	192.0	29.4	27239	24,800	85.5	4,200	14.5	29,000
7907673	F/B EL.VENIZELOS	175.5	28.5	38261	29,828	86.6	4,610	13.4	34,438
8616336	F/B BLUE HORIZON	187.0	27.0	27320	22,400	83.8	4,320	16.2	26,720
9035876	F/B BLUE GALAXY	192.0	27.0	29992	29,160	90.0	3,240	10.0	32,400

Table 19: MRV data of CO_2 emissions variation within ports and between ports

IMO Number	Ship Name	CO_2 emissions occurred within ports (t)	Participation to Total CO_2 Emissions	CO_2 emissions between ports (t)	Participation to Total CO_2 Emissions	Total CO_2 Emissions (t)
7814046	F/B KRITI I	2319.86	27.86%	6007.84	72.14%	8327.70
7814058	F/B KRITI II	3854.53	13.01%	25778.13	86.99%	29634.66
7907673	F/B EL.VENIZELOS	2251.85	20.61%	8674.30	79.39%	10926.18
8616336	F/B BLUE HORIZON	1963.00	11.72%	14788.00	88.28%	16751.00
9035876	F/B BLUE GALAXY	1819.31	6.33%	26929.39	93.67%	28748.70

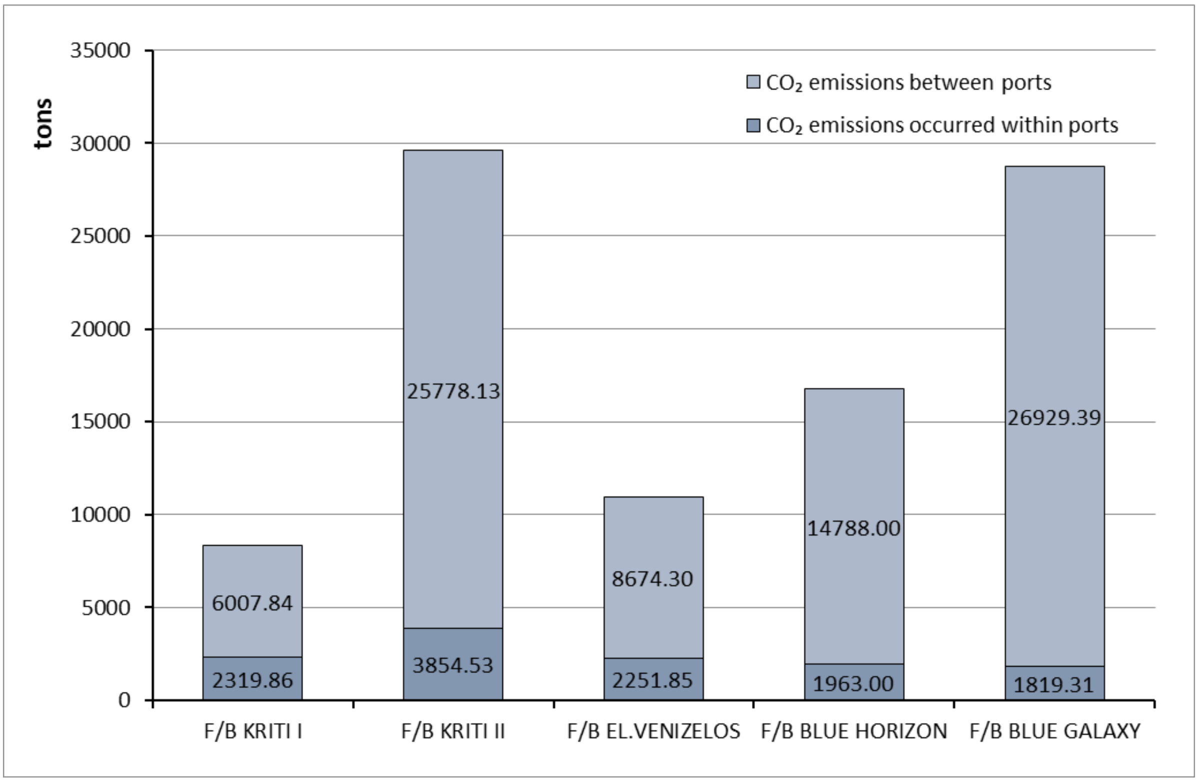


Figure 13: CO_2 emissions based on MRV within ports and between ports.

In order to determine the required duration of each operating phase (at port or at sea) after studying and validating ships itineraries, arrivals and duration of port calls and AIS activity, table 20 depicts the variation of annual time spent at sea between the EMSA/THETIS-MRV Database and our study. MRV reports the duration of "Annual Time spent at sea" which is similar to the analytical itineraries presented here, except for F/B EL.VENIZELOS that has a significant variation on annual time spent at sea. As it will be explained in the results later, this is probably a reporting mistake in EMSA/THETIS-MRV Database, since all other results for this ship have a much less difference. The small difference on annual time spent at sea duration is a first good sign that the validation of operational phase's duration that was performed during this study is correct. Also this factor takes part in the air emissions calculation and is important to be as accurate as possible.

Table 20: Passenger ferries operational phase's duration

IMO Number	Ship Name	Ship calls	Annual time at port (h)	Annual time at sea (h)	MRV Annual time spent at sea (h)	Difference (h)	Difference (%)
7814046	F/B KRITI I	81	1372.00	769.50	781.48	11.98	1.9%
7814058	F/B KRITI II	294	4293.75	2719.50	2739.52	20.02	0.7%
7907673	F/B EL.VENIZELOS	63	958.00	651.00	1210.72	559.72	46.2%
8616336	F/B BLUE HORIZON	177	2543.25	1829.00	1960.00	131.00	6.7%
9035876	F/B BLUE GALAXY	307	4415.00	2686.25	2651.38	-34:87	-1.3%

Table 21 compares the results of fuel consumption calculation for the five specific vessels for year 2020 following the bottom-up methodology described earlier in our case study and total fuel consumption reported by MRV. The annual total fuel consumption is presented separately for ME and AE. This separation is necessary later for accurately estimation of CO_2 air emissions, since ME and AE consume different type of fuel (0.5% and 0.1% sulphur content respectively) with different emission factor for each of them (3.114 or 3.206 respectively).

Table 21: Annual (2020) calculated total fuel consumption comparison with actual reported by MRV

IMO	Ship Name	ME Fuel (t)	%	AE Fuel (t)	%	Total (t)	MRV Total fuel consumption (t)	Difference
7814046	F/B KRITI I	1,940.13	67.69	925.94	32.31	2,866.07	2,652.90	-8.04%
7814058	F/B KRITI II	6,847.77	68.35	3,171.26	31.65	10,019.03	9,482.68	-5.66%
7907673	F/B EL.VENIZELOS	2,327.28	62.27	1,410.19	37.73	3,737.47	3,485.59	-7.23%
8616336	F/B BLUE HORIZON	4,613.60	81.25	1,064.55	18.75	5,678.15	5,354.22	-6.05%
9035876	F/B BLUE GALAXY	8,965.84	86.99	1,340.91	13.01	10,306.75	9,214.79	-11.85%

As depicted in Figure 14 there is increased consumption of fuel at ME (depending on ship it is from 62.27% to 86.99%) comparing to total fuel consumption. This is normal since ME are bigger engines in power (kW) and they need more fuel to operate (compared to AE). Actually ME power account for about 83.8% to 90% comparing to total and the rest percentage belongs to AE (table 18b).

Comparing the results of total fuel consumption from the bottom-up methodology and MRV report (Table 21) and as graphically presented in Figure 15 it is clearly inferred that total fuel consumption calculation has a small difference compared to actual fuel consumption (MRV). The variation is from -5.66% to -11.85% (Table 21-last column) and can be rated as particularly low.

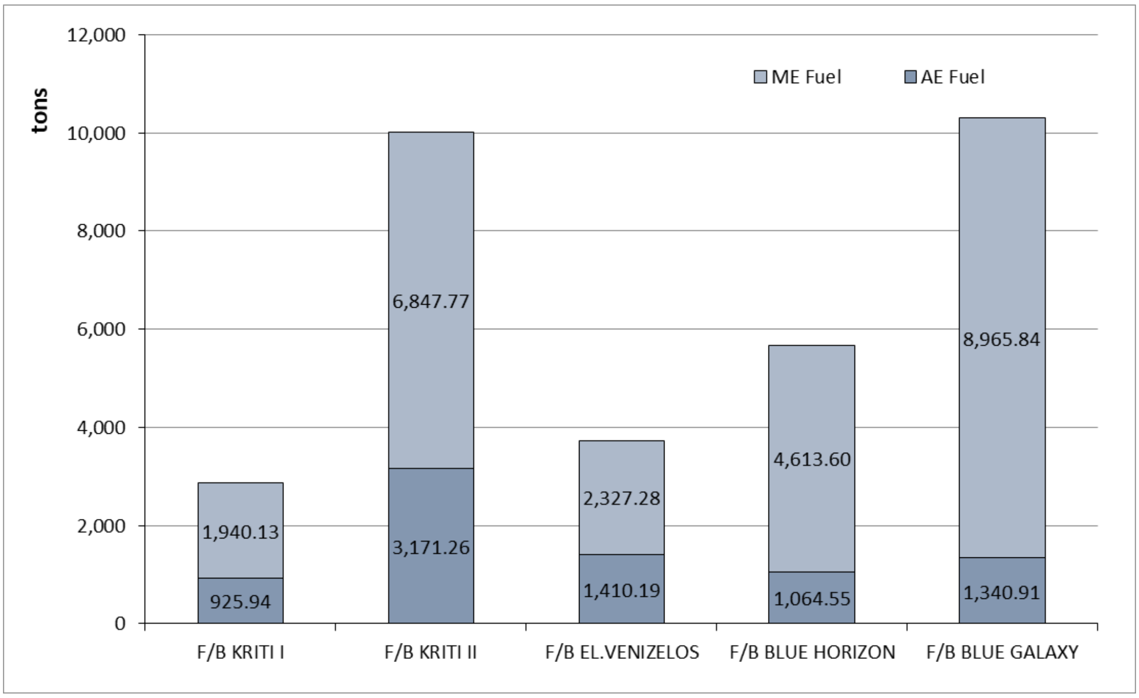


Figure 14: Bottom-up methodology results - Annual fuel consumption per ship and engine type

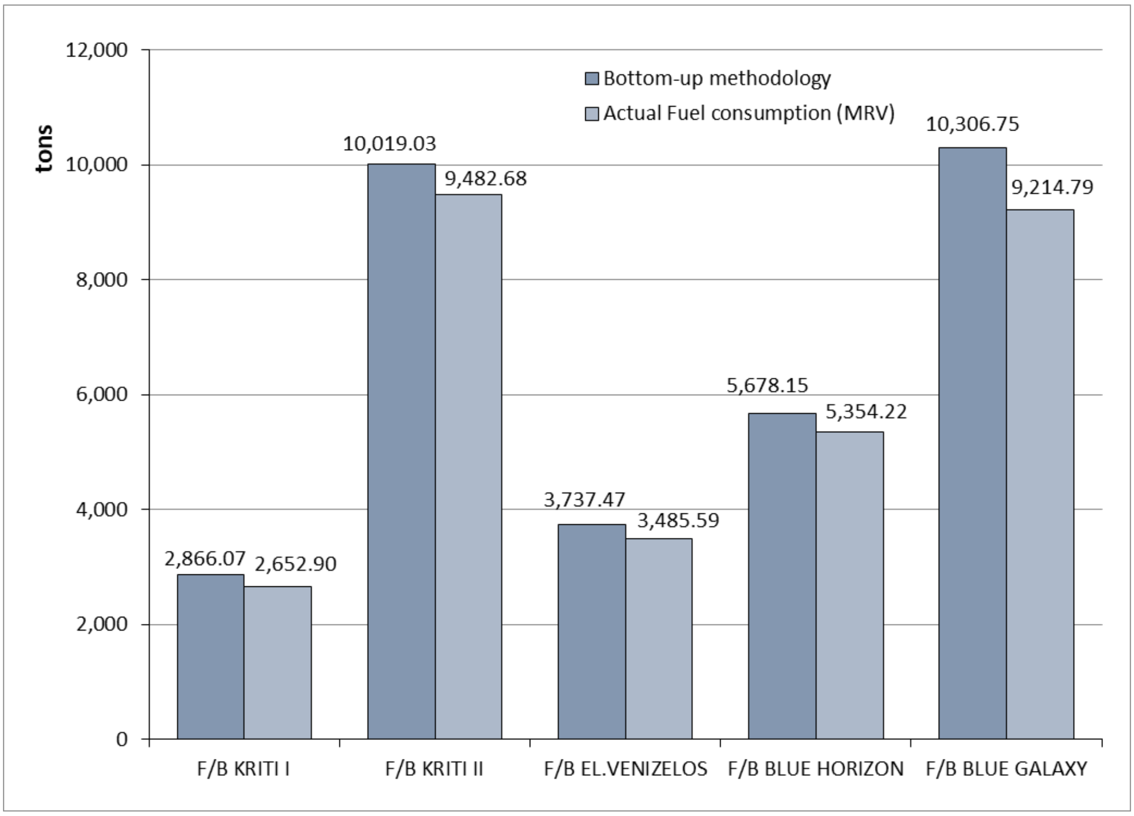


Figure 15: Comparison of total fuel consumption results of bottom-up methodology and MRV report

By multiplying the fuel consumption of each engine type (fuel type) by CO_2 emission factor (per fuel type) we finally estimate CO_2 emissions of fuel consumption. The estimation of CO_2 can allow the confirmation that the results of the presented methodology are very close to actual CO_2 emissions reported by MRV. These are depicted in Table 22 and presented in Figure 16, where it is observed that the difference between estimated and actual CO_2 emissions is very small and in similar levels of fuel consumption variation. By all these we can conclude that all parameters point to a successful application of the calculation methodology that leads to results very close to CO_2 emissions reports to MRV for the ships and ports in study.

Table 22: Passenger ferries total estimated CO_2 emissions comparison with actual reported by MRV

IMO Number	Ship Name	ME CO_2 (t)	AE CO_2 (t)	Total CO_2 (t)	CO_2 MRV (t)	Difference
7814046	F/B KRITI I	6,041.57	2,968.57	9,010.14	8327.70	-8.19%
7814058	F/B KRITI II	21,323.96	10,167.04	31,490.00	29634.66	-6.26%
7907673	F/B EL.VENIZELOS	7,247.15	4,521.06	11,768.21	10926.18	-7.71%
8616336	F/B BLUE HORIZON	14,366.75	3,412.95	17,779.70	16751.00	-6.14%
9035876	F/B BLUE GALAXY	27,919.61	4,298.97	32,218.58	28748.70	-12.07%

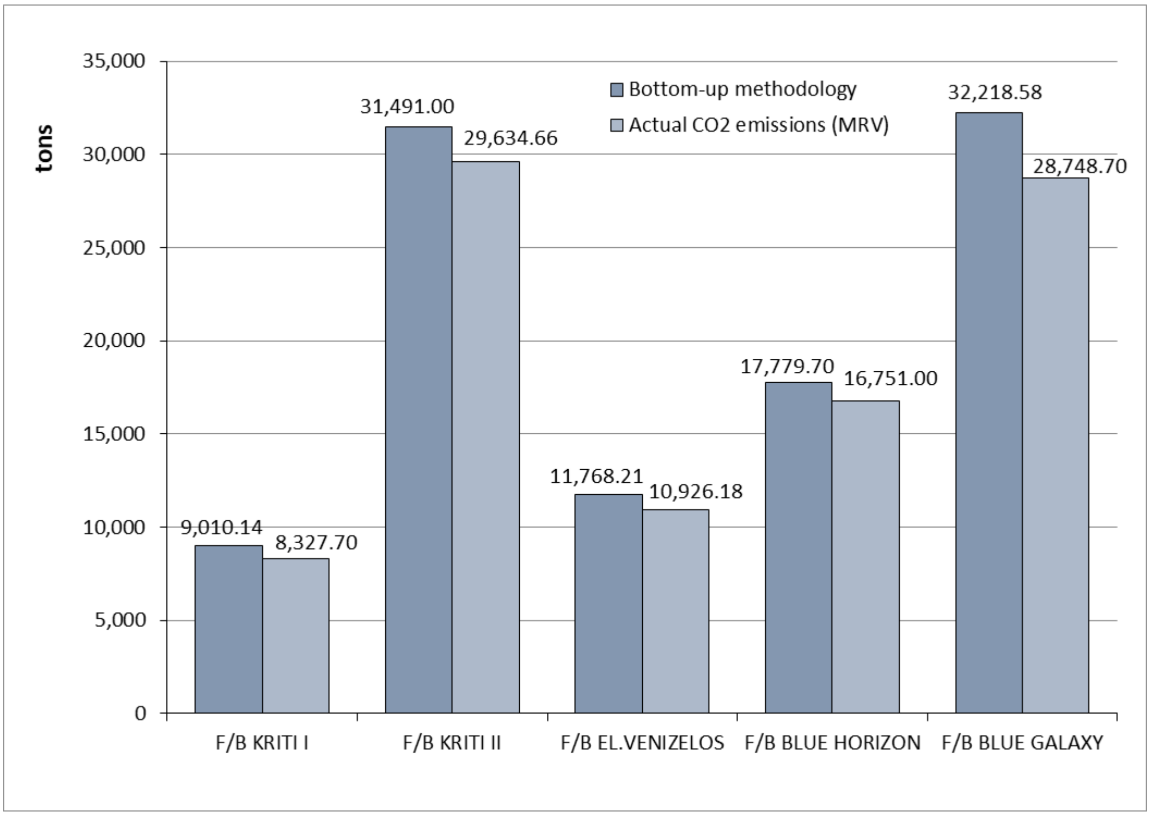


Figure 16: Comparison of total CO_2 emissions of bottom-up methodology and MRV report.

In paragraph 3.3 we examined four alternative scenarios on fuel consumption and air emissions estimation and in current paragraph we followed the methodology described as basic scenario (determining SFOC through regression analysis and ME, AE based on manufacturer's data). The rest three scenarios were using different typical methodologies of determining SFOC (through adjustment factors) ME, AE power and AE/ME ratio (using data based either on average World fleet or Mediterranean Sea fleet).

Different estimations on main parameters of the calculation methodology lead to different results and in the case of scenario for estimating SFOC through adjustment factors, provides higher fuel consumption values for both ME & AE, with significant difference for ME while for AE the values seem to be similar and in terms of the air emissions, seems to provide slightly higher air emissions values in total. In the case of scenarios for estimating SFOC through adjustment factors and ME, AE power and AE/ME ratio using data based on average World fleet and Mediterranean Sea fleet, both fuel and energy consumption is significantly underestimated and thus this results to significantly reduced air emissions.

Focusing on the results of the basic bottom-up methodology scenario of fuel consumption and CO_2 emissions of ships for year 2020 and comparing them to reported emissions data from EMSA/MRV-THETIS Database, we find that the difference for the total fuel consumption is about -5.66% to -11.85% and the difference for total CO_2 emissions is about -6.14% to -12.07%. As we understand from the comparison between the four scenarios, none of the alternatives is appropriate to be used for air estimation based on the itineraries, ships and ports in study.

CHAPTER 4: EXTERNAL COSTS ESTIMATION

4.1 The concept of external costs

An external cost (or externality), in general, is interpreted as the cost of the impacts that arise from the activities (social or economic) of a group of people to another group of people (CE Delft, 2019). External costs are not simple to calculate and they can be distinguished into seven categories: accident, noise, congestion, habitat damage, air pollution, climate change and well-to-tank emissions. In most cases, these costs are not taken into account by the group of people who cause them (Ramalho & Santos, 2021) and, for example, shipping companies argue that external costs should not be considered at all for their sector due to the social nature of their activities. This is certainly not very realistic, and even though maritime transportation promotes economic growth and removes isolation between islands or different geographic areas in general, it also contributes to the above-mentioned seven impact categories. In order to evaluate the costs and benefits of shipping to society, it is necessary to consider all benefits and costs, including the externalities.

Using market-based instruments to internalize external costs is generally regarded as an efficient way to limit the negative side effects of transport and/or to generate income for the government (CE Delft, 2019). Applying these instruments in an efficient way requires detailed and reliable estimates of external costs. This is the main objective of this study, which progresses compared to relevant previous studies and publications from the authors. The European Commission (EC) recently stated (European Commission, 2019) that the full impact of transport may only be accounted for by implementing the main principles of "polluter pays". This urges the internalization of external costs, which means making the transport user accountable for the full costs of their transport decisions. Towards this, the EC will propose to extend the European Emissions Trading System (ETS) and include the maritime sector, and to reduce the EU emissions trading system allowances allocated for free to airlines.

4.2 Air emission costs

This chapter focuses on the external costs due to air emissions from passenger ships (ferries and cruise vessels). As we described already in chapter 1, the air emissions from shipping can lead to various types of damage, with the most relevant being the health impacts due to air pollutants. Further, also relevant is the damage caused to various buildings and monuments, biodiversity and crop losses.

Hofbauer and Putz (Hofbauer & Putz, 2020), in their recent publication, presented a literature review to estimate the number of studies found in academic databases dealing with external costs for the transportation sector and identified the most commonly used external cost calculation methods for inland waterways. The results show that while there is already a significant amount of papers dealing with the external costs for road (556) and rail (242), the amount of papers focused on external costs for shipping is rather low (i.e., 20 for inland waterways and 30 for maritime transport). Thus, it is clear that there is available research space for more studies on the external costs of shipping with suitable and original case studies. Further, as far as we know, by the time of this analysis, there has been no recent similar study for passenger ships (both cruise and passenger ferries) for the presented ports. Additionally, it is always useful for the local communities to know the environmental burdens of specific sectorial activity (in our case ferries and cruise vessels), which promote economic development and growth, but ultimately, can cause external costs to local societies due to emitted air pollutants.

4.3 External Costs Estimation Methodologies

The externalities in this study cover health effects, materials and building damages, biodiversity and crop losses loss caused by air emissions. There are two levels of calculation, which results in the total external costs per pollutant and these are explained by the block diagram in Figure 17.

In the first level, we perform a calculation of the fuel/energy consumption of ports/ships in study (applying the bottom-up approach which extensively described in chapter 3) and in conjunction to specific emission factors (per emitted air pollutant) we calculate the total air emissions.

In the second level for the calculation of the total external costs, we use as input values the cost factor per pollutant which is originally calculated based on the New Energy Externalities Developments for Sustainability (NEEDS) approach and by taking into account the most recent results presented in the "Handbook on the external costs of transport" (CE Delft, 2019). This handbook was prepared for European Commission Directorate-General for Mobility and Transport and it presents the best practices on the methodology to estimate different categories of external costs of transport, extended to all EU member states, including emissions from other sources and maritime sector.

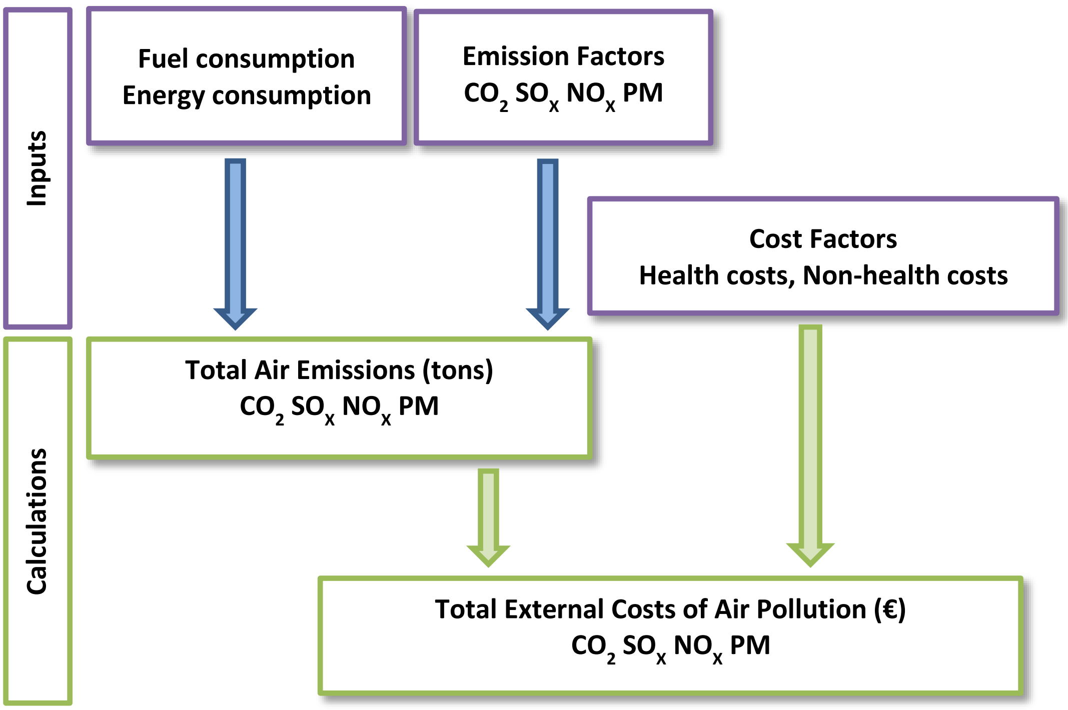


Figure 17: Total external costs methodological framework

The maritime sector and specifically the inland waterway transport is the part of the handbook that we focused on. The estimation of cost factors includes a broad update of the values originally provided by NEEDS. Overall, the cost factors per country and per air pollutant are derived from the updated cost factors, although further update is recommended, since NEEDS has not been updated and developed further from 2009. Additionally, the other similar method for estimation of cost factors, i.e., the “Clean Air for Europe” (CAFE) Program of the EU, was updated recently, as International Institute for Applied Systems Analysis (IIASA) reported (Amann & Wagner, 2014). For this reason the cost factors presented in NEEDS have been adjusted as presented in “Handbook on the external costs of transport” and in our detailed methodological approach.

4.4 Cost factors

In Table 23 (first line) we see the external cost factors for inland waterway transport of Greece, derived from CE Delft (CE Delft, 2019). “Metropole” applies to port-cities with more than 500 thousand residents, while “City” applies to population under 500 thousand and “Rural” area is named when the port is outside of city/metropole. In the first line of table 23 the cost prices are per kg of gaseous pollutants during the year 2016. Because our study focuses to the last five years (2017-2021) we have to adjust these cost prices using the country-specific Harmonized Index of Consumer Prices (HICP). For Greece the official authority to calculate and publish HICP is Hellenic Statistics Authority, which for 2016 published 100.02. From 2016 and following years (for 2017-2021) we filled in extra lines with HICP and adjusted cost prices.

Table 23: Greece’s air pollution external costs in **€/kg** emission for inland waterway transport

Year	HICP	SO_2	NO_X (City)	NO_X (Rural)	$PM_{2.5}$ (Metropole)	$PM_{2.5}$ (City)	$PM_{2.5}$ (Rural)	PM_{10} (Average)
2016(base)	100.02	5.90	5.10	3.10	267.00	86.00	33.00	8.50
2017	100.15	5.91	5.11	3.10	267.35	86.11	33.04	8.51
2018	100.94	5.95	5.15	3.13	269.46	86.79	33.30	8.58
2019	102.46	6.04	5.22	3.18	273.51	88.10	33.81	8.71
2020	101.17	5.97	5.16	3.14	270.07	86.99	33.38	8.60
2021	101.75	6.00	5.19	3.15	271.62	87.49	33.57	8.65

4.5 EU Emission Trading Scheme (ETS)

The overall EU policy regarding the reduction in maritime-originated GHG emissions focuses on the “polluters pay” principle and the implementation of the MRV system; the definition of reduction targets and the application of market-based measures (European Commission, 2013) aim at this direction with a long-term target on, including these in the EU ETS.

The estimated CO_2 emissions in this study seem to be a good proxy to calculate the anticipated future cost of CO_2 emissions. We could consider it as a variant of the avoidance cost approach but it is understandable that additional policy interventions are required to force users to switch to different forms of fuels and energy resources in general.

Figure 18 shows the analytical development of the market price of CO_2 emissions (€/tCO_2), data provided by European Energy Exchange (EEX), where the increasing trend is obvious until the end of

2020 and the strong increase for year 2021.

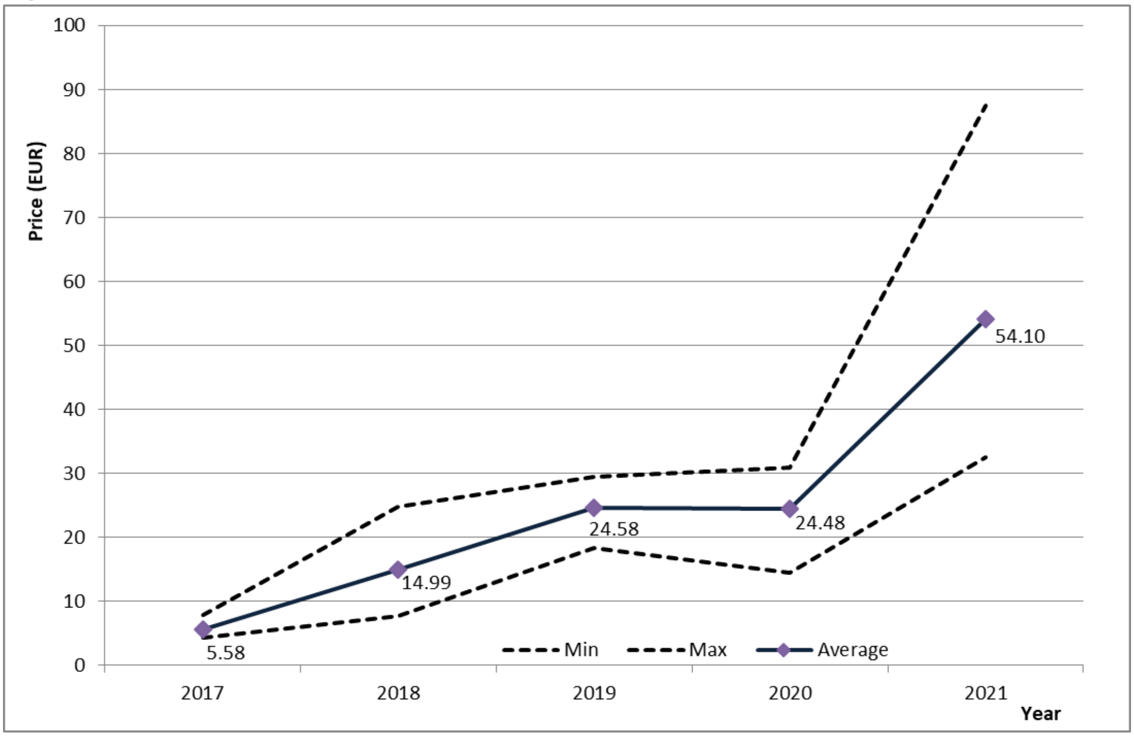
Figure 18: EEX Emissions CO_2 market (2017-2021 average price in €)

At this point, we have to clarify that this price is the CO_2 emissions cost and not "Carbon cost", since 3.67 tons of CO_2 emissions are equivalent to one ton of carbon (OECD, 2016a). The air emissions estimation results (chapter 3) presented annual CO_2 emissions and the annual average market price was taken into account. In Table 24 and Figure 19, the annual market price cost of CO_2 in EUR/t CO_2 for years 2017 to 2021 is presented. We observe a significant annual increase, even from year to year (+168.6% from 2017 to 2018, +68% from 2018 to 2019 and +121% from 2020 to 2021) or from the first year 2017 (+340.5% from 2017 to 2019, +869.5% from 2017 to 2021).

Table 24: EEX Emissions CO_2 market price for years 2017-2021 in €/tCO_2 (EEX, 2022)

Year	Min (€/tCO_2)	Max (€/tCO_2)	Average (€/tCO_2)	Variation from Previous year (%)	Variation from 2017 (%)
2017	4.30	7.87	5.58		
2018	7.65	24.86	14.99	+168.6	
2019	18.33	29.42	24.58	+64.0	+340.5
2020	14.47	30.93	24.48	-0.4	+338.7
2021	32.61	87.48	54.10	+121.0	+869.5

Figure 19: Annual EEX Emissions CO_2 market price (2017-2021, min, max and average price in €)



4.6 External Costs Estimation

4.6.1 Air emissions

As depicted in table 16, CO_2 emissions are the vast majority of all other gas emissions in study. Actually they account for about 97-98% in terms of total air emissions every year. 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). So obviously CO_2 is not a pollutant and we have to present it separately. The detailed annual CO_2 air emissions quantities during five years period 2017-2021 are graphically presented in figure 8.

Gaseous pollutants SO_X, NO_X, $PM_{2.5}$ and PM_{10} are also depicted in Table 16 and Figure 10 presents the quantity of air pollutants (NO_X, SO_X, $PM_{2.5}$, PM_{10}) for the five years in study.

4.6.2 External costs

Applying the methodology described in paragraph 3.2 and by combining table 16 (air emissions) table 23 (air pollution cost factors) and table 24 (average CO_2 market price) leads to the estimation of air pollutants' external costs. The results depicted in table 25a (cruise sector) and 25b (passenger ferries sector).

Figure 20 presents the external costs in EUR per ship call, and it is evident that the sector of passenger ferries at Heraklion port leads for all years, followed by the cruise sector at Souda port (for 2017–18–19) and cruise at Heraklion port (for 2020–21). For Souda port, the cruise sector leads with a wider difference for years 2017–18–19 and a small difference for the last year 2021.

As we notice from the air emissions results (Table 16) there was a significant reduction for SO_X and PMs for 2020-21 due to new regulations initiated from 2020 (scrubbers, 0.5% S fuel). This reduction affected external costs also, even if at the last year (2021) CO_2 price was +121% higher.

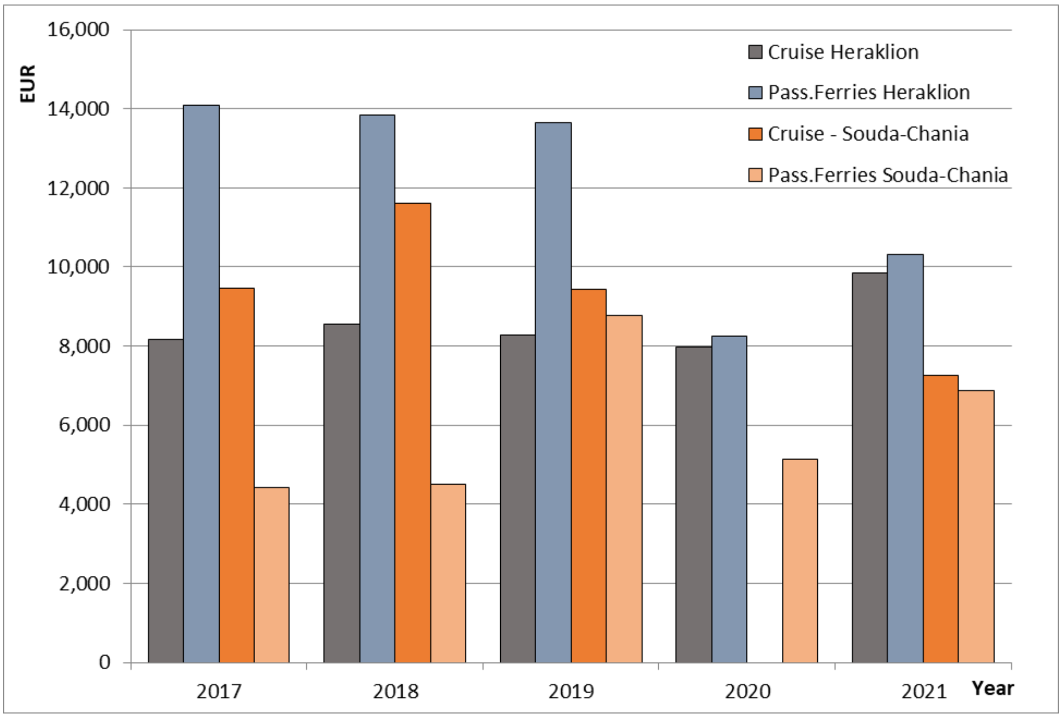


Figure 20: External costs in € per ship call (2017-2021 for passenger ferries and cruise ships)

Table 25a: Air emissions externalities for cruise sector of ports Souda and Heraklion

Year	Port	Ship calls	CO_2 (€)	SO_X (€)	NO_X (€)	$PM_{2.5}$ (€)	PM_{10} (€)	Total (€)	Externalities per ship call (€)
2017	Souda	89	22,128.15	118,369.90	364,733.01	333,481.46	2,865.83	841,578.35	9,455.94
	Heraklion	129	28,460.98	129,676.67	509,823.88	382,819.91	3,289.82	1,054,071.26	8,171.10
2018	Souda	80	68,670.04	116,048.24	414,308.20	326,579.29	2,807.43	928,413.19	11,605.16
	Heraklion	188	122,684.28	151,557.98	829,246.10	501,255.48	4,309.02	1,609,052.87	8,558.79
2019	Souda	148	147,608.71	177,559.80	587,383.39	481,044.66	4,135.52	1,397,732.08	9,444.14
	Heraklion	204	206,091.65	158,485.30	824,735.95	493,608.37	4,243.53	1,687,164.80	8,270.42
2020	Souda	0	-	-	-	-	-	-	-
	Heraklion	19	36,550.26	2,852.98	67,517.90	44,299.72	380.83	151,601.68	7,979.04
2021	Souda	70	185,591.22	6,588.04	208,622.98	106,288.12	913.79	508,004.14	7,257.20
	Heraklion	116	393,768.38	14,101.34	497,205.97	236,237.65	2,031.00	1,143,344.34	9,856.42

Table 25b: Air emissions externalities for passenger ferries of ports Souda and Heraklion

Year	Port	Ship calls	CO_2 (€)	SO_X (€)	NO_X (€)	$PM_{2.5}$ (€)	PM_{10} (€)	Total (€)	Externalities per ship call (€)
2017	Souda	382	56,192.11	180,261.68	945,440.72	502,320.85	4,316.77	1,688,532.13	4,420.24
	Heraklion	690	210,223.61	1,683,750.39	3,424,553.70	4,361,635.10	37,482.41	9,717,645.20	14,083.54
2018	Souda	536	177,453.58	309,871.90	1,110,530.98	816,949.37	7,022.87	2,421,828.70	4,518.34
	Heraklion	731	558,492.25	1,710,003.49	3,406,769.74	4,400,244.95	37,826.54	10,113,336.98	13,834.93
2019	Souda	709	597,203.67	941,058.00	2,233,870.96	2,423,568.90	20,835.30	6,216,536.84	8,768.04
	Heraklion	745	885,742.94	1,661,924.97	3,330,075.83	4,246,471.25	36,506.70	10,160,721.69	13,638.55
2020	Souda	677	537,771.02	84,548.36	2,017,762.39	834,327.89	7,172.46	3,481,582.12	5,142.66
	Heraklion	722	927,113.29	113,388.98	3,465,418.71	1,437,278.01	12,355.83	5,955,554.82	8,248.69
2021	Souda	683	1,346,140.60	89,081.16	2,304,611.58	954,338.26	8,204.69	4,702,376.29	6,884.88
	Heraklion	707	2,110,931.74	106,254.73	3,593,428.12	1,462,692.28	12,575.14	7,285,882.01	10,305.35

4.7 Understanding the financial cost of externalities

One way to understand the true cost of the externalities is by comparing them with the shipping companies' revenues and estimate the impact they would incur if they were asked to pay this cost. Currently, this comparison is possible only for the passenger ferries sector, since there are publicly available data: average ticket fare price per transportation category of passengers, vehicles and cargo vessels, shipping companies' annual financial statements and/or info from travel agents, which allows the calculation of the annual revenue per transportation category and route line (Table 26).

Table 26: Annual revenue per transportation category for passenger ferries

Year	Port	Ship Calls	Passengers		Vehicles		Cargo Vehicles		Total Revenue (€)
			Quantity	Price (€)	Quantity	Price (€)	Quantity	Price (€)	
2017	Souda	382	379,553	26.58	60,457	44.96	26,530	220.90	18,854,631.91
	Heraklion	690	523,448	25.33	77,637	44.72	59,804	250.49	31,941,528.12
2018	Souda	536	439,043	26.54	69,287	42.30	30,067	199.24	20,486,784.86
	Heraklion	731	500,163	24.55	76,490	42.89	59,138	249.97	30,643,770.70
2019	Souda	709	463,669	26.95	78,669	36.24	33,431	207.08	22,363,264.02
	Heraklion	745	550,590	21.40	86,530	38.63	57,607	255.69	29,908,545.52
2020	Souda	677	224,707	29.79	47,503	38.64	29,150	218.50	14,940,490.81
	Heraklion	722	271,103	23.64	53,744	40.59	54,309	256.19	22,654,566.23
2021	Souda	683	269,259	31.90	65,922	39.59	33,009	219.20	18,415,386.68
	Heraklion	707	311,596	25.90	71,591	42.11	62,237	258.78	27,361,421.93

Table 27 depicts the total annual revenue and by combining the externalities per port and year, we can derive some important findings (blue columns). Thus, the externalities represent a significant amount of total revenue (about 25–35% from 2019 to 2021), which about 7-8% (for year 2021) comes from CO_2 external cost and the rest from NO_X, SO_X, PM.

Table 27: Annual revenue and external costs for passenger ferries

Year	Port	Ship Calls	Revenue Total (€)	Externalities					
				CO_2 (€)	CO_2 (%)	NO_X, SO_X, PM (€)	NO_X, SO_X, PM (%)	Total (€)	Total (%)
2017	Souda	382	18,854,631.91	56,192.11	0.3	1,632,340.02	8.7	1,688,532.13	9.0
	Heraklion	690	31,941,528.12	210,223.61	0.7	9,507,421.60	29.8	9,717,645.20	30.4
2018	Souda	536	20,486,784.86	177,453.58	0.9	2,244,375.12	11.0	2,421,828.70	11.8
	Heraklion	731	30,643,770.70	558,492.25	1.8	9,554,844.72	31.2	10,113,336.98	33.0
2019	Souda	709	22,363,264.02	597,203.67	2.7	5,619,333.16	25.1	6,216,536.84	27.8
	Heraklion	745	29,908,545.52	885,742.94	3.0	9,274,978.75	31.0	10,160,721.69	34.0
2020	Souda	677	14,940,490.81	537,771.02	3.6	2,943,811.10	19.7	3,481,582.12	23.3
	Heraklion	722	22,654,566.23	927,113.29	4.1	5,028,441.53	22.2	5,955,554.82	26.3
2021	Souda	683	18,415,386.68	1,346,140.60	7.3	3,356,235.69	18.2	4,702,376.29	25.5
	Heraklion	707	27,361,421.93	2,110,931.74	**7.7**	5,174,950.27	**18.9**	7,285,882.01	**26.6**

That means if shipping companies are called to pay for these costs, then a significant revenue loss will occur. Most likely, this is not something that ship owners could absorb and they would probably pass this cost to ticket fares and adopt it as "Externalities Surcharge". From this point of view, this "Externalities Surcharge" was estimated and we decided to estimate separately the "expected externalities surcharge" due to CO_2 and "indirect externalities surcharge" due to NO_X, SO_X, and PM. The cost of CO_2 is the most immediate and feasible to pay, since there is a statutory procedure and way if the sector joins the CO_2 trading system and that's why we call it as "expected". In the other hand the cost of gaseous pollutants NO_X, SO_X and PM, is not something that is paid until now and there is no system that charges these pollutants.

Assuming that the total annual revenue represents the total annual external costs, then according to the revenue sharing per transportation category and year, we can share the external costs. According to the data of table 26 by multiplying quantity and average price (€) for each transportation category we calculate the percentage of annual revenue sharing which is depicted to table 28.

Table 28: Annual revenue sharing per transportation category of passenger ferries

Year	Port	Passengers %	Vehicles %	Cargo Vehicles %
2017	Souda	54.2%	14.7%	31.1%
	Heraklion	42.0%	11.1%	46.9%
2018	Souda	56.9%	14.2%	28.9%
	Heraklion	40.7%	11.0%	48.3%
2019	Souda	56.3%	12.7%	31.0%
	Heraklion	39.6%	11.2%	49.2%
2020	Souda	45.2%	12.3%	42.5%
	Heraklion	28.9%	9.7%	61.4%
2021	Souda	46.5%	14.1%	39.3%
	Heraklion	30.0%	11.1%	58.9%

By combining the above data with annual external costs of passenger ferries (Table 25b), we can estimate the total annual external cost per transportation category (Table 29).

Table 29: Passenger ferries total annual external costs per transportation category

Year	Port	Passengers €	Vehicles €	Cargo Vehicles €
2017	Souda	914,974.03	248,452.75	525,105.35
	Heraklion	4,077,030.88	1,082,065.49	4,558,548.83
2018	Souda	1,379,052.53	343,807.97	698,968.21
	Heraklion	4,116,792.29	1,114,360.19	4,882,184.49
2019	Souda	3,499,181.43	789,317.74	1,928,037.67
	Heraklion	4,024,674.45	1,134,300.26	5,001,746.98
2020	Souda	1,572,985.68	428,022.32	1,480,574.11
	Heraklion	1,718,974.43	579,360.60	3,657,219.80
2021	Souda	2,188,378.56	663,637.69	1,850,360.03
	Heraklion	2,187,078.84	809,982.08	4,288,821.08

By this, it is possible to make an approach to the "Externalities surcharge", by dividing the external cost amount, in EUR, of each category by its transportation units, provided by Table 26 and then share by the percentages provided in Table 27 for CO_2 and NO_X, SO_X, PM. This is depicted in Table 30a for Souda port and 30b for Heraklion port, where we observe a remarkable additional amount and corresponding surcharge percentages for each category (especially for the last year 2021).

Table 30a: Passenger ferries additional fare cost per transportation unit for Souda port

	Passengers		Vehicles		Cargo Vehicles	
Year	CO_2	NO_X, SO_X, PM	CO_2	NO_X, SO_X, PM	CO_2	NO_X, SO_X, PM
2017	0.08€ (+0.3%)	2.33€ (+8.8%)	0.14€ (+0.3%)	3.97€ (+8.8%)	0.66€ (+0.3%)	19.13€ (+8.7%)
2018	0.23€ (+0.9%)	2.91€ (+11.0%)	0.36€ (+0.9%)	4.60€ (+10.9%)	1.70€ (+0.9%)	21.54€ (+10.8%)
2019	0.72€ (+2.7%)	6.82€ (+25.3%)	0.96€ (+2.7%)	9.07€ (+25.0%)	5.54€ (+2.7%)	52.13€ (+25.2%)
2020	1.08€ (+4.6%)	5.92€ (+19.9%)	1.39€ (+3.4%)	7.62€ (+19.7%)	7.85€ (+3.1%)	42.95€ (+19.7%)
2021	2.33€ (+7.3%)	5.80€ (+18.2%)	2.88€ (+7.3%)	7.19€ (+18.1%)	16.05€ (+7.3%)	40.01€ (+18.3%)

Table 30b: Passenger ferries additional fare cost per transportation unit for Heraklion port

	Passengers		Vehicles		Cargo Vehicles	
Year	CO_2	NO_X, SO_X, PM	CO_2	NO_X, SO_X, PM	CO_2	NO_X, SO_X, PM
2017	0.17€ (+0.7%)	7.62€ (+30.1%)	0.30€ (+0.7%)	13.64€ (+30.5%)	1.65€ (+0.7%)	74.58€ (+29.8%)
2018	0.45€ (+1.9%)	7.78€ (+31.7%)	0.80€ (+1.9%)	13.76€ (+32.1%)	4.56€ (+1.8%)	78.00€ (+31.2%)
2019	0.64€ (+3.0%)	6.67€ (31.2%)	1.14€ (+3.0%)	11.97€ (+31.0%)	7.57€ (+3.0%)	79.26€ (+31.0%)
2020	0.99€ (+4.2%)	5.35€ (+22.6%)	1.68€ (+4.1%)	9.10€ (+22.4%)	10.48€ (+4.1%)	56.86€ (+22.2%)
2021	2.03€ (+7.9%)	4.99€ (+19.2%)	3.28€ (+7.8%)	8.04€ (+19.1%)	19.97€ (+7.7%)	48.95€ (+18.9%)

4.8 Discussion on external costs results

The main objective of this chapter is to present an analytical methodological framework to estimate the external costs of air emissions from passengers shipping. The ports under study reported significant decreased cruise ship calls during the last two Covid-19 years 2020, 2021 (2020 comparing to 2019: -90.7% for Heraklion and -100% for Souda and 2021 comparing to 2019: -43.1% for Heraklion and -52.7% for Souda) and this affected to fuel and energy consumption also. Although the assumption that passenger ferries' ship calls would decrease due to Covid-19 as happened with cruise sector seemed reasonable, finally the observed reduction is not so significant (2020 comparing to 2019: -3.1% for Heraklion and -4.5% for Souda and 2021 comparing to 2019: -5.1% for Heraklion and -3.7% for Souda).

Due to our study it is evident that even if the trend of all types (passengers, vehicles, cargo) from 2017 to 2019 is increased, in 2020 there is a significant decrease especially to passengers (around 50% for both ports) and vehicles (-39.6% for Souda and -37.9% for Heraklion), due to Covid-19 applied travel restrictions and the insecurity of people to move freely.

Even 2021 was not a recovery year since significant reduction occurred: passengers -41.9% for Souda and -43.4% for Heraklion, vehicles: -16.2% for Souda and -17.3% for Heraklion. After 2019, cargo vehicles had a decrease also, but not so large (2020: -12.8% for Souda and -5.7% for Heraklion, 2021: -1.3% for Souda and +8% for Heraklion) like passengers and vehicles.

The most fuel/energy consuming sector and as a consequence the air emissions sector per ship call differs for the two ports: the passenger ferries dominate in terms of fuel/energy consumption in Heraklion (until 2019) while for Souda cruise ships prevail for all years. For years 2020 and 2021 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.

The externalities in study cover health effects impacts, materials and building damages, biodiversity and crop losses loss caused by the air emissions. We also examined and presented annual CO_2 emissions and calculated the annual market price cost of CO_2 for years 2017 to 2021, where we see significant annual increase, even annually (+168.6% from 2017 to 2018, +68% from 2018 to 2019 and +121% from 2020 to 2021) or from the first year in study (+340.5% from 2017 to 2019, +869.5% from 2017 to 2021).

The external costs in € per ship call evident that constantly at the first place for all years and all ports is the sector of passenger ferries at Heraklion port followed by cruise sector at Souda port (for 2017-18-19) and cruise at Heraklion port (for 2020-21). For Souda port cruise sector is at the first place with wider difference for years 2017-18-19 and small difference for the last year 2021. As we noticed, SO_X and PM's significantly reduced for 2020-21 due to new regulations initiated from 2020 (scrubbers, 0.5% S fuel). This reduction affected external costs also, even if at the last year (2021) CO_2 price was +121% higher.

From all the above we conclude that externalities is a significant amount and in comparison with revenues it ends up being about 25-35% for the last years of our study (2019 and after). Obviously is a significant revenue loss for shipping companies and assuming that ship-owners will pass these costs to ticket fares, an attempt was made to estimate "Externalities surcharge" (which we define it as the burden of external costs to ticket fares per transportation category). "Externalities surcharge" estimation indicates a significant additional ticket cost and specifically for the last year 2021:

- Souda, about +25.5% to all transportation categories: +8.13 € for passengers, +10.07 € for vehicles and +56.06 € for cargo vehicles,
- Heraklion, about +26.6 to +27% to all transportation categories: +7.02 € for passengers, +11.31 € for vehicles and +68.91 € for cargo vehicles.

CONCLUSIONS

Ports and shipping activities are essential for global economic activity. Despite this important place they hold in our international economy, ports and the shipping industry create harmful air pollutants and particles which negatively impact human and marine health, the surrounding air, and the environment. Ports and the shipping industry both impact air quality; however, both can take action to improve their harmful emissions near coastal towns and cities

Nowadays with even more tightening regulations for the shipping industry and increased public concern for the environment, keeping close tabs on what vessels are emitting has become more important than ever. As we see in current study top-down air emission estimation methodology and specifically the basic scenario is a reliable approach to quantify the air emissions from ships. Until now air emissions were monitored in some ports through specific procedures from port state control. Checking is done at the port, with inspectors boarding a ship usually chosen at random or because of suspicious indicators (e.g. smoke darkness or quantity).

Regulatory enforcement is certainly the main driver for ship emissions monitoring, but there are also significant efforts being put into tracking emissions that aren't currently regulated at all, namely CO_2. Awareness and concern about the impact of greenhouse gasses, of which CO_2 is the prime culprit, have reached all levels of the industry. Monitoring the combined carbon output of the global fleet has thus far been done using a bottom-up approach, with owners and operators of vessels larger than 5,000 GT required to report fuel consumption and CO_2 emissions to both the IMO and the EU.

Apart from these the most harmful and most regulated gases in shipping industry, are SO_X and PM and nevertheless are not monitored from EU or IMO. SO_X and PM emissions are directly dependent on the Sulphur content of the fuel. For ships that do not have emission reduction devices (scrubbers) installed, the emissions can be derived from the BDN reports and a fuel sample from the fuel tank to verify and confirm Sulphur content. This is an easy way of monitoring emissions because anything that goes into the ship as fuel, burned in the engine and is coming out as exhaust. The fuel sample is examined through a certified lab to extract the fuel's Sulphur percentage to see whether it complies with regulated limits – 0.1% for ports or Sulphur Emissions Control Areas (SECAs) and 0.5% everywhere else. The challenge for the maritime industry is to use alternative, greener and more expensive fuels or alternatively exhaust gas treatment systems (scrubbers). Of course all these are extra costs that ship-owners are facing or will face in the future.

Air quality standards are a major priority for European and American ports. With standards becoming stricter, it is important that ports and shipping companies know their air quality impact in real-time. Ports have a key role for the economy, so it is important that they monitor air quality to ensure they comply with regulations for continued activity by knowing the exact source of pollutants and how to reduce them before it becomes a problem. When ports care about how their activities are impacting air quality, they gain more community support for their activities. This improves the image of the port authorities. For example, when an air-polluting event occurs, port authorities are notified in real-time and can handle this event quickly.

Ports are adopting air quality monitoring systems to have real-time information about the current air quality of their port and surrounding area. With environmental monitoring systems, port authorities can monitor air quality impacts in real-time, in turn helping the surrounding community. To improve air quality, ports need to know the cause of pollution. Once the source is identified, ports can then develop a strategy to reduce pollution.

By implementing an air quality monitoring system, ports can see real-time key indicators which give them situational awareness of all activities. Ports can see which activities could increase air pollution during which time periods, allowing them to use concrete data to make key decisions and be more aware of which activities are causing harm.

Other more hi-tech monitoring procedures are monitoring emissions through optical sensors. This method is getting some space while experimental applications with passive measurement systems are operating nowadays. Solar light is reflected on the ocean, and it's reflecting up into sensors in telescopes that there are on an aircraft. From this, the scientists can see the ratio of SO_2 to CO_2. The more close-up tools for checking are ships sensors that come into contact with the exhaust itself. Flying sensor-equipped drones can measure air emissions near ships' plumes or, as they are in Denmark and Germany, air emissions sensors can be mounted under bridges where ships should pass to approach port. The one drawback of all these high-tech solutions is that they are a few years ahead of the legislation. Courts in the EU and elsewhere cannot accept these findings as proof on their own, so the systems are mainly used as indicators, showing Port State Control officers where to target their onboard fuel checks.

For the other highly-regulated types of emissions, NO_X policing is more complicated. Neither NO_X is monitored from EU or IMO. Though technically speaking, optical and sensor monitoring of NO_X can be done in the same way as with SO_X, NO_X emissions allowances for each ship depends on the engine type, year of build and other factors. For this reason, NO_X controls typically happen at the stage of engine installation.

In this study we presented in detail all the main parameters, i.e. engine load, SFOC, emissions factors, included in existing methodologies for calculating ships' on-board emissions and emphasized on the importance of having accurate SFOC values especially for low engine load levels. The proposed technical approach to define SFOC via publically available operational data was compared to typical methodologies (i.e. application of adjustment factors either on manufacturers' values or on IMO/ENTEC data) and the results indicated that the application of adjustment factors leads to systematically overestimated SFOC values especially during the "hoteling" phase.

A detailed comparative analysis has been performed between different approaches for calculating on-board ship's emissions and fuel/energy consumption, mainly focusing on the effect of SFOC and engine power in the obtained results. The most accurate estimations were performed when SFOC was calculated based on a regression analysis on widely available engines' technical data, and this was considered as the basic scenario for comparison to alternative approaches. The use of SFOC values calculated through adjustment factors applied on engines' data resulted in average energy consumption identical for all sectors and ports, while in terms of air emissions it provided slightly higher values in total. On the other hand, when the SFOC values were calculated through adjustment factors and the ME power was estimated via ship's GT (using data based either on average World fleet or Mediterranean sea fleet), both fuel and energy consumption were underestimated thus leading to a significant underestimation of air emissions. The basic scenario reflects a complete methodological framework that various stakeholders can follow to conduct air emissions calculations based on ships' operational data.

Regarding the comparison between passenger ferries or cruise vessels for the studied ports, in terms of air emissions the results from the current study clearly show that the most polluting sector differs for the two ports: passenger ferries dominate in Heraklion (until 2019) while for Souda cruise ships prevail for all years. For years 2020 and 2021 Heraklion cruise has a significant increase on air emissions per ship call in port and as we observe from our dataset this is due to longer average duration of stay at port for the cruise vessels. Longer stay means more fuel/energy consumption and air emissions at port.

Focusing on the results of the basic bottom-up methodology scenario of fuel consumption and CO_2 emissions of ships and comparing them to the most recent annually reported emissions data from EMSA/MRV-THETIS Database, we find that the difference for the total fuel consumption is about -5.66% to -11.85% (MRV reported is less) and the difference for total CO_2 emissions is about -6.14% to -12.07% (MRV reported is less) which we characterize it as particularly low. Because the results of the basic scenario are very close to the reported data and as we saw from the comparison between the four scenarios the alternatives are significantly underestimating both fuel/energy consumption and air emissions we conclude that none of them is accurate for current case study and only basic scenario is appropriate to be used for air emissions estimation based on the itineraries, ships and ports in study.

By estimating the external costs for the air emissions we notice that this cost is a significant amount of the shipping companies revenues and as we calculated it ends up being about 25-35% for the last years of our study (2019 and after). Obviously this is a significant revenue loss for shipping companies and assuming that ship-owners will pass these costs to ticket fares, an attempt was made to allocate the "externalities surcharge": the burden of external costs to ticket fares per transportation category.

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CURRICULUM VITAE

EMMANOUIL DOUNDOULAKIS

Personal Info

Born December 1970, lives at Chania Crete Greece

LinkedIn profile : https://www.linkedin.com/in/emmanouil-doundoulakis-212ab92b/

Working experience

February 2001 – present, **ANEK Lines S.A. (www.anek.gr)**

Senior Software Developer – Project Manager

Since January 2003 is the head responsible officer of the Software development department, under the IT Division, with the following responsibilities :

- Development/maintenance and support of the company's software for head offices, head-quarters, travel agencies and ships
- Project manager of BTS online booking ticketing system, for ANEK Lines group of companies: ANEK Lines, AIGAION Pelagos, ANEK-SUPERFAST Joint-Venture (technologies used : Oracle DB, Oracle RAC, Oracle Application Server, Oracle Forms, Oracle PL/SQL, XML Webservices, Java, Javascript)
- Website Development (INTERNET and INTRANET based)

October 2020 – present, **Merchant Marine Academy of Crete (Dept of Marine Engineers)** - seasonal

Laboratory Associate - Electrical & Automation Engineer

- Theory of Electric Circuits, Electric Machines I & II, Digital Circuits-PLC, Automatic control systems, Hydraulic-Pneumatic systems

May 1996–February 2001, **Mediterranean Agronomic Institute of Chania (www.maich.gr)**

IT Systems Specialist

Research Experience

- "Smartgreen" project, Technical University of Crete
- "Synthesis" project, under the EU program Marco Polo II (ANEK Lines)
- Design and Programming of the IT part of the European program DIMITRA Project for finding and displaying optimal channels for distribution of agricultural products (MAICh)
- Analysis, design and programming of a data bank according to EU measure 8.3 "Export Promotion" to support export activities of agricultural products (Hellenic Ministry of Agriculture, Agricultural Policy & Documentation Department) (MAICh)

- Design and Programming a multimedia CD-ROM for e-learning on Food-Quality Management. Developed under the needs of a European program entitled "Food Internet-based Distance European Learning (F.I.D.E.L.)" and the e-lesson entitled "Human Resource Management". It is entirely in English language and works on all major OS (Windows, Unix, Mac) (MAICh)

Seminars-Conferences

6th HAEE Energy Transition Symposium

Sep 30, 2021

Hellenic Institute of Acoustics (EL.IN.A.)

08/10/2019-09/10/2019, Conference «Acoustics 2018» organized by EL.IN.A. in collaboration with the University of Patras

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Academic Studies

October 2018 – September 2022, Technical University of Crete (www.tuc.gr)
PhD - School of Production Engineering & Management
PhD Thesis title : "Comparison of methodologies for the calculation of air emissions in shipping. Model development and optimization of fuel consumption"

September 2015 – May 2020, Hellenic Open University (www.eap.gr)
Msc "Quality Management and Technology"
Master Thesis title : "Environmental Port Management. Recognition, quantification and policies to reduce the environmental impact of the operation of the major ports of Crete"

September 2015 – April 2018, Technical University of Crete (www.tuc.gr)
Msc "Production Engineering & Management"
Master Thesis title : "Comparison of methodologies for the calculation of air emissions in shipping"

October 1989 – May 1994, Piraeus University of Applied Science
Bsc "Automation Engineer"

Publications

Doundoulakis, E. & Papaefthimiou, S. (2022) "**Comparative analysis of fuel consumption and CO_2 emission estimation based on ships activity and reported fuel consumption: the case of short sea shipping in Crete**", Greenhouse Gases: Science and Technology – *Accepted 19/7/2022*

Doundoulakis, E., Papaefthimiou, S. & Sitzimis, I. (2022) "**Environmental impact assessment of passenger ferries and cruise vessels: the case study of Crete**", European Transport\Trasporti Europei. http://dx.doi.org/10.48295/ET.2022.87.2

Doundoulakis, E. & Papaefthimiou, S. (2022) “**Estimation of externalities of major ports of Crete: Analytical methodological framework**”, Climate Journal 10(7), 100. https://doi.org/10.3390/cli10070100

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Doundoulakis E. & Papaefthimiou S. (2020) “**Ancillary Benefits of Climate Policies in the Shipping Sector**” In: Buchholz W., Markandya A., Rübbelke D., Vögele S. (eds) Ancillary Benefits of Climate Policy. Springer Climate. Springer, Cham. https://doi.org/10.1007/978-3-030-30978-7_15