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QUALITATIVE AND QUANTITATIVE MODELING OF MARITIME AIR POLLUTANTS: CONTROL TECHNOLOGIES, ENVIRONMENTAL IMPACTS AND COST ASSESSMENT

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Title: Qualitative and quantitative modeling of maritime air pollutants: control technologies, environmental impacts and cost assessment.

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Abstract: This thesis examines the costs and benefits of reduction measures for the shipping industry. Also, this paper provides a wider viewpoint by integrating the technological cost of the reduction methods and the social environmental benefits from emission reduction. We quantitatively analyse the merits of the control methods available in marine air pollution control practice by using data based on already related studies. After that, detailed NO_x, SO_2 and $PM_{2.5}$ emissions have been estimated for cruise ships in the main Greek ports for the years 2013 and 2014. All the data used were, carefully collected from local Port authorities and compared with similar data of other sources to harmonize any discrepancies. Generally, it is quite difficult to find a general acceptable solution for every ship, because each ship has different needs. However, the results of our study showed that the most feasible and cost-effective technologies may be found among Sea Water Scrubbing, Selective Catalytic Reduction or LNG and Shore Side Power (Cold Ironing).

Keywords: Air pollution, Shipping emissions, Reduction technologies, Greek ports, Cruise ships, Social cost, NEEDS methodology, Net environmental profit

Language: English

Modality: Research Work

Περίληψη

Η περιβαλλοντική ευαισθησία έχει αυξηθεί ριζικά τα τελευταία χρόνια. Για το λόγο αυτό, έχουν καταβληθεί μεγάλες προσπάθειες σε παγκόσμιο επίπεδο για τον περιορισμό της ρύπανσης σε όλες τις μορφές της. Η παρούσα διπλωματική εργασία έχει ως αντικείμενο τη μελέτη των αέριων ρύπων που οφείλονται στον τομέα της ναυτιλίας, καθώς αυτοί αντιπροσωπεύουν περίπου το 3% της παγκόσμιας αέριας ρύπανσης.

Σκοπός της εργασίας αυτής είναι η αναλυτική αποτίμηση των διαθέσιμων τεχνολογιών που μπορούν να εφαρμοστούν για τη μείωση των σχετικών ρύπων. Θα καταγραφούν ποσοτικά οι βασικότεροι αέριοι ρύποι της ναυτιλίας από κρουαζιερόπλοια εντός των βασικότερων λιμανιών της Ελλάδας και έπειτα θα συγκριθεί το εξωτερικό κόστος κάθε ρύπου με το κόστος εγκατάστασης για κάθε μέθοδο μείωσης επιπτώσεων ξεχωριστά. Έτσι τελικά θα εξαχθούν συμπεράσματα για το ποιες μέθοδοι είναι προτιμητέοι προς εφαρμογή για να επιτευχθεί η μεγαλύτερη μείωση των αέριων ρύπων με το μικρότερο κόστος για την κοινωνική ζωή σε συνδυασμό με το μικρότερο κόστος εγκατάστασης. Η σκιαγράφηση της υπάρχουσα κατάστασης έχει διεξαγχθεί χρησιμοποιώντας πραγματικά δεδομένα από μετρήσεις που έχουν πραγματοποιηθεί σε κρουαζιερόπλοια, τη χρονική διάρκεια των ετών 2013 και 2014.

Αρχικά στο πρώτο κεφάλαιο παρουσιάζονται γενικές πληροφορίες που αφορούν τους αέριους ρύπους στην ναυτιλία καθώς και το πώς αυτοί σχετίζονται με την επιβάρυνση της υγείας των κατοίκων που ζουν κοντά σε λιμάνια. Η επόμενη ενότητα αναφέρεται στην συμβολή των αέριων ρύπων στο φυσικό περιβάλλον, παρουσιάζοντας μια σχετική έρευνα που αφορά τις προκλήσεις που αντιμετωπίζει ένα λιμάνι στις ημέρες μας με βάση την σημαντικότητα τους. Στη συνέχεια, παρουσιάζεται άλλη μια έρευνα που αναφέρει τους κύριους παράγοντες που επιδρούν στις προσπάθειες βελτίωσης των αέριων ρύπων σε λιμένες, καταλήγοντας στο συμπέρασμα ότι οι βελτιώσεις στην μείωση των ρύπων συνδέονται άμεσα με τους αυστηρούς εθνικούς και τοπικούς κανονισμούς που θεσπίζονται και όχι τόσο με την ανησυχία της υγείας των εργαζομένων στα λιμάνια. Ενώ πάλι σε επόμενη έρευνα διακρίνεται ότι παρόλη την σοβαρότητα της επίδρασης των αέριων ρύπων NO_x και SO_x στο περιβάλλον, δεν λαμβάνονται υπόψη τόσο σοβαρά από τις εταιρίες.

Το δεύτερο κεφάλαιο αναφέρεται στον διαχωρισμό των πλοίων ως προς την μορφή τους και τα χαρακτηριστικά τους. Έτσι γίνεται η ανάλυση των πλοίων, σε αυτά που

μεταφέρουν επιβάτες και αυτά που μεταφέρουν φορτία. Επίσης γίνεται αναφορά στον διαχωρισμό των πλοίων σε σχέση με το μέγεθος της μηχανής τους, καθώς και της ηλικίας κατασκευής τους. Ενώ τέλος αναφέρονται και οι βασικότεροι τύποι καυσίμου που μπορεί να χρησιμοποιήσει κάθε πλοίο.

Το τρίτο κεφάλαιο αναφέρεται στις πηγές εκπομπής ρύπων που σχετίζονται με την ναυτιλία καθώς και στους παράγοντες που καθορίζουν την ποσότητα των ρύπων που εκπέμπονται. Μερικοί τέτοιοι παράγοντες είναι: ο τύπος της μηχανής που χρησιμοποιείται, το κύριο και δευτερεύον καύσιμο, το βάρος καθώς και η συνολική κατάσταση λειτουργίας του πλοίου. Γνωρίζοντας αυτούς τους παράγοντες, μπορεί να υπολογιστεί αναλυτικά το μέγεθος των εκπομπών κάθε πλοίου για κάθε διαδρομή που ακολουθεί. Είναι σημαντικό να γνωρίζουμε τις εκπομπές ρύπων των πλοίων σε κάθε κατάσταση λειτουργίας τους, έτσι ώστε να μπορούν να βρεθούν οι απαραίτητες λύσεις για την μείωση τους. Ένα ταξίδι μπορεί να διαιρεθεί σε τρία λειτουργικά στάδια. Στην ελεύθερη πορεία, όπου το πλοίο ταξιδεύει με σταθερή ταχύτητα, στην κατάσταση ελιγμών όπου βρίσκεται πλέον στην περιοχή του λιμανιού και τέλος στην ακίνητη κατάσταση όπου είναι αγκυροβολημένο στο λιμάνι. Ένα ακόμη ενδιαφέρον ζήτημα είναι η κατανάλωση ενέργειας κατά την διάρκεια λειτουργίας ενός πλοίου, η οποία συνδέεται κατά κύριο ρόλο με το μέγεθός του, τον τύπο κινητήρα που χρησιμοποιεί καθώς και με το λειτουργικό στάδιο που βρίσκεται. Γνωρίζοντας αυτές τις πληροφορίες μπορούμε να κατανοήσουμε σε ποιές καταστάσεις δαπανάται περισσότερη ενέργεια, δηλαδή τα σημεία που ένα πλοίο εκπέμπει περισσότερους ρύπους. Η αναφορά όλων των παραπάνω γίνεται μέσω ερευνών που έχουν ήδη πραγματοποιηθεί. Στην συνέχεια του κεφαλαίου επίσης αναφέρεται πιο αναλυτικά η επίδραση των βασικών αέριων ρύπων που εκπέμπονται από τα πλοία στους ανθρώπους και στο φυσικό περιβάλλον.

Στις ημέρες μας οι ρύποι στην ναυτιλία έχουν αυξηθεί δραματικά και προβλέπεται να αυξηθούν 50-250% περισσότερο έως το 2050, ανάλογα με τις τάσεις της μελλοντικής οικονομίας και τις ενεργειακές εξελίξεις. Το τέταρτο κεφάλαιο παρουσιάζει μέσα από ορισμένες μελέτες που έχουν πραγματοποιηθεί, την ραγδαία αυτή αύξηση των ρυπογόνων ουσιών από την ναυτιλία. Αρχικά παρουσιάζεται μια μελέτη που πραγματοποιήθηκε στις Ηνωμένες Πολιτείες της Αμερικής και παρέχει τις μετρήσεις ρύπων για όλα τα μέσα μεταφοράς. Στην συνέχεια, η επόμενη έρευνα αναφέρεται στην συμβολή του τομέα των μεταφορών στις συνολικές εκπομπές των κύριων ατμοσφαιρικών ρύπων για το έτος το 2009, όπου και εκεί ο τομέας της ναυτιλίας κατέχει πρωταγωνιστικό ρόλο. Ακολουθεί μια μελέτη που παρέχει τα ποσοστά των αέριων ρύπων που προέρχονται από την ναυτιλία σε παγκόσμιο επίπεδο, τα περασμένα έτη. Τέλος παρουσιάζονται οι εκτιμήσεις ερευνών για την πορεία των ρύπων στις χερσαίες μεταφορές και την ναυτιλία παγκοσμίως στο πέρας των ετών, έως το 2050.

Στο πέμπτο κεφάλαιο παρουσιάζονται αναλυτικά οι νέες τεχνολογίες που έχουν σκοπό την μείωση των αέριων ρύπων στην ναυτιλία. Στόχος αυτού του κεφαλαίου είναι να παρουσιαστούν διαφορετικές τεχνολογικές λύσεις που να καλύπτουν κάθε είδους πλοίο, καθώς και τα τεχνικά χαρακτηριστικά τους. Παρ' όλα αυτά, λόγω του ότι κάθε πλοίο εξυπηρετεί διαφορετικές ανάγκες, είναι σχεδόν αδύνατον να βρεθεί μια γενικά αποδεκτή λύση για κάθε πλοίο. Στην παρούσα διπλωματική εργασία ο τύπος των πλοίων που αναλύονται ως αναφορά τους ρύπους, είναι τα κρουαζιερόπλοια. Οι τεχνολογίες μείωσης των ρύπων στην έρευνα αυτή έχουν χωριστεί σε τέσσερις γενικές κατηγορίες. Αρχικά αναφέρονται οι τεχνολογίες που αφορούν τροποποιήσεις στις μηχανές των πλοίων και έπειτα ακολουθούν οι τεχνολογίες που πραγματοποιούν το έργο τους μετά την διαδικασία της καύσης στον κινητήρα. Συνεχίζεται η αναφορά σε μεθόδους μείωσης των ρύπων με αλλαγή της καύσιμης ύλης και τέλος ακολουθούν τα εναλλακτικά συστήματα ανατροφοδότησης ενέργειας στα πλοία. Σε αυτό το κεφάλαιο, για κάθε κατηγορία από τις παραπάνω παρουσιάζονται σε πίνακες οι τεχνολογίες που τις αποτελούν. Οι πίνακες αναφέρουν πληροφορίες σχετικές με την τοποθέτηση των τεχνολογιών σε νέα ή ήδη υπάρχον πλοία και για το εύρος μείωσης των αέριων ρύπων που μπορούν να επιτύχουν. Επίσης υπάρχει συνοπτική ανάλυση για κάθε τεχνολογία-μέθοδο που περιλαμβάνει τον τρόπο λειτουργίας τους καθώς και τα πλεονεκτήματα-μειονεκτήματα τους.

Το έκτο κεφάλαιο αναφέρεται στο κόστος μείωσης των ρύπων NO_x, SO_x και PM με την χρήση των παραπάνω τεχνολογιών. Γενικά, υπάρχει αρκετά μεγάλη αβεβαιότητα όσον αφορά τις εκτιμήσεις κόστους των τεχνολογιών μείωσης ρύπων, λόγω του ότι βασίζονται από πολλούς παράγοντες. Μετά από έρευνα που πραγματοποιήθηκε, προέκυψαν ορισμένα στοιχεία που αφορούν τα κόστη κάθε τεχνολογίας, τα οποία καταγράφηκαν σε αναλυτικούς πίνακες. Συγκεκριμένα, για τις βασικότερες τεχνολογίες που υπήρχαν διαθέσιμα δεδομένα, συγκεντρώθηκαν τα αποτελέσματα διάφορων μελετών σε πίνακες, ακολουθώντας παρακάτω τα οικονομικά αποτελέσματα της μελέτης Entec 2005 η οποία αποτελεί την πιο εμπεριστατωμένη έρευνα πάνω στο συγκεκριμένο αντικείμενο. Για κάθε τεχνολογία που υπήρχαν διαθέσιμα δεδομένα, αναφέρονται τα λειτουργικά κόστη, τα κόστη συντήρησης, καθώς και η διάρκεια ζωής του εξοπλισμού κάθε μεθόδου. Στη συνέχεια παρουσιάζονται τα οικονομικά αποτελέσματα της Entec 2005 για το κόστος αποτελεσματικότητας κάθε μεθόδου. Στην παρούσα διπλωματική εργασία λήφθηκαν ιδιαίτερα υπόψη τα στοιχεία της Entec 2005, τα οποία ορίζουν το κόστος κάθε τεχνολογία με βάση τους μειωμένους ρύπους που επιτυγχάνονται από κάθε τεχνολογία.

Το έβδομο κεφάλαιο παρουσιάζει αρχικά το μοντέλο που χρησιμοποιήθηκε για την μέτρηση των ρύπων στα κύρια λιμάνια της Ελλάδας. Οι μετρήσεις έλαβαν υπόψην την πορεία που ακολούθησαν τα πλοία, το τύπος της μηχανής, το μέγεθος τους, το καύσιμο που χρησιμοποιούσαν, καθώς και ο χρόνος που ήταν αγκυροβολημένα στο λιμάνι. Στην παρούσα διπλωματική εργασία, για την ολοκληρωμένη καταγραφή των αποτελεσμάτων υπολογίστηκε ακόμη, το κοινωνικό κόστος. Ο υπολογισμός του κοινωνικού κόστους της εργασίας έγινε με βάση τη σχετική μεθοδολογία εν ονόματι 'NEEDS' για τους αέριους ρύπους στα κυριότερα λιμάνια της Ελλάδας τις χρονιές 2013 και 2014. Η μεθοδολογία αυτή αποτελεί την πιο σύγχρονη έκδοση για τον υπολογισμό του κοινωνικού κόστους. Μετά από υπολογισμούς, τα αποτελέσματα τις διπλωματικής παρουσιάζονται σε τέσσερις τελικούς πίνακες. Οι πρώτοι δύο πίνακες παρουσιάζουν πληροφορίες για όλες τις τεχνολογίες που μελετήθηκαν, όπου αφορούν την μορφή που μπορούν να χρησιμοποιηθούν (σε νέο ή ανακατασκευασμένο πλοίο), την διάρκεια ζωής του εξοπλισμού τους, το εύρος των ποσοστών μείωσης που καταγράφηκε από παλιότερες μελέτες, το κόστος κάθε τεχνολογίας με βάση το ποσοστό μείωσης που παρέχει καθεμία και τις αναφορές από τις οποίες συλλέχτηκαν αυτά τα δεδομένα. Δημιουργήθηκαν δύο πίνακες διότι δεν υπάρχουν πλήρη διαθέσιμα δεδομένα για το κόστος όλων των τεχνολογιών. Έτσι έγινε ο διαχωρισμός των τεχνολογιών σε αυτές που έχουν διαθέσιμα δεδομένα για το τεχνολογικό κόστος τους και σε αυτές που δεν είναι ακόμα ορισμένο το κόστος τους. Ο επόμενος πίνακας παρουσιάζει όλες τις απαραίτητες πληροφορίες για τα λιμάνια που μελετήθηκαν. Συγκεκριμένα χωρίζει τα λιμάνια σε αστικά, ημιαστικά και αγροτικά ανάλογα τον πληθυσμιακό τους αριθμό. Επίσης παρουσιάζει το άθροισμα της ακριβής τιμής των ρύπων που μελετήθηκαν για τις χρονιές 2013 και 2014, για κάθε λιμάνι και κάθε είδος ρύπου ξεχωριστά. Ενώ τέλος παρουσιάζει το κοινωνικό κόστος που απέφεραν οι ρύποι αυτοί καθένας τους ξεχωριστά, καθώς και το συνολικό κοινωνικό κόστος για τις δυο χρονιές που μελετήθηκαν. Ο τελικός πίνακας παρέχει όλες τις πληροφορίες από τους υπολογισμούς που πραγματοποιήθηκαν. Συγκεκριμένα, αναγράφονται όλες οι τεχνολογίες μείωσης των ρύπων, η μορφή που μπορούν να χρησιμοποιηθούν, ο αριθμός των ρύπων που απελευθερώθηκαν στα λιμάνια το 2013-2014 (αθροιστικά), το κοινωνικό κόστος που απέφερε ξεχωριστά κάθε ρύπος αλλά και αθροιστικά, τα ποσά των μειωμένων ρύπων μετά την χρήση των τεχνολογιών, το κόστος κάθε τεχνολογίας που μελετήθηκε, το κοινωνικό κόστος που θα παρατηρούνταν μετά την χρήση κάθε τεχνολογίας και τέλος το οριακό περιβαλλοντικό κέρδος μετά την χρήση κάθε τεχνολογίας. Για την ευκολότερη ανάλυση και ερμηνεία των αποτελεσμάτων έχουν δημιουργηθεί απαραίτητα διαγράμματα.

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Chapter 1: Maritime industry

1. Introduction

Throughout the last decades, transport demand has strongly increased and maritime trade has become the most important way for merchandise transfer. Everyday thousands of ships carry products or transfer people worldwide. However, maritime transport is one of the largest contributors to air pollution. In the present study the emissions from maritime transport and emission reduction potential in the main ports of Greece were studied. At first, is described general information about environment and ships such as the environmental challenge and the ships classification. Then, the pollutants that are emitted from marine diesel engines are described and also their negative affect. Subsequently, some studies about the energy demand during the modes of operation for a single port-to-port ship transit are presented and then the propulsion emissions are mentioned. This study also has some emissions estimation in order to show that shipping emissions are projected to increase over the coming decades. Furthermore, a data collection has done in order to find information about the emission abatement technologies in shipping. Thus, from older studies we collected information about how each technology is used and how much it can reduce the shipping emissions. After that, all the necessary data gathered into tables that provide a summary of all these different reduction technologies highlighted in this study. Also, a brief presentation of these technologies is provided. In order to estimate emissions based on detailed individual activities of cruise ships in the selected ports a ‘’bottom-up’’ method has been used. Also, for every ship call, the emissions were calculated through a specific application that is referred with more details below. The calculated emissions are referred on years 2013 and 2014 in the studied Greek ports. In this study in order to make the final conclusion required to have the technological cost of the reduction methods. Generally, costs vary with ships size and may differ greatly when the technology is installed in existing or in retrofitting vessels. For this reason it is quite difficult to calculate the exactly cost of a reduction technology. A large number of studies have estimated the total cost of available technologies for reducing ship emissions. Generally, these studies are quite old and there are not be made very often. This is because these kind of studies are extremely costly. The emissions reduction potential in this study was evaluated based on already studies on emission reduction technologies for ship engines. The most authoritative and comprehensive evaluation of the abatement costs is a study by Entec (2005) for the European Commission that have been used also in this study. Furthermore, this study tried to use also newest estimates of capital and operational costs, based on recent studies for abatement technologies. In this report except from the cost of the abatement technologies, also the external cost is calculated and taken into account for the study's final results. Thus, in order to estimate the total external cost due to emissions to air in studied ports, is using one damage cost methodology named New Energy Externalities Development for Sustainability (NEEDS). Through calculations and data analysis, the net environmental profit of this study is calculated. This net environmental profit shows us which method is the most beneficial from cost perspective, in order to make our final conclusions.

1.1 Air Pollution in Shipping Industry

Nowadays, maritime transport activity is becoming one of the most important topics on sustainability debate. Apart from industrial activity and energy production, maritime transport is one of the largest contributors to air pollution. Throughout the last decades, transport demand has strongly increased and maritime trade has become the most important way for merchandise transfer. Today, almost 90% of the world products are carried by sea and maritime transport accounts for over 90% of European Union external trade and 43% of its internal trade [1]. Also, due to low energy need, shipping is a highly carbon-efficient transport mode, namely carbon dioxide emissions are low compared to the weight of cargo transported. Generally, shipping can reach being up to four times more efficient than road transport. Since its relatively small contribution to greenhouse gas emissions, shipping is also good in terms of mitigation of climate change.

Nevertheless, until recently, air pollution from ships has been unregulated. Increased air concentrations and deposition of air pollutants have had several negative effects. Air quality problems associated with ship emissions, especially in coastal areas, are a major concern because of their impacts on public health and greenhouse gas emissions. Exposure to air pollution is associated with a great number of health risks including heart and respiratory diseases, premature death and cancer. Port communities have the most negative consequences. More specifically, air pollution emitted from port-related activities adversely affects the health of port workers, as well as residents of nearby port areas and this contributing significantly at regional air pollution problems. Because of the fact that their air pollutant emissions still remain comparatively unregulated, ships and port facilities are among the world's most polluting combustion sources per ton of fuel consumed [2].

Since more than 50% of a ship's operating expense is generally the cost of fuel oil, most of the world's ship operators use degraded residue heavy fuel oil in marine power plants, for its advantages in fuel economy. During the last few years, certain problems have appeared due to its use, these including: the barriers of compliance with the new emissions regulations [3], the increase of the fuel cost, which presents the main element in the ships operating cost as mentioned [4] and finally the sustainability issue [5]. Uncontrolled emissions from ships burning traditional marine fuel oils onboard, have a significant impact upon our environment, especially with ship emissions' quantity increasing: Nitrogen oxides (NO_X), Sulfur oxides (SO_x), Carbon Di-oxide (CO_2), Mono-oxide (CO), Particulates Matter (PM) and Hydrocarbons (HC) [6].

Currently, as a method to reduce ship emissions, the IMO regulations have forced the ships to use expensive fuel type in Ship Emissions Control Areas (SECAs) and will be forced to do so worldwide by year 2020 [7]. Also, currently, international shipping and port industry has adopted new technologies such as improvement of fuel quality and ship engine technology as well as operation changes at port in order to reduce the air pollution from ship and other transport modes.

1.2 Environmental challenge

Air quality is the most challenging environmental issue within the ship-port interface today. According to a research about the importance of air quality [8], a significant majority of interviewees indicated air quality as a very much-perceived challenge, as depicted in Figure 1. Port authorities gave the highest average score; illustrating the impact that air quality challenges have on their everyday operations and on the general future expansion plans. According to the survey results, the importance of Greenhouse Gas (GHG) and noise are also high and follow air pollutants.

The contribution of ships and port activities to regional air quality started being a serious issue for several large ports in the 1990s as the combination of increasing land-side emissions and growing ports led to exceedances of the air quality standards set. These same issues affected more and more ports in the next decade as scientific studies on PM, ozone and other major air pollutants clarified their impacts on human health. In the middle of the last decades the IMO worked to pass Annex VI to MARPOL to reduce NO_x and SO_x emissions from the world maritime fleet.

In Europe (in the context of Directive 2012/33/EU and its predecessors) and North America, government authorities and ports implemented their own fuel sulfur programmes and have begun to devise strategies to further reduce NO_x and PM from port-related sources. As we can see from the figure, nowadays, air pollutants and GHGs are becoming more pressing concerns around the world. For that reason ports are engaged in a renewed effort to limit these air emissions. An interesting survey result is that noise exposure for the port community is also perceived as an environmental challenge, although to a somewhat lesser extent. Finally, although biodiversity is not specifically raised during the years, it has also been a challenge in some cases.

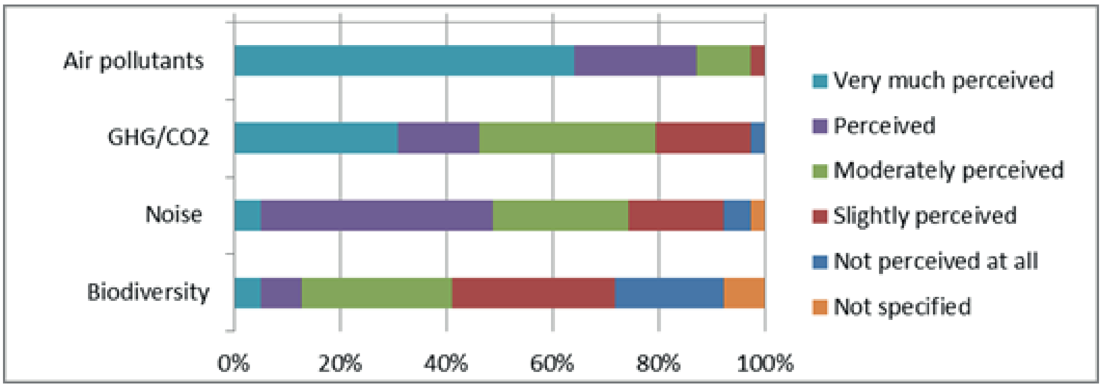

Figure 1: Environmental challenges perceived by ports [8].

1.3 Drivers

Many drivers play a role in reducing emissions in a port. For that reason recent a study tried to calculate these drivers and after a research made the following results. The most relevant drivers relating to reduce the environmental impacts in the ship-port interface are illustrated in Figure 2.

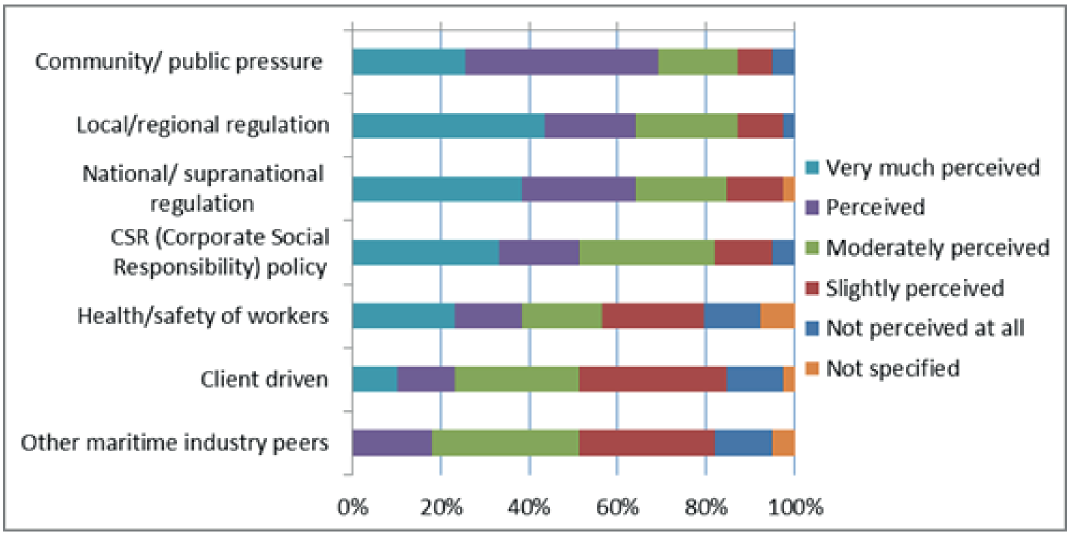

Figure 2: Relative importance of drivers [8].

The survey results indicate that there are four primary environmental improvement drivers at the ship-port interface:

- Community and public pressure
- Local and regional regulation
- National and supranational legislation
- Corporate social responsibility (CSR)

The other environmental drivers, such as the health and safety of workers and pressure of cargo owners and other maritime industry peers, are found less important for the uptake of emission reduction measures, according to the responses of the research. It is quite interesting to note that while worker health and safety was indicated as a strong driver by ship owners, technology suppliers evaluated this as having nearly no importance.

So by this figure we can understand that the most important reason for implementing measures at the ship-port interface are local or national regulations. That is the main purpose in order to measure the ship pollutants in ports and after that is following the human health.

Another report that illustrate this issue about the importance of the reduction emission problem is by Sustainalytics [9], that show us how important are new regulations for shipping companies. In an attempt to answer this question, it mentions the elements that a shipping company named Maersk has published by used a materiality matrix method, which shows which ESG issues are most material to the business and most important to stakeholders (i.e. employees, suppliers, customers, communities etc). Factors such as impacts on cost, revenue and compliance have been taken into consideration to measure the impact on the business.

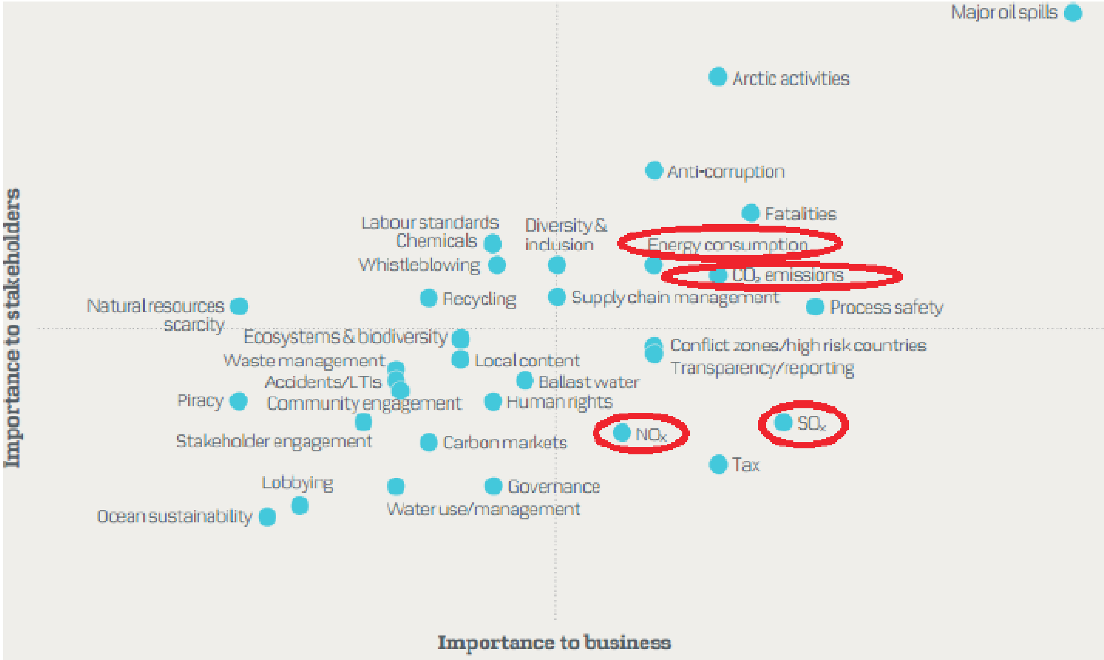

Figure 3: Materiality Matrix [9].

Together with safety aspects and major oil spills, the issue of SO_x emissions is the sustainability-related issue that is currently most important to Maersk's business. Of the 30 sustainability issues listed by the company, the issues CO_2 emissions, energy consumption and NO_x emissions rank fifth, seventh and eleventh, respectively. Regulations have major impacts on shipping companies, since they affect fuel costs, which represent around 50% of total costs for a shipping company.

Chapter 2: Ships classification

Ships are difficult to classify, mainly because a plurality of criteria can be adopted in order to make the classification. Excluding the military vessels, the most used classifications for commercial ships generally take into consideration the vessels activities, the engine size and the ship's age. The first one makes the distinction between passengers and cargo. The second one, based on engine size, is related to energy consumption and is generally used to analyze the environmental impacts of maritime transport. The last one considers the age of the vessels and the distribution age between developed and developing countries [10].

2.1 Passengers and cargo

Based on the vessel activity, Passengers and Cargo is one of the most important ships classifications for commercial vessels. The main difference between passenger and cargo ships is that passenger ships have larger engines in relation to their tonnage than cargo ships. Passenger ships are also faster than cargo ships especially in the smallest size classes [11].

Passengers are ships that do not carry cargo but passengers. They include:

- Ferries which transport more than 120 passengers, vehicles and one or more cargo decks for short-sea trips;
- Ocean Liners that transport passengers and cargo for longer-sea trips;
- Cruise ships used for tourism.

Cargo is a more heterogeneous category and can be further categorized according to their structure and type of cargo. It includes all the vessels that carry cargo, goods, commodities and materials form one port to another [12]. They include:

- Cargo ferries: they transport less than 120 passengers and cargo;
- Bulk carriers: they carry bulk solids or unpacked cargo such as coal;
- Other dry cargo vessels: are regular cargo vessels, which are loaded up with derricks through hatchway
- Container ships: are designed to transport standard-sized containers;
- Tankers: are designed to transport crude oil, chemical or gas;

- Roll on/Roll off (RoRo): they are classified as cargo ferries, because they carry wheeled cargo: automobiles, trailers and railway carriages;
- Reefers: They transport dairy products that is needed to keep cool such as fruits, vegetables, dairy products, fish and meat;
- Smaller vessels: the include fishing vessels, recreational boats or vessels of sea salvage service. Depending the temperature control the reefers are similar to other dry cargo vessels or containers [11].

Dry cargo and container are the most important shipments. Dry cargo account for 63.9% of total goods loaded, increasing by 12.8% in 2004, 8.7% in 2005 and 13.5% in 2006 [1]. There are also smaller vessels such as fishing vessels and boats, work vessels and recreational boats. Work vessels include Barges and Icebreakers and are the smaller shipping category.

2.2 Engine size

In general, the main engines consist almost without exception of one or several two- or four-stroke diesel engines and they produce the energy needed for propulsion system. In larger cargo ships (gross tonnage more than 5,000) the most common main engines are the low-speed two-stroke engines. Low-speed diesels run at low engine revolutions enabling a direct drive application to turn propellers. In smaller cargo ships (gross tonnage less than 5,000) the most common main engines are usually medium speed four-stroke engines. According to reports, the 96% of installed engine power is produced by diesel engines and the vast majority of ships are powered by slow-speed, two-stroke diesel engines [13]. The classification based on Engines Size is generally considered as the most important one in order to analyze the environmental impacts of transport activities, since pollution and energy consumption are notably related to vessels size. Also the engines' sizes vary a lot depending on the energy demand on board, which is very different for different kinds of ships. On average, the size of the auxiliary engines is about 10% of the size of the main engines [12], [14]. In this paragraph two classifications are considered but a classification based on vessels size category and vessels activities is also reported.

The first one, proposed by the U.E. Environmental Protection Agency [15] identifies tree ships categories according to their sizes.

Category 1 considers ships engines that are similar to land-based of-road engines. They have a rated power at or above 37 kW and a specific displacement of less than 5 liters per cylinder.

Category 2 considers the water-based counterparts of locomotive engines. They have a specific displacement of 5 to 30 liters per cylinder.

Category 3 considers ships that have very large engines with a specific displacement at or above 30 liters. These engines are the size of land-based power plant generators and they are used for propulsion in the large ocean-going vessels. These engines are designed for maximum fuel efficiency without considering the impacts on the NO_x emissions. According to this their NO_x emissions levels are very high. Also these engines already have advanced controls of charge air temperature and pressure, which are considered to be emission control strategies for smaller engines [15].

The second classification, notably related to energy consumption, considers the engines used to produce the power needed on ships. It distinguishes between the auxiliary and the main engines and classifies vessels into small, medium and large:

- **Small vessels** have a main engine size of 3,000 kW and an auxiliary engine size of 500 kW.
- **Medium vessels** have 10,000 kW of main engine and 1,500 kW of auxiliary engine size.
- **Large vessels** have 25,000 kW of main engine size and 4,000 kW of auxiliary engine size.

Based on the Entec report (2005) the small ships are the 60% of the total ships worldwide. The medium are the 30% and the large only the 10%.

2.3 Age

Another way to classify the ships is based on age. Three categories are generally considered: new, young and old. Vessels are new if built in the last year, young if built in the last fifteen years and old if built before 1990 [16]. Assuming an annual renewal rate of 4% [16], estimate that the new vessels are the 4% of the total population, young vessels are the 56% and old vessels are the 40% of the total population. The next table reports the distribution of vessels based on their ages and world regions [1].

	Type of vessel	0 – 4 years	5 – 9 years	10 – 14 years	15 – 19 years	20 – + years	Average age
Developed Countries							
	Tankers	36.5	35.4	14.3	6.7	7.1	7.7
	Bulk carriers	19.6	25.5	23.9	6.1	24.9	11.9
	General cargo	14.9	23.9	15.8	12.8	32.6	13.7
	Containerships	30.6	31.6	19.1	8.8	9.9	8.9
	All others	22.4	19.9	15.0	10.7	31.9	13.0
	All ships	28.4	29.9	17.6	7.8	16.3	9.9
Developing Countries							
	Tankers	28.0	21.0	17.7	17.5	15.8	10.8
	Bulk carriers	23.1	18.3	18.6	9.6	30.5	12.8
	General cargo	9.6	10.9	10.7	8.5	60.4	17.9
	Containerships	35.9	24.4	19.3	7.2	13.1	9.1
	All others	17.6	12.9	10.5	7.8	51.2	15.9
	All ships	24.6	18.9	17.1	11.8	27.7	12.4

Table 1: The distribution of vessels by ages and world regions in 2007 [10].

The results reported in table 1 show that a similar age distribution exists between developed and developing countries: most ships are old, more than 20 years or young, less than 4 years. A smaller percentage age of ship's age is between 5 and 19 years old. Nevertheless, as we can observe from the table, the average age for the ships of developing countries is higher than the average age of ships for developed countries (12.4 years for developing countries and 9.9 years for developed countries). Most interesting is the case of containerships due to the fact that in developing countries, containerships are replacing general cargo vessels. As a consequence, 35.9% of the containerships are younger than five years and the old general cargo (more than 20 years) are the 60.4%. Containerships are the most popular ships to transport goods globally, since shipping industry plays a major role on the global transportation. That is why in both categories (in developed and developing countries) the containerships are new ships in most cases. On the contrary, in developed countries containerships have already replaced general cargo because only 32.6% of them are more than 20 years old.

2.4 Classification of fuel oils

Fuel oil is a fraction obtained from petroleum distillation, either as a distillate or a residue. Broadly speaking, fuel oil is any liquid petroleum product that is burned in a furnace or boiler for the generation of heat or used in an engine for the generation of power, except oils having a flash point of approximately 40°C (104°F) and oils burned in cotton or wool-wick burners. In this sense, diesel is a type of fuel oil.

Marine fuels are divided into two categories: heavy fuel oil (HFO) and light marine distillates. The light marine distillates are further divided into marine diesel oil (MDO) and marine gas oil (MGO), the latter often having the lowest sulfur content. HFO more often than not has high sulfur content. Large ships mostly use HFO as standard fuel but at the same time they might use lighter fuel in their auxiliary engines. Small vessels use light marine distillates in their main engines as well [17].

Chapter 3: Considerations

There are plenty of considerations in order to reduce shipping emissions. First of all, it is very useful to know the ship-related emission sources and generally everything it has to do with these sources. For that reason this chapter refers on the ship-related emission sources and on the level of ship emissions that depends on certain factors such as shipping route, ship deadweight, engine type, fuel type and ship operation condition. The emission amounts are thus computed on a detailed level and can be applied to specific vessels and routes. A round trip can be divided into three operational stages, namely free sailing, maneuvering and berthing. Thus, it is important to know the emissions of a ship by mode in order to find measures that will reduce them. Another interesting consideration is the energy consumption on the base of vessel activity, size and engine in order to understand where one ship needs more energy which means that in this point the ship emits more pollutants. Air pollution and health impacts from port operation are also very serious too. The diesel engines at ports, which power ships, trucks, trains, and cargo-handling equipment, create vast amounts of air pollution that affect the health of workers and people living in nearby communities and contribute significantly to regional air pollution. Finally, a cost consideration is also referred in this chapter in order the costs that are associated with ships.

3.1 Ship-related emission sources

Generally, all ship activities are responsible for air pollutant emissions. The emission sources of ships are associated with their related operations and include: propulsion engines, auxiliary engines, auxiliary boilers (boilers), VOC working losses associated with bulk liquid cargos and refrigerants. Propulsion engines or main engines are used to provide power directly (direct drive or gear drive) or indirectly (diesel-electric) based on the ship's configuration. On the other hand, auxiliary engines are usually four-stroke engines which produce the energy needed on board for electricity, pumps cooling and hydraulic device. On average, a ship has 1.4 main engines and 3.5 auxiliary engines installed on board [18]. Auxiliary boilers provide steam power for pumps, inert gas for volatile organic bulk liquid operations, crew needs, etc. The most common propulsion and auxiliary engines are diesel cycle engines, although there has been recent growth in natural gas engines running either as gas only or dual fuel configurations.

One huge problem in shipping industry is emissions which are the result of engines burning fuel oil in a diesel combustion process. Concerning air pollutants, vessels can produce significant amounts of nitrogen oxides (NO_x) and particulate matter (PM) from burning of fuel in the propulsion engines, auxiliary engines and auxiliary boilers. These three sources can either have the same magnitude in emissions or one or two can be dominant over the others, depending on the geographical configuration of the port area and type of vessels. According to the ship position in port area or in open water, auxiliary engines and propulsion engines are typically the dominant ship-related emission sources.

Diesel engines are the most common choice for use in maritime operations both on ships and in terminal equipment, because of engines' energy efficiency, reliability, longevity and power. In the port area, marine engines are typically the last major engine group to be regulated. That is why nowadays one of the most significant challenges and opportunities related to improving air quality in port areas is to reduce emissions from diesel engines on ships.

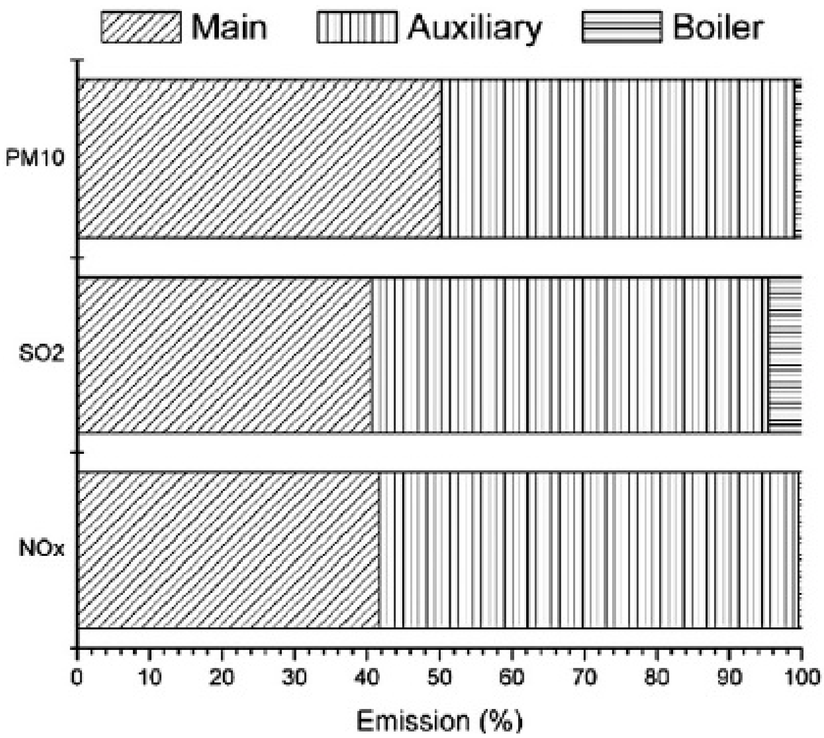

Figure 4: Emissions comparison between main, auxiliary engine and boiler [19].

3.2 Emission sources through the various modes associated with the port area

One unique challenge that marine industries have and associated with the port area, is how to reduce ship emissions at each stage of its activities within the port area. To achieve that is important to know how the emission sources listed above operate through the various modes associated with the port area. The following figures (figures 6,7,8) provide a graphical representation of how the three power systems (propulsion system, auxiliary power system and boilers) change in activity by operating mode on a typical ship, during each of its activities within the port area [20].

In the transition and maneuvering modes, the propulsion engine is operating with variable loads and is even turned off/on depending on the specific area the ship is maneuvering through. Although emissions at port during maneuvering and berthing account for only a small proportion of trip emissions, it is important to note their harmful health effects on the local population. By contrast, emissions during free sailing have less damaging effects on human health because of the sparse population. In the next modules would be a specific analysis for this issue. The ship emissions for a round trip between port i and port j are depicted in Figure 5:

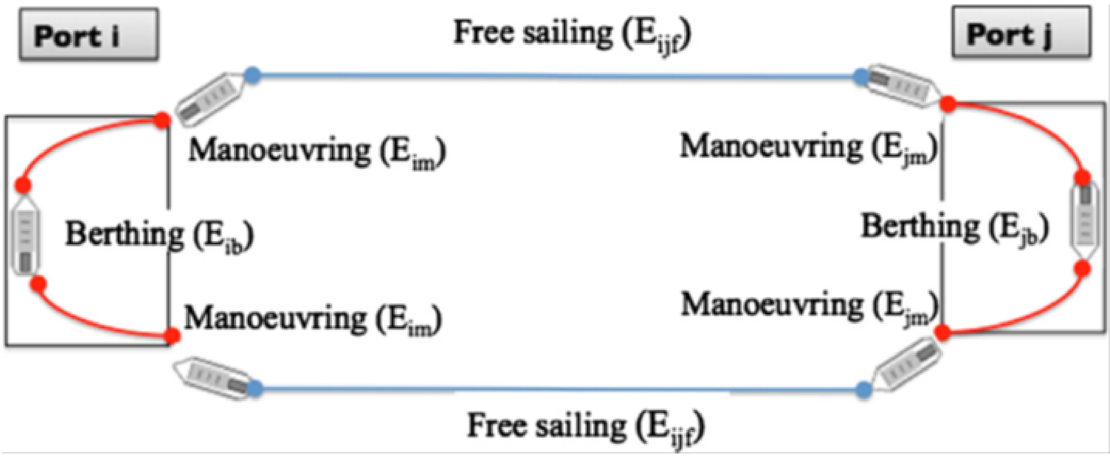

Figure 5: Ship emissions of the round trip [21].

Transit or free sailing - During this mode, a ship is sailing in the open ocean/unrestricted waters. Typically,

- the ship is travelling at its sea-speed or cruising speed;
- propulsion engines are operating at their highest loads;
- auxiliary engine loads required by the ship are at their lowest loads;
- auxiliary boilers are off and economizers are on because of the high propulsion engine exhaust temperatures;

- vessel fuel consumption is at its highest level due to the propulsion system's power requirements and auxiliary fuel consumption is low.

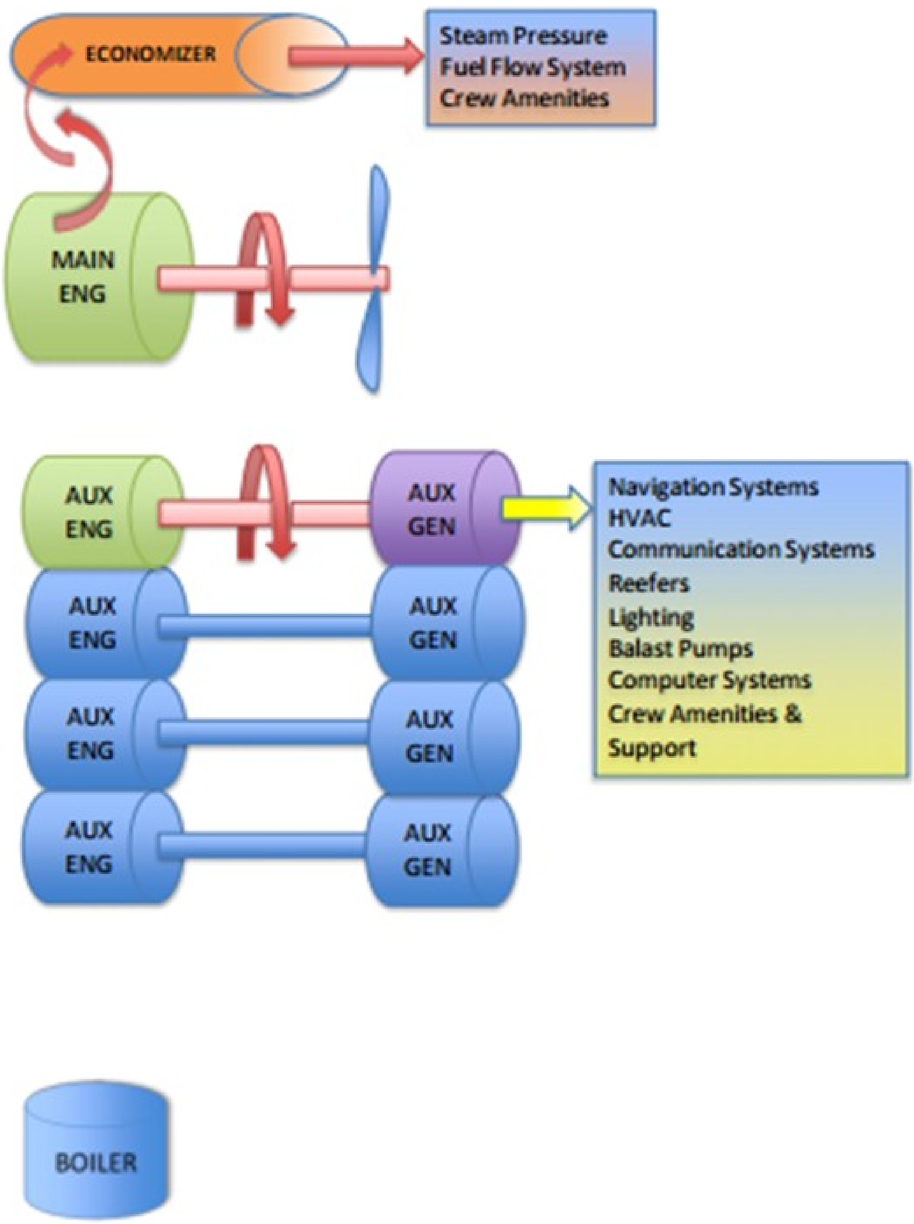

Figure 6: Illustration of vessel systems in operation during transit mode [20].

Transitioning and maneuvering - During this mode, a ship is typically operating within confined channels and within the harbor approaching or departing its assigned berth. The distance associated with this mode is unique for each port depending on geographical configuration of the port. Typically,

- the ship is transiting at its slowest speeds;

- propulsion engines are operating at low loads;
- auxiliary engine loads are at their highest load of any mode;
- auxiliary boilers are on because the economizers are not functioning due to low propulsion engine loads and resulting lower exhaust temperatures; this generally does not apply to large diesel-electric powered vessels, which produce sufficient exhaust heat to power economizers at maneuvering speeds;
- vessel fuel consumption is very low for the propulsion system, is highest for the auxiliary engines and low for the auxiliary boilers.

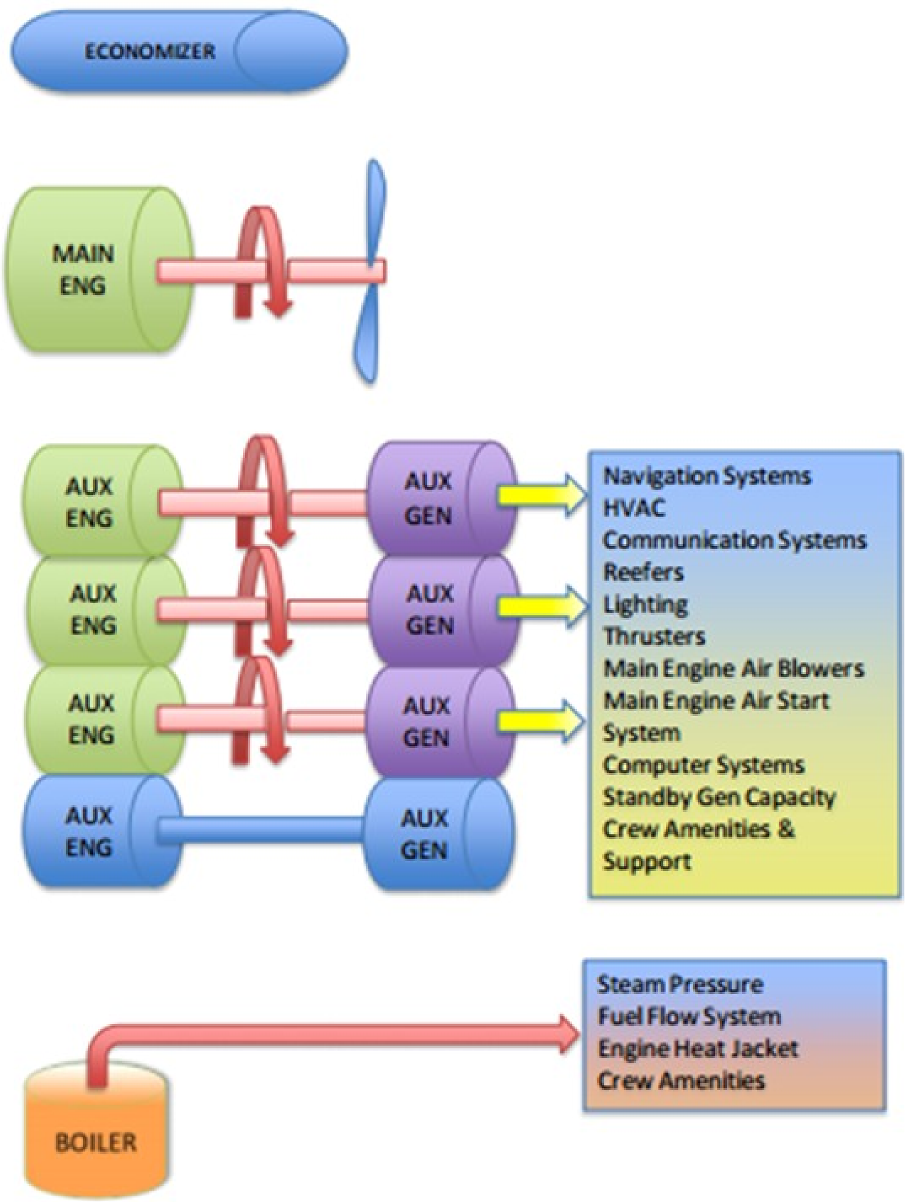

Figure 7: Illustration of vessel systems in operation during maneuvering mode [20].

At berth or anchored - During this mode, a ship is secured and not moving. Typically,

- propulsion engines are off;
- auxiliary engine loads can be high if the ship is self-discharging its cargo, as with general cargo vessels, auto carriers and roll-on roll-off (RoRo);
- auxiliary boilers are operated to keep the propulsion engine and fuel systems warm in case the ship is ordered to leave port on short notice, for crew amenities and, for certain types of tankers, for offloading cargo through the use of steam-powered pumps;
- vessel fuel consumption can be medium to high for auxiliary engines and can be medium to very high for boilers.

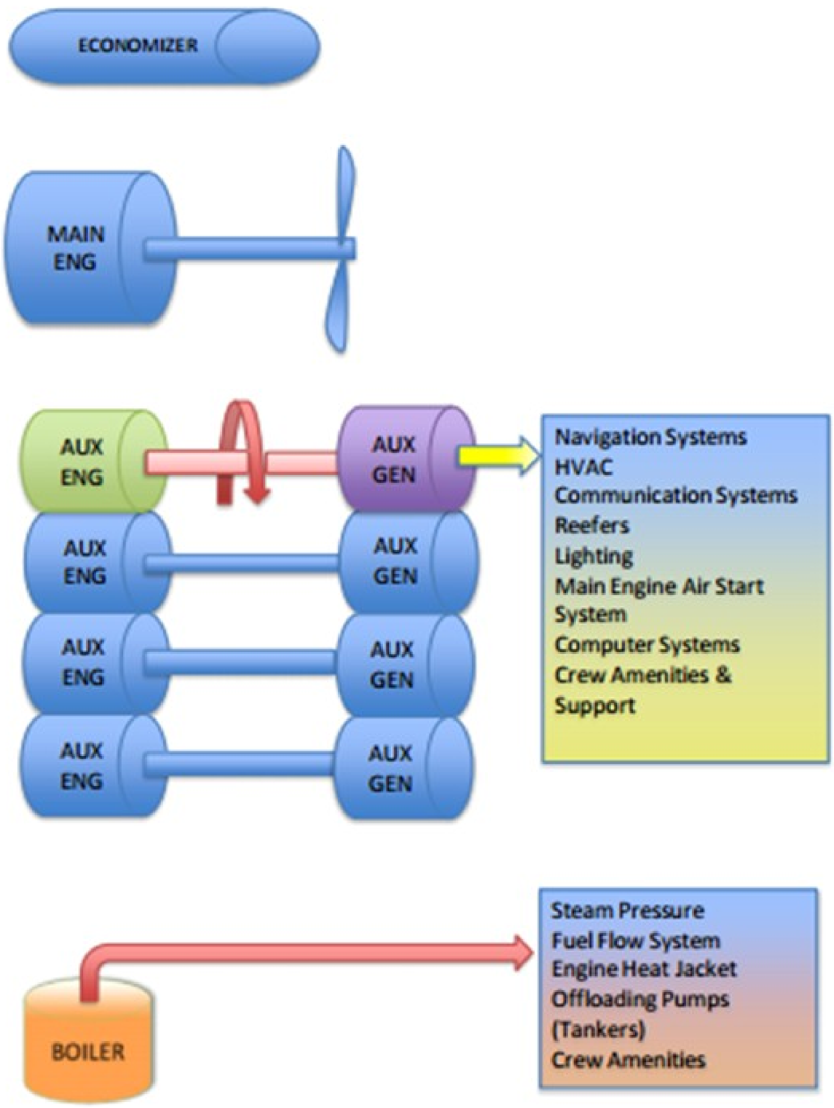

Figure 8: Illustration of vessel systems in operation during at-berth mode [20].

3.3 Energy consumed

The majority of ship owners, operators and engine manufacturers focus their efforts in reducing NO_x and increasing efficiency for at-sea conditions, as opposed to the port area. Typically, most ships move from one port area to another and for these ships, a majority of the ship's energy consumption over the life of the ship is at sea. Ship emissions estimation studies show total ship carbon dioxide (CO_2) emissions in the port area range from 2% at the Port of Los Angeles as compared to the entire voyage of the ship to 6% at the Port of Rotterdam as compared to greater North Sea area. Figure 9 emphasizes this point by illustrating the magnitude of time and energy spent at sea versus time and energy spent during the modes that define the port area.

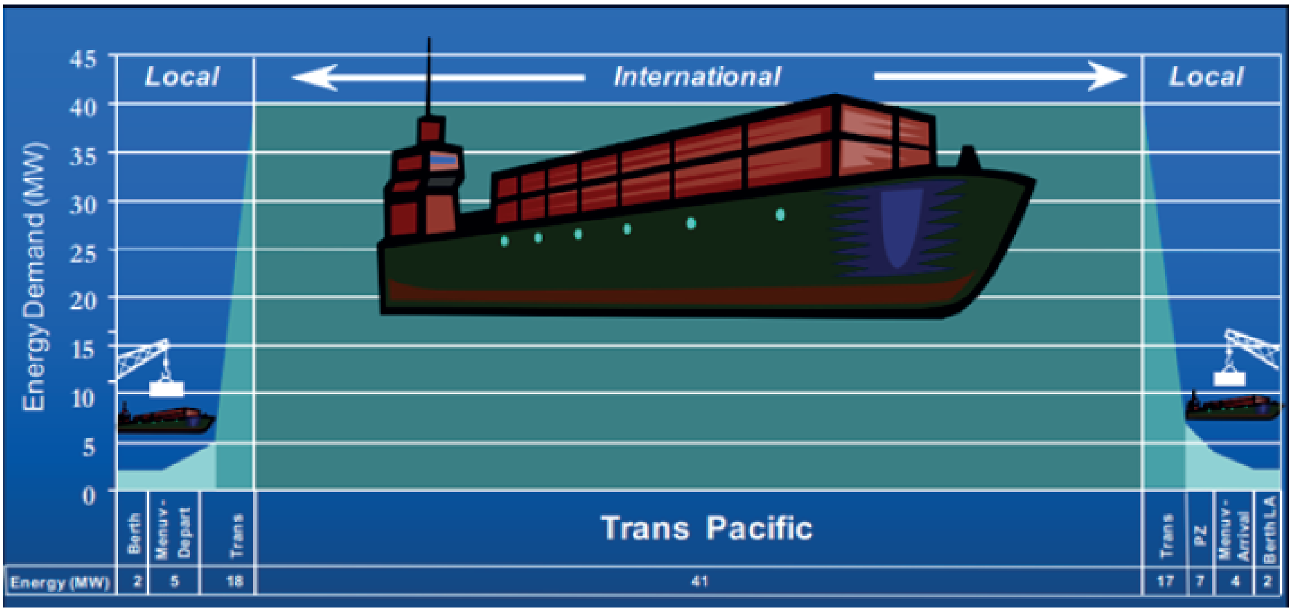

Figure 9: Relative energy demand during modes of operation for a single port-to-port ship transit [8].

Since energy consumption is strictly related to each operating activity (at sea, at berth or maneuvering), a classification based on vessels size category and activity can be useful to estimate the total amount of energy used. The next table reports the main results provided by Entec (2005). It estimated the energy consumption on the base of vessel activity, size and engine.

	Small	Medium	Large
Main Engine			
At Sea	14,400	48,00	120,000
At Berth	21	70	175
Manoeuvring	12	40	100
Total Main Engine	14,433	48,110	120,275
Auxiliary Engines			
At Sea	1,008	2,664	6,840
At Berth	157	414	1,064
Manoeuring	6	15	38
Total Auxiliary Engines	1,170	3,093	7,942
Total Usage	15,603	51,203	128,217

Table 2: Assumed per vessel activity size and engine (MWh/year) [22].

As reported in table 2, if total energy consumption is considered, small vessels use less energy than large vessels. However, in unitary terms, large vessels results to be more efficient than small vessels. According to [23], in order to reduce the total energy consumption, the use of large ships, like container ship, tankers and bulk carriers, should be promoted.

3.4 Ship propulsion emissions

Studies about globally emission inventory for ocean going ship found that ocean-going ships are major contributors to global emissions of nitrogen and sulfur, and to a lesser extent, to global emissions of CO_2, PM, hydrocarbons (HCs), and CO. They insisted that approximately 80% of the worldwide fleet is either harbored (55% of the time) or near a coast (25% of the time). This means most ships spend only about 20% of the time at sea and far from land [2]. It also means that most ship emissions occur near enough to land to influence not only local air quality in coastal and harbor areas but also soils, rivers, and lakes in those areas. Studies making use of geographic marine activity data have estimated that about 70–80% of all ship emissions occur within 400 km (248 miles) of land [24]. In North Sea, for example, the 90% of emissions is emitted within 90 km of land [11]. Other studies estimated CO_2, NO_x, and SO_x emission and found that international marine vessels account for about 30% of global NO_x emissions from all sources and 9% of global SO_x emissions [25], [26].

In 2005 another report elaborated by Entec estimated the total amount of SO_2 and NO_x emissions. It calculated the emissions in EU water considering a distribution of times spent in EU waters and distinguishing between engines, dimensions and operations of vessels. It came to the conclusion that marine sources contribute about 14% of worldwide NO_x emissions and 6.5% of all SO_x emitted by fuel. Table 3 reports the main results and shows that the vast portion of emissions occurs while at sea.

	Small		Medium		Large	
	NO_x	SO_x	NO_x	SO_x	NO_x	SO_x
Main Engine						
At Sea	216	158	720	528	1,800	1,320
At Berth	0.3	0.2	1.1	0.8	2.6	1.9
Manoeuvring	0.2	0.1	0.6	0.4	1.5	1.1
Total Main Engine	216	159	722	530	1,805	1,323
Auxiliary Engines						
At Sea	15	11	40	29	103	75
At Berth	2.4	1.7	6.2	4.6	16.0	11.7
Manoeuring	0.1	0.1	0.2	0.2	0.6	0.4
Total Auxiliary Engines	18	13	46	34	119	87
Total Usage	234	172	768	564	1,924	1,411

Table 3: Estimated annual NO_x and SO_x emissions per vessel (ton/year) [16].

3.5 Key pollutants in the port area

Air pollution and health impacts from port operation are also very serious. During the burning process in marine diesel engines, boilers, and incinerators, these fuels can produce significant amounts of black smoke, particulate matter (PM), volatile organic compounds (VOCs), nitrogen oxides (NO_x), unburned hydrocarbons (UHC), sulfur oxides (SO_x), carbon monoxide (CO), carbon dioxide (CO_2), etc. NO_x and VOC are precursors of ozone, which is a common air pollutant of concern around port areas. Ozone is not directly emitted from combustion sources but rather formed from NO_x and VOC mixing in the atmosphere and with the addition of sunlight. Typically, NO_x is the primary pollutant emitted by fuel-oil-powered sources that is controlled in relation to ozone. Because of the physical and chemical properties involved, the main challenge of emission control for diesel engines is reducing PM and NO_x. The challenge becomes even more complex because the formation of PM and NO_x is inversely linked by the physical and chemical characteristics of the combustion process. Often, when one pollutant is reduced by engine process changes, (for example by lowering the combustion temperature) the other pollutant increases. Currently, controlling NO_x, PM and SO_x emissions is the central focus for most national and regional regulatory agencies and therefore the same for ports and maritime organizations throughout the world. GHGs, including CO_2, are starting to be seriously addressed by regulatory agencies, although in the port area, health effects typically take the priority over GHGs. Not all CO_2 reducing strategies also result in reductions in NO_x and PM and therefore in the port area consideration of control strategy effects need to be aligned with the air quality regulatory agency's goals. In this report NO_x, SO_x, and PM emissions are considered.

Nitrogen Oxides (NO_x)

NO_x is a colorless and odorless gas that is formed when fuel is burned at high temperatures, as in an internal combustion engine. Contributing to acidification, formation of ozone and to smog formation, NO_x are deemed between the most harmful gases to the environment. They can be transported over long distances and generate problems to areas not confined to areas where NO_x are emitted. Also another environmental impact from NO_x includes acid rain, nutrient overload in water bodies and visibility impairment when combined with atmospheric particles.

Health Effects of NO_x: NO_x does not have substantial direct human health impact. Instead, through a complex series of chemical reactions in the atmosphere, NO_x combines with VOC to create ground level ozone (O_3), a very potent human respiratory irritant and short-term climate forcing gas. Ozone can be transported by wind currents and cause health impacts far from original sources.

Also ozone it can compromise the immune system and can cause inflammation in the respiratory system that leads to coughing, choking and reduced lung capacity over long periods of exposure. It affects, in particular, children and people with respiratory diseases and is common in urban areas with high ozone pollution. The effects of ground level ozone are more frequent during the warmer summer months. Children, elderly people and people who work or exercise outdoors are especially vulnerable to the impacts of ground level ozone. Moreover, since particle smog is formed by PM (ultra-fine particles of soot) it can contribute to damage hearth and lungs.

Particulate matter (PM)

Unlike other pollutants that have a specific chemical definition, particulate matter is a general term used to describe aerosols that can have a wide range of physical and chemical properties. PM consists of mixtures of solid particles and liquid droplets found in the air. Regulatory and control purposes define PM primarily by size. There are two forms of particle pollution that are regulated due to their potential impact to human health; inhalable coarse particles with diameter larger than 2.5 micrometers and smaller than 10 micrometers (PM_{10}) and fine particles that are 2.5 micrometers and smaller in diameter ($PM_{2.5}$). As a point of reference, the average human hair is about 70 micrometers in diameter.

Health Effects of PM: The effect of PM on public health is very direct, causing acute respiratory stress and contributing to a range of chronic illnesses from long-term exposure. PM contains microscopic solids or liquid droplets that are so small that they penetrate deep into human lungs and cause serious health problems. For example, particulates that are smaller than 10 micrometers can penetrate deeper into the lungs and can even enter the blood stream. According to the above information, the size of the particles is a key determinant of how severe PM's effect of human health can be. As measurement techniques and epidemiologic studies have improved in recent decades, increasing attention is being given to the effects of particles even smaller than $PM_{2.5}$. Many health authorities have listed PM that specifically comes from diesel engines (diesel PM, or "DPM") as a "toxic air contaminant" indicating it has specific and demonstrated carcinogenic effects.

Sulfur Oxides (SO_x)

Sulfur oxides are caused by the oxidation of the sulfur in the fuel into SO_2 and SO_3. Sulfur is found in raw materials such as crude oil, coal and ore that contain common metals (aluminum, copper, zinc, lead and iron). Fuel containing sulfur, such as coal and oil, when burned can lead to the production of SO_x gases. Sulfur oxides gases in an exhaust stream serve as an accumulation point for a range of toxic organic chemicals and other substances in the exhaust stream creating additional PM. Despite regulations that have helped to decrease sulfur concentrations in fuel around the world, SO_x emissions from ships and land-based equipment remain a significant concern.

Health Effects of SO_x: They are caused by the exposure to high levels of SO_2 and include breathing problems, respiratory illness and worsening respiratory and cardiovascular disease. While SO_x gases can itself be harmful in high concentrations, they interact with other substances in the air to create particulate matter. PM created from SO_x is harmful both as a physical lung irritant and for its chemical characteristics, making it particularly harmful to sensitive groups. People with asthma or chronic lung or heart disease are the most sensitive to SO_2. They also include people with developing, decreasing or hyperactive lung function such as children, elderly people and active adults, respectively. In addition to health effects, SO_x in the atmosphere can create significant aerosols that impair visibility and can contribute to the formation of acid rain.

Each of these ship emissions have not the same effect at the same ranges from the emissions sources as mentioned above. The illustration in Figure 10 shows the actual range of impacts that cause concern for pollutants varies from nearby to worldwide.

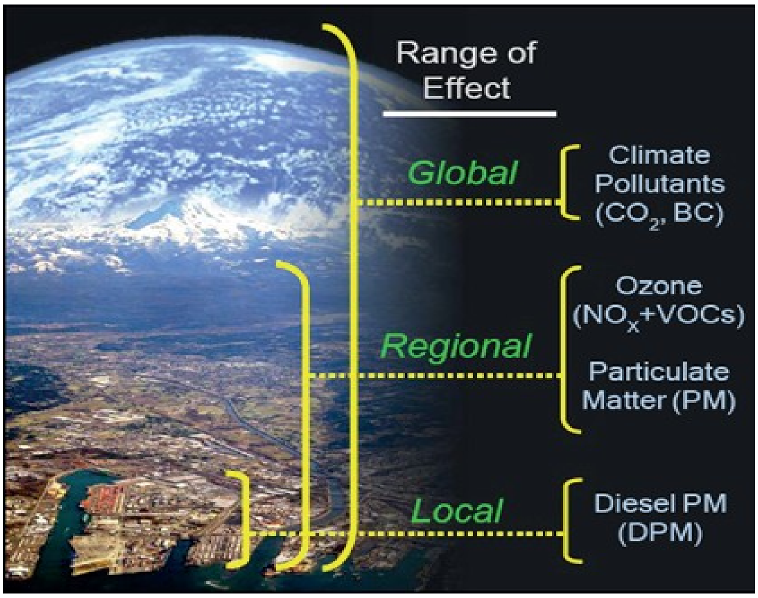

Figure 10: Range of impacts for various pollutants related to the ship-port interface [8].

Port communities facing bad consequences and health effects, because they are in very close distance to port facilities. Especially, air pollution emitted from port-related activities adversely affect the health of port workers, as well as residents of nearby port area, and contribute significantly to regional air pollution problems. Since for many years' air pollutant emissions had remained comparatively unregulated, ships and port facilities are now among the world's most polluting combustion sources per ton of fuel consumed.

Chapter 4: Emissions estimation

Nowadays, shipping emissions has strongly increased and actually are predicted to increase between 50% and 250% by 2050, depending on the future economy and the energy developments. To understand this major emission increase this chapter presents some emission estimations. Emission estimates are quite important for developing emission control strategies in order to reduce the emissions. The following tables contain emissions from the entire transport sector in order to compare the shipping emissions between the other transport sectors.

4.1 Emissions estimation and fuel consumption for marine vessels and on-road vehicles

An estimation of the proportion of air pollutant emitted from ships has been proposed [27]. This estimation provides an intermodal comparison of transport emissions for US case study. Specifically, they found that large ships generated the 30% of total nitrogen oxides emissions in year 2003. Moreover, they estimate that a single cargo ship coming into harbor can release as much pollution into the sky as 350,000 cars in one hour. Also, 16 container ships in port can produce as many emissions as one million cars and a cruise ship in port produces as many emissions as 12,400 cars. Table 4 reports the main results of their intermodal comparison analysis.

	Emissions (g/kg fuel)[4]		Carbon intensity[5]	Fraction of CO_2	Size of fueling station	No. of fueling stations
	NO_x	CO_2	($/tC)	(%)	(power)	
Marine	71	16	950	6	175 MW	28-40[6]
Autos[7]	14	130	2300	56	2.7 MW	180,000
Aircraft	3	17	2100	8.7	240 MW	72[8]
Heavy trucks	30	17	2800	16	20 MW	5,500
Rail	76	9	3500	2.3		

Table 4: Intermodal comparisons [27].

While greenhouse gas emissions from non-transport sectors fell 15% between 1990 and 2007, transport emissions increased by 33% over the same period. They have started falling only recently due to high oil prices and improved vehicle efficiency. More than two thirds of transport-related greenhouse gas emissions are from road transport, which contributes about 20% of the EU's total emissions of CO_2. According to EEA-32 report, Figure 11 has the contribution of the transport sector of total emissions of the main air pollutants for the year 2009. Transport accounts more than non-transport in NO_x's case, as it constitutes the 58% of total emissions. The dominant cause of NO_x pollutants in transport is created by road transportations, followed by those of international shipping with 15% and domestic shipping with 4%. Also, in SO_x' s case transport contains the 21% of total emission compared with non-transport and this time international shipping is the dominant cause of SO_x pollutant with 19%. In case of PM_{10} and $PM_{2.5}$, it is estimated that the road transport exhaust and the international shipping have the same contribution in world pollutant (by 7% and 10% for each case).

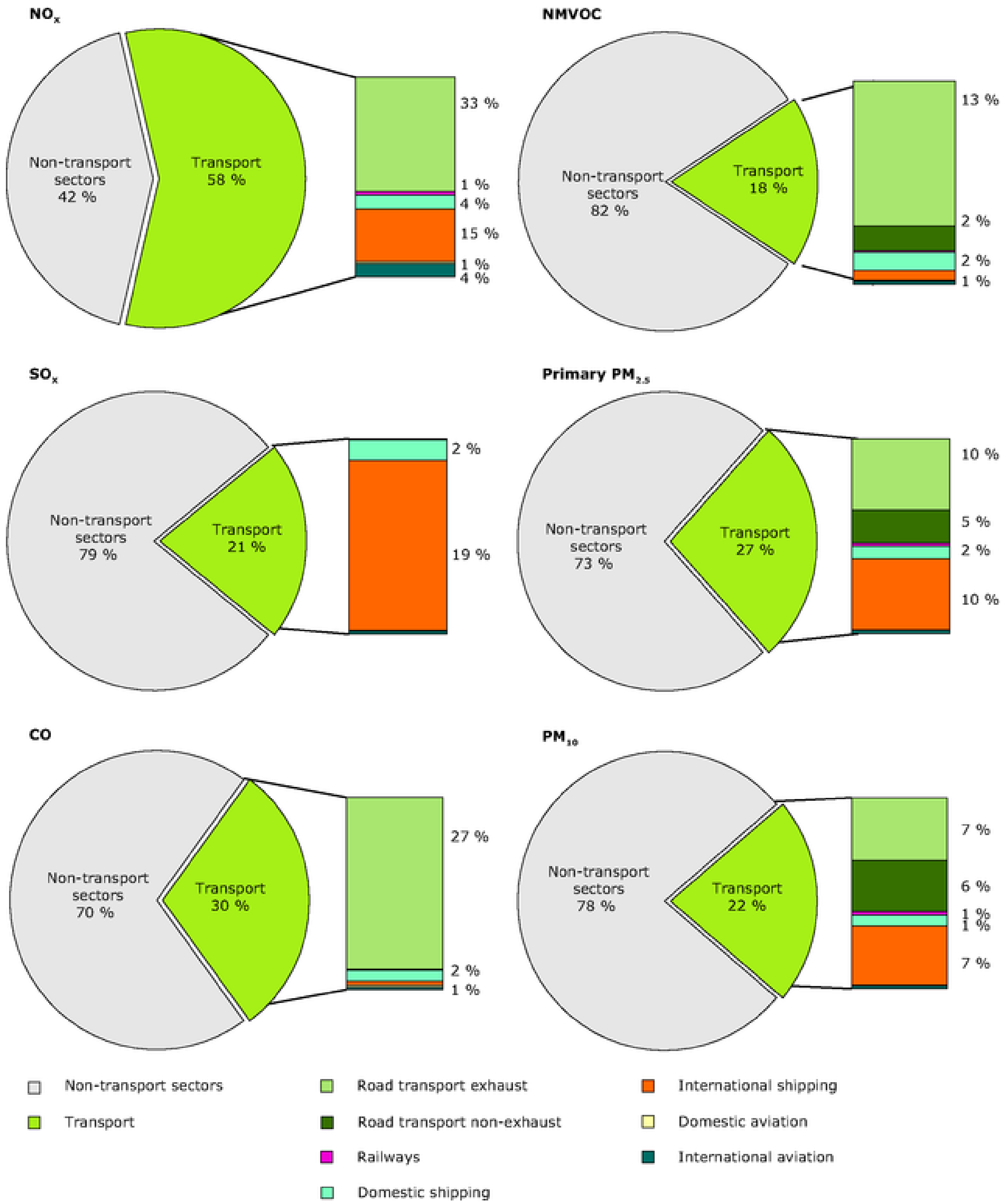

Figure 11: The contribution of the transport sector to total emissions of the main air pollutants in 2009 [28].

Sea shipping results to be the most environmental friendly mode of transport for goods, when measured in terms of emissions per ton-km (tones of goods per km). However, for the absence of an emission reduction strategy, the growth rate of maritime shipping, which is expected to continue in the future due to the global supply chain, will be translated in an emissions growth of the same magnitude. Many similar reports support the finding that ship emissions are significant compared to emissions from on-road sources [29], [30]. Also, other reports that reported below, estimate the amount of pollutant emissions and other calculate the trend for the future emissions.

4.2 Emission estimation in shipping industry

Shipping could in one way be considered a relatively clean transport mode. One of the main aspects is that carbon dioxide emissions in many cases are lower for ships than for road transports calculated in relation to amount of goods transported (per tons km). Typical ranges of CO_2 efficiencies of ships are between 0 and 60 grams per ton-kilometer, this range is 20-120 for rail transport and 80-180 for road transport (IMO 2009). There is considerable variety between vessel types and CO_2 efficiency generally increases with vessel size. As already mentioned, it has estimated that CO_2 emissions from shipping are being around 2-3% of total global emissions. Also, the emissions from sulfur dioxide are presently considerably larger than from road transports and the nitrogen oxides emissions are about twice the emissions from road transports in relation to amount of good transported (per tons km). According to this, table 5 could help in understanding of the range between pollutants in the port area. Specifically, non-GHG emissions are in the range of 5-10% for SO_x emissions and 17-31% for NO_x emissions (Table 5).

Compared with other transport modes, shipping emissions are also substantial. Whereas CO_2 emissions of shipping might be approximately a fifth of those of road transport, NO_x and PM emissions are almost on a par, and SO_x emissions of shipping are substantially higher than those of road transport by a factor of 1.6 to 2.7 [31]. According to Eyring et al. (2003) international shipping produces about 9.2 more NO_x emissions than aviation, approximately 80 times more SO_x emissions and around 1200 times more particulate matter than aviation, due to the high sulfur content in ship fuel. These emissions have increased at a large pace over the last decades and are expected to increase in the future. Eyring et al. (2003) show that main shipping emissions (CO_2, SO_x, NO_x and PM) grew with a factor of approximately 4 over the period 1950-2001, faster than the increase of the number of ships over that period, which tripled. Shipping emissions are projected to increase over the coming decades. For example, the IMO assumed in 2014 that shipping-related carbon dioxide emissions would increase with a factor two to three up till 2050 [32].

Although most of these emissions take place at sea, the most directly noticeable part of shipping emissions takes place in port areas and port-cities. It is here that shipping emissions have the most direct health impacts.

	Estimation (mln tonnes)	Year	Share of total emissions	Source
CO_2	949	2012	2.7%	IMO 2014
	1050	2007	3.3%	IMO 2009
	944	2007	-	Psaraftis & Kontovas 2009
	695	2006	-	Paxian et al. 2010
	813	2001	3%	Eyring et al. 2005
	912	2001	3%	Corbett & Koehler 2003
	501	2000	2%	Endresen et al. 2003
	419	1996	1.5%	IMO 2000
SO_x	10	2012	-	IMO 2014
	15	2007	-	IMO 2009
	14	2005	10%	ICCT 2007
	12	2001	9%	Eyring et al. 2005
	13	2001	9%	Corbett & Koehler 2003
	6.8	2000	5%	Endresen et al. 2003
	16.5	2005	-	Cofala et al. 2007
NO_x	17	2012	-	IMO 2014
	25	2007	-	IMO 2009
	22	2005	27%	ICCT 2007
	24.3		-	Cofala et al. 2007
	21.4	2001	29%	Eyring et al. 2005
	22.6	2001	31%	Corbett & Koehler 2003
	12	2000	17%	Endresen et al. 2003
PM_{10}	1.3	2012	-	IMO 2014
	1.8	2007	-	IMO 2009
	1.9		-	Cofala et al. 2007
	1.7	2001	-	Eyring et al. 2005
	1.6	2001	-	Corbett & Koehler 2003
	0.9	2000	-	Endresen et al. 2003

Table 5: Overview of studies on global shipping emissions [33].

Ocean-going vessels contribute significantly to global emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM). Indeed it is estimated that by 2020, ship emissions contributions to the European Union (EU) NOx and SO_x inventories will surpass total emissions generated by all land-based mobile, stationary and other sources in the twenty-eight nations. Because their air emissions remain comparatively unregulated all these years and only recent in 2016 new and more strict measures adopted, ships are now among the world's most polluting combustion sources per ton of fuel consumed [2]. Due to government policies implemented over the last several decades, land-based pollutant emissions in many countries have declined rapidly, even as energy use and transportation demand have grown. Landbased SO_x emissions in Europe have declined last decades, and are projected to continue to decline as new standards are phased in. Land-based emissions of other air pollutants such as NO_x and volatile organic compounds (VOCs) have also declined in many countries, but to a lesser extent.

The emissions of air pollutants from ships engaged in international trade in the seas surrounding Europe – the Baltic, the North Sea, the north-eastern part of the Atlantic, the Mediterranean, and the Black Sea were estimated to have been 2.6 million tons of sulfur dioxide and 3.6 million tons of nitrogen oxides (expressed as NO_2) in year 2000. While pollutant emissions from land-based sources are gradually coming down, those from shipping show a continuous increase.

Also several inventory studies suggested that in 2000, ocean-going ships have emitted around (600-900) thousands tones of CO_2, 15% of all global NO_x emissions and 4-9% of global SO_2 emissions [34]. While in 2007, the quantity of gases emitted from ships estimated to be 25 and 15 million tons of NO_x and SO_x respectively, and have estimated around 2.7% of all global CO_2 are attributable to ships [35]. Other studies revealed that shipping-related PM emissions are responsible for 3-8% of global $PM_{2.5}$ related mortalities [36].

For the Baltic Sea, the North Sea and the English Channel, it is expected that shipping emissions of SO_2 and NO_x will increase by 40–50 % between the year 2000 and 2020. By 2020 the emissions from international shipping around Europe are expected to equal or even surpass the total from all land-based sources in the 25 EU member states combined (see Figures 12 and 13).

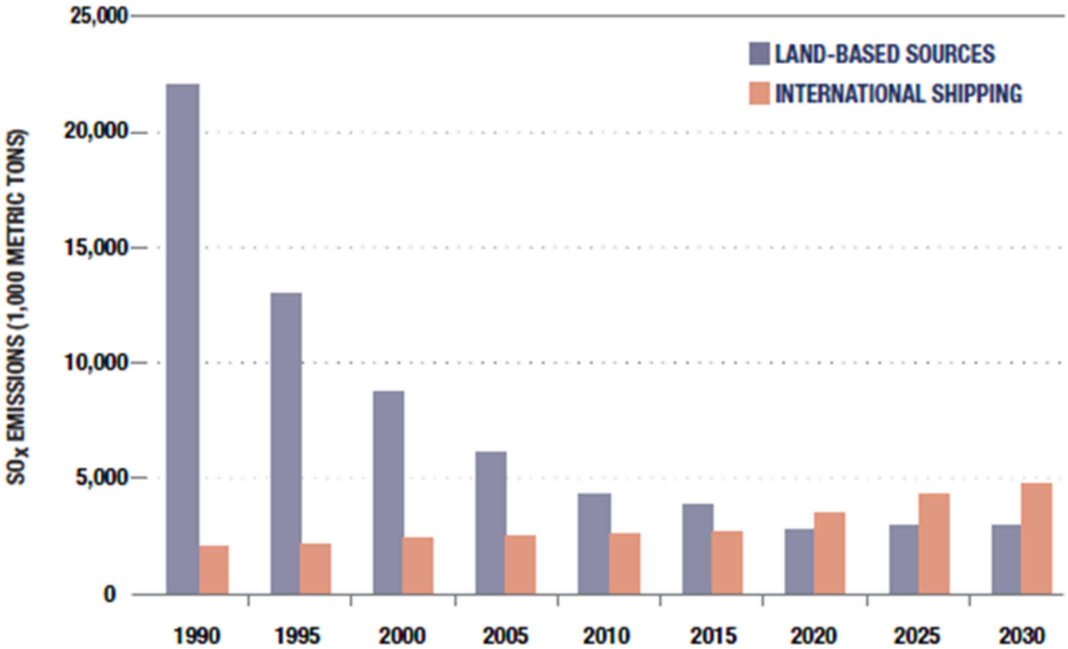

Figure 12: Inventories and Projections of SO_x Emissions in Europe from Land-based and International Shipping [31].

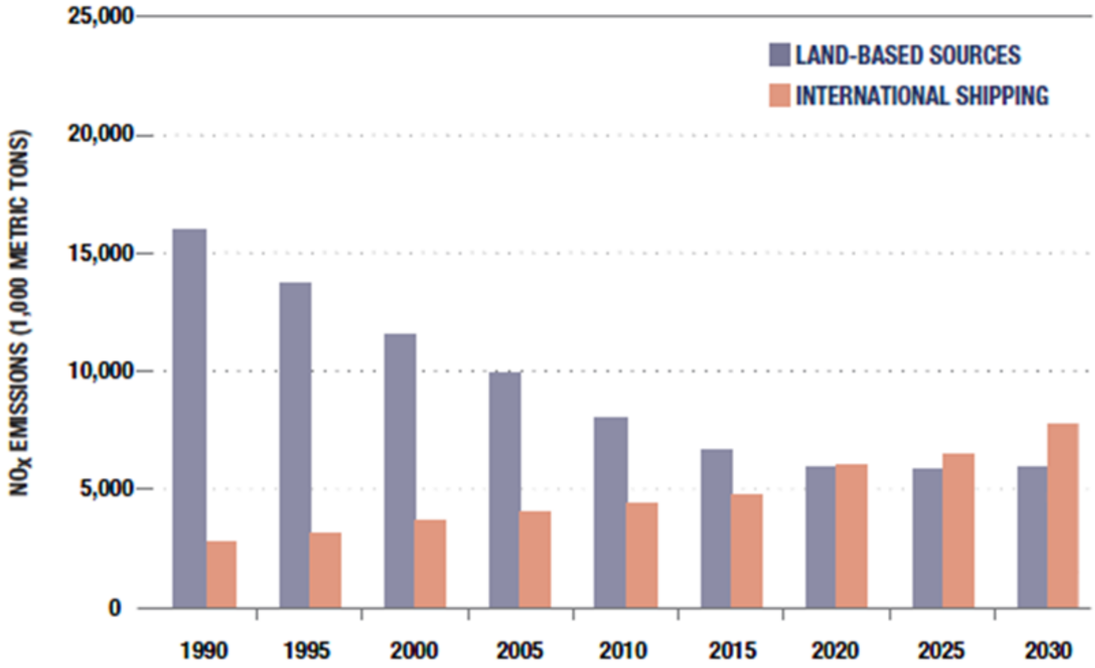

Figure 13: Inventories of NO_x Emissions in Europe from Land-based and International Shipping [31].

It should be noted that these figures, high as they are, refer only to ships in international trade. They do not include emissions from shipping in countries' internal waterways or from ships plying harbors in the same country, which are given in the domestic statistics of each country.

Nevertheless, if the recent international agreements for SO_2 and NO_x emission standards is implemented, by 2020 emissions of SO_2 should come down significantly, and those of NO_x will not increase as much as previously anticipated.

4.3 Estimated shipping emissions in ports in 2050 - Future Emissions from International Shipping

The data that was used in this study bellow, collected by Lloyd's Maritime Intelligence Unit (LMIU)[37] and include vessel movements of ships world-wide. Most shipping emissions in ports will grow fourfold up to 2050. This is the case for CH_4, CO, CO_2 and NO_x emissions. This would bring CO_2 emissions from ships in ports to approximately 70 million tons in 2050 and NO_x emissions up to 1.3 million tons. The level of PM_{10} and $PM_{2.5}$ emissions from ships in ports remains at the level of 2011 emissions and SO_x emissions decline slightly compared to the 2011 level (Figure 14). The growth in most shipping emissions is driven by growing demand for certain commodities and goods fueled by growth of population, economy and trade. The projections are based on the ITF freight model that predicts the flows of 18 different cargo types between 226 places in 84 different countries. These growth rates for cargo types have been translated into growth projections of port calls of the corresponding ship types in each country. In this calculation assumed that ship turnaround times remain at a similar level and that all international obligations that have an impact on ship emissions will be implemented in the timelines currently foreseen. Thus, the reduction of the maximum allowed sulfur content in fuels would be reduced to 0.5% by 2020, and already from 2015 in emission control areas the allowed sulfur content is 0.1% [33]. However, there is some probability that the introduction of the 0.5% global limit would be postponed until 2025 [38].

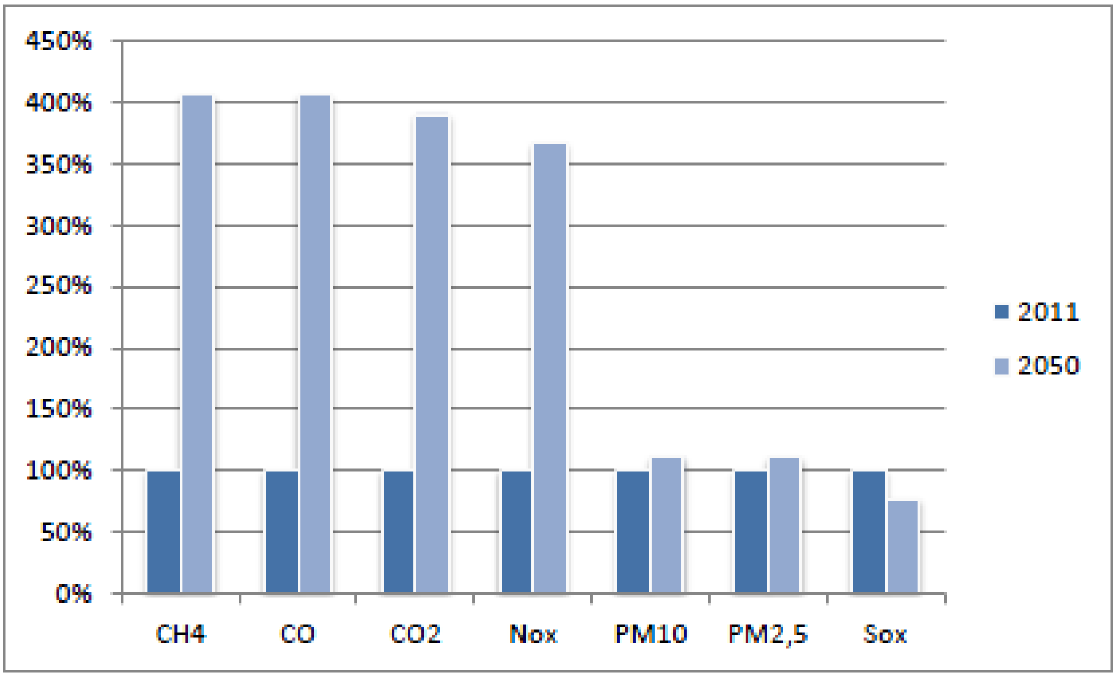

Figure 14: Increase in shipping emissions in ports 2011-2050 [33].

Many projects have similar results with the above study. Thus, the next study [31] agree that commercial shipping is at the heart of an ongoing expansion of global trade and that shipping emissions will be increased in the future. Ship traffic has increased continuously over the last two decades and is expected to continue growing for the foreseeable future. This growth has important implications for the magnitude of the ship contribution to future air pollution and greenhouse gas inventories. Figure 15 through figure 16 summarize emissions projections for marine operations through 2050. Figure 16 and figure 17 present the shipping sector's contribution relative to projections of emissions from the Intergovernmental Panel on Climate Change (IPCC) [39]. However, PM emissions are not included because an estimate of global emissions for this pollutant is not currently available.

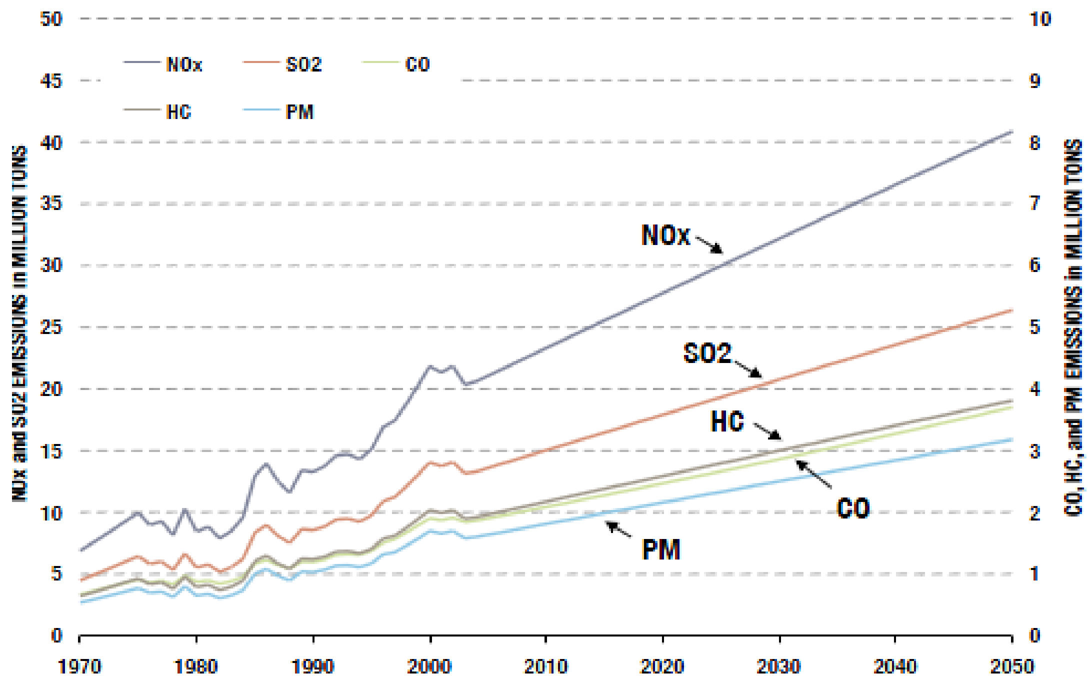

Figure 15: NO_x SO_2, CO, HC, and PM Emissions from International Shipping: 1970–2050 [31].

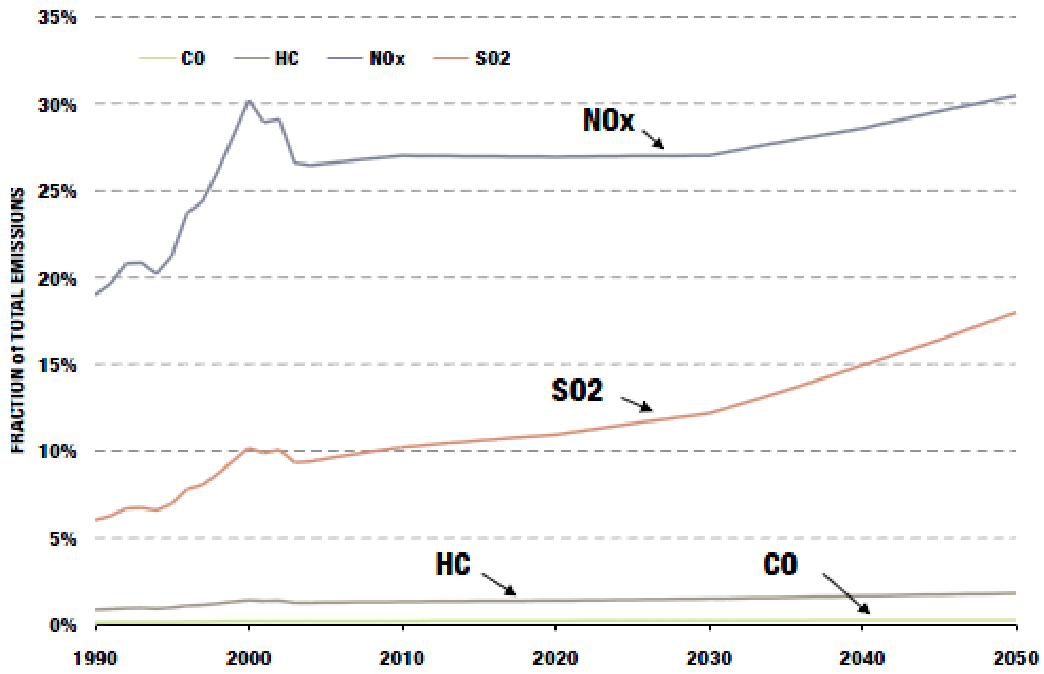

Figure 16: Shipping Emissions as a Fraction of Estimated Global NO_x, SO_2, CO, and HC Emissions: 1990–2050 [31].

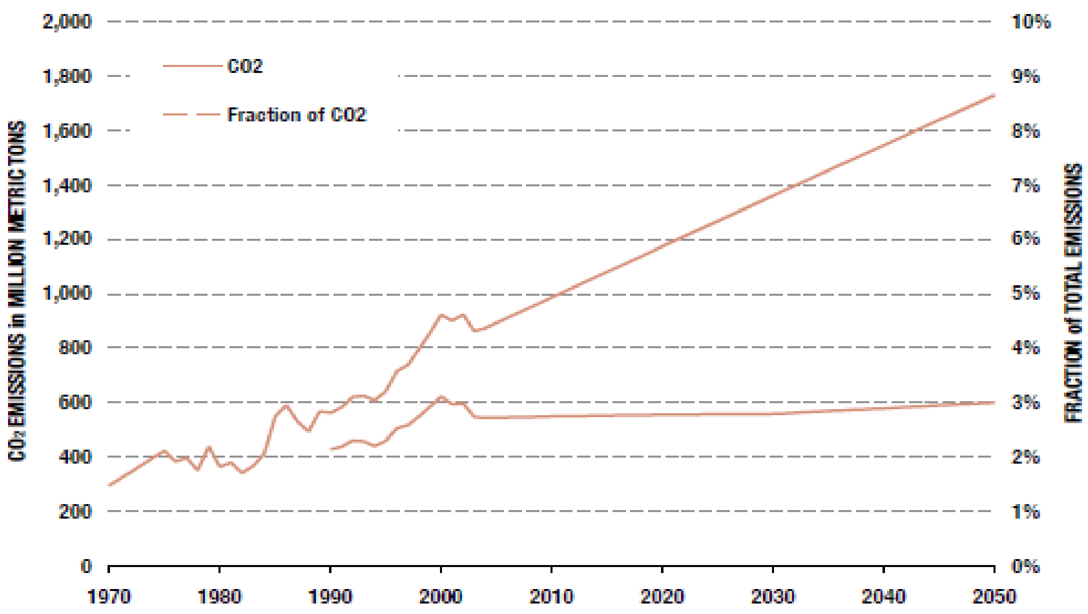

Figure 17: Global CO_2 Emissions from International Shipping and Fraction of Total Emissions: 1970–2050 [31].

This specific emission inventory of [31] study is based on a simplified bottom-up approach in which global marine cargo shipments were used to derive historic and future activity levels for the international shipping fleet. As with the Corbett and Koehler (2003) [26] and the Eyring et al.(2005a) [29] analyses, the ICCT 2007 [31] analysis did not rely on marine bunker fuel statistics. Energy consumption for the international shipping fleet was calculated by multiplying global marine cargo movements in ton-kilometers by global marine operating efficiency. The ICCT 2007 analysis [31] is more limited than the studies summarized in previous sections in that it does not attempt to place emissions spatially. It also makes some judicious simplifying assumptions that tend to underestimate rather than overestimate fuel consumption and emission levels.

In 2005, international shipping accounted for 27% of global NO_x emissions, 10% of global SO_x emissions, and 3% of global CO_2 emissions. If current trends continue, the ship contribution as a % of global emissions in 2050 is expected to rise to more than 30% for NO_x, 18% for SO_x, and 3% for CO_2. Total ship emissions of fine particles are also estimated to more than double in that period [31].

Chapter 5: Techniques for reducing emissions from ships

This chapter is about a presentation of the different technologies for reducing shipping emissions. The goal of this part is to present different solutions for ships and their technical drawings. These arrangements are compared to each other about their emission reduction rate that could achieve and the complexity of their technical drawings in order to find, at the end, the best settings for the ships. Since every ship has different requirements, it is quite difficult to find a general acceptable solution for every ship, thus each decision is based on different factors. In our report the ship type that analyzed is cruise ship, without meaning that the solutions are just for this type of ships only.

Technologies for emissions reduction can be divided into four general areas: In – engine technologies, after-treatment technologies, fuel–related technologies and alternative power systems. In this chapter, every emission reduction category will be presented on a table with a summary of the different technologies for each category. This table consists by five columns. The first column examined if a technology is retrofittable on existing ships (Y-Yes) or limited to only new builds (N-No). The following three columns denote the shipping pollutants that examine in this study and the reduction rate that could be achieved with the use of each technology. Also for each pollutant the table presents some darts that show if the use of one technology affects some pollutant positive or negative. Thus, are used the following indicators:

- ↑ for increases
- ↓ for decreases
- ↕ for either increase or decrease depending on various factors

Also, if the available data are limited such that the reductions cannot be quantified at this time, they are denoted as “to be determined” (tbd). Finally, each application of a measure needs to be evaluated on a case-by case (cbc) due to the different conditions and specific parameters that have to be considered to determine the most appropriate reduction level. The last column denotes the references-sources that used in this study for each abatement technologies.

The most emissions reductions technologies are concerned with NO_x and SO_x emissions due to their bad effect on the marine environment [5]. These techniques are also very cost-effective compared to further emission reduction costs for land-based sources that are already relatively efficiently controlled. The most common methods to reduce sulfur dioxide (SO_x) emissions are the switch from fuels with a high sulfur content to low-sulfur ones and also the introduction of the seawater scrubbing technology. For nitrogen oxides (NO_x) abatement the most promising methods are internal engine modifications, selective catalytic reduction (SCR), water injection techniques and exhaust gas recirculation (EGR). Particulate matter (PM) emissions partially reduced with the sulfur dioxide reduction measures and for further reduction oxidation catalysts and particulate filters can be used. Carbon monoxide and hydrocarbon emissions from ships are usually low and therefore there are no commercial techniques developed to reduce them separately from marine engines. Nevertheless, some of the reduction methods, such as the SCR and EGR systems, also lower amounts of CO and HC emissions. Also the emissions of the different pollutants can be reduced by optimizing ships' design, using alternative power sources and using shore-side electricity at ports. In the following is given more detailed presentation of various emission reduction methods.

Reduction by internal engine adjustments

Many parameters influence the combustion efficiency and emission formation in the combustion process. These include fuel injection timing, combustion chamber geometry, compression ratio, valve timing, turbulence, injection pressure, fuel spray geometry and rate, peak cylinder temperature and pressure and charge air temperature and pressure. Methods have the aim to reduce NO_x emissions by lowering the peak temperature and the pressure in the cylinder. Generally, this decreases the engine's thermal efficiency and increases the amount of particular matter (PM) emissions (and also CO and HC emissions). Despite this fact, there are some internal engine adjustments can be done to compensate the negative effects. As a result, the control of several in-cylinder parameters is important in diesel engines to ensure low emission levels and fuel economy. Three categories are generally considered about the parameters that affect the combustion process and the formation of emissions: charge air characteristics, fuel injection characteristics and combustion conditions in the combustion chamber. The techniques to improve those three segments are described in the sections below. The charge air characteristics are improved with turbo-charging and after-cooling of the charged air. For the development of fuel injection system, it is necessary to develop correctly the fuel injection pressure, the nozzle geometry, the control of injection timing and rate, the common rail fuel injection, the electronic-hydraulic control of fuel injection and the exhaust valve actuation [40], [41]. Usually engine manufacturers use a combination of several engine modification techniques to limit the emissions from diesel engines [18]. Table 6 provides a summary of all these different engine technologies highlighted in this study with further details for each provided below.

	Retrofittable	% NO_x reduction	% SO_x reduction	% PM reduction	References
Engine Technologies					
Increase of Injection Pressure - "Common Rail Technology"	Y	25	-	↓ cbc	[8]
Exhaust gas re-circulation	Y	10-60	75-99	tbd	[8], [10], [11], [16], [31], [42]
Rotating fuel injection controls	N	25	cdc	40	[8]
Electronically controlled lubrication system	Y	-	-	20-30	[8]
Automated engine monitoring /control system	N	25	3	tbd	[8]
Internal engine modifications (IEM)	Y	20-40	-	50	[10], [11], [16], [31], [42]–[45]
Continuous water injection (CWI)	Y	30	-	5-18	[8], [10], [43]
Direct water injection (DWI)	Y	50-60	-	↕ cbc	[8], [10], [11], [16], [31], [43]–[46]
Fuel water emulsions (FWE)	Y	10	-	-	[8], [11], [31], [42], [43], [47]
Humid air motor (HAM)	Y	70-80	↑ cbc	↑ cbc	[8], [10], [11], [16], [31], [42], [44]–[46], [48]
Two stage turbochargers	Y	40	-	tbd	[8]
Turbocharger cut off	Y	40	-	tbd	[8]
Selective Non-Catalytic Reduction	**Y**	**50**	**-**	**-**	**[10], [11]**

Table 6: Summary of engine technologies that reduce ship emissions.

Increase of Injection Pressure - "Common Rail Technology"

Common rail permits the continuous and load-independent control of fuel injection timing, injection pressure and injection volume. In the common rail system injection pressure and rate are controlled independently from the engine speed and load. It has applicability on propulsion and auxiliary engines. Also it has the potential to reduce emissions during sea, transition and maneuvering. The common rail system comprises pressurizing fuel pumps, fuel accumulators and electronically controlled fuel injectors. The fuel pumps are driven by the camshaft and each pump and accumulator serve two cylinders. All system functions are controlled by the embedded control system on the engine. Because of the flexibility of the fuel injection process, NO_x emissions, fuel consumption and exhaust opacity can be improved by varying injection pressure when the fuel injection is started, relative to piston location in the cylinder. It can achieve to reduce NO_x emissions up to 25% and CO_2 emissions up to 5% [8]. The system's main advantages are that the fuel injection pressure can be kept at a sufficiently high level over the entire load range, which helps reduce NO_x and eliminates visible smoke from the exhaust, at low loads. Besides smokeless operation the common rail technology helps to achieve lower and more constant running speed, reduces fuel consumption especially at part loads and improves combustion process thus the efficiency due to optimized fuel injection [49].

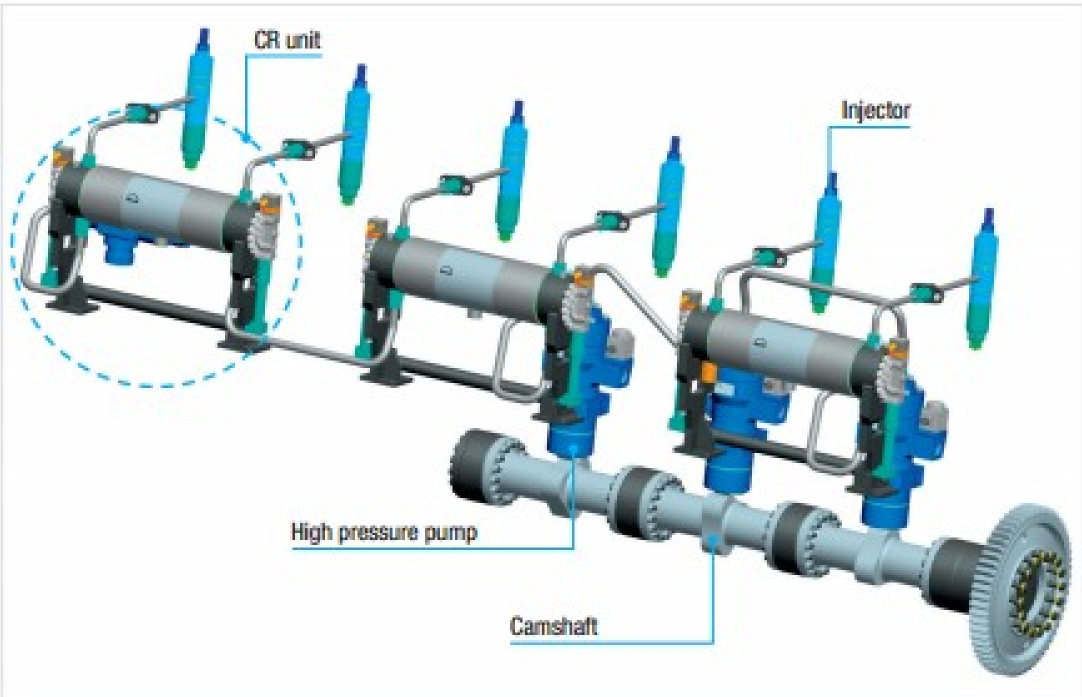

Figure 18: Common rail illustration, by MAN [8].

Exhaust gas recirculation

In exhaust gas recirculation (EGR), engine exhaust gas is recirculated into the charged air after the turbocharger, thus reducing the oxygen content in the cylinder and increasing the specific heat capacity of the air. This in turn decreases the peak temperatures and hence the formation of NO_x during the combustion process. EGR is sensitive to sulfur content of the fuel being combusted, as higher sulfur content can lead to soiling and component corrosion.

Due to the reduced amount of oxygen and longer burning time the PM emissions tend to increase especially at the high loads. This problem can be minimized by reducing the recirculated gas flow during the operation at high loads. Thus EGR works well with exhaust gas scrubber technologies that remove sulfur and PM from the exhaust gas. It has applicability on propulsion and auxiliary engines. Also it has the potential to reduce emissions during sea, transition and maneuvering. The focus of EGR development has been on two-stroke, slow speed engines, but is under way the development for four-stroke medium speed engine EGR.

EGR systems can achieve NO_x reductions typically up to 60%, although some systems are showing promise up to 80% support the most recent report by IMO 2015. Entec also reports the reduction of 30% in NO_x emissions with exhaust gas recirculation [18]. Another study [42] reports the reduction of NO_x be up to 10-30% after exhaust gas recirculation technique. MAN B&W has made some tests at 75% engine load and NO_x emissions were decreased by 50% at the 20% recirculation rate. Also PM emissions were decreased by 20% and HC emissions by 10%. However, fuel consumption increased slightly and CO emissions doubled. Finally, US EPA 2003 [40] outlines that a switch from 2.7% sulfur RO to 0.3% MD reduces PM by 63%. The PM reduction to 0.1% MD will therefore be slightly higher than 63%. Generally, this technique is not appropriate when residual fuel is used due to high sulfur content.

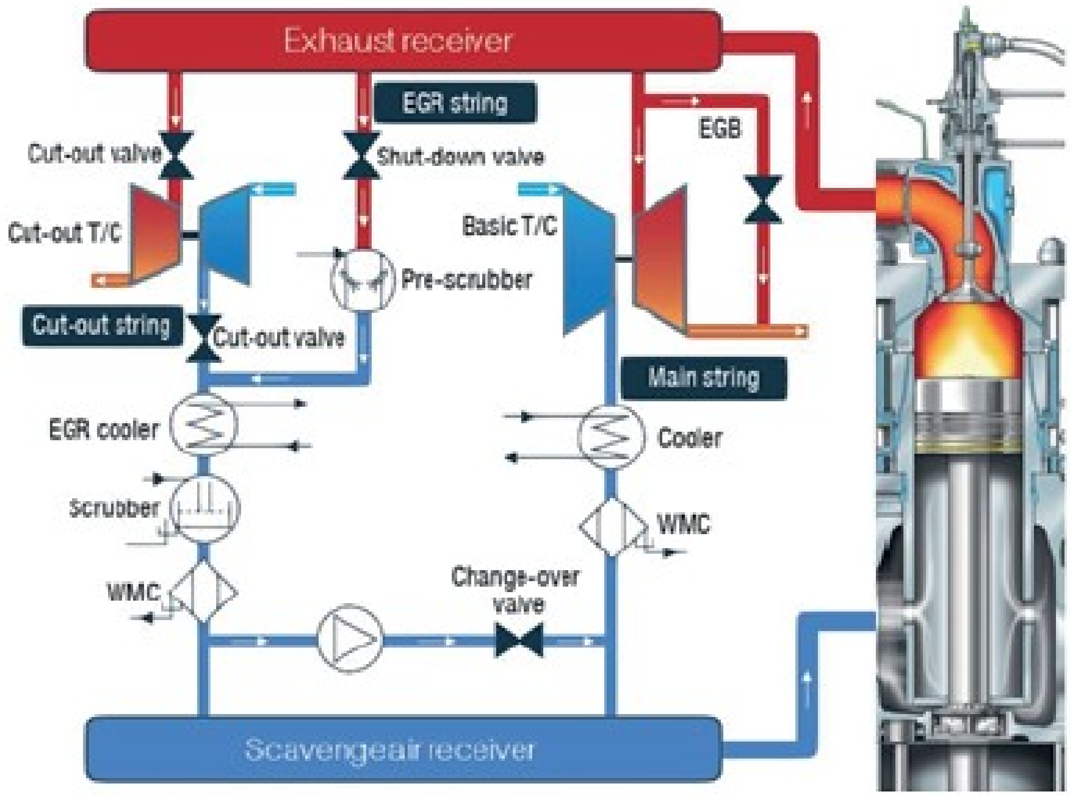

Figure 19: EGR illustration, by MAN [8].

Rotating fuel injector controls

Rotating fuel injector systems are found on some electronically controlled marine propulsion engines, specifically the Wärtsilä RT-Flex engine line, in conjunction with use of a common rail system. At low loads, which occur when complying with vessel speed reduction, these systems reduce the fuel injection from three nozzles, as in a standard engine, to two or one nozzle(s) that are rotated one position with each firing in order to maintain even cylinder wall temperatures. The result is that reduced fuel amounts are injected into the cylinder at low loads when fuel demand decreases, which optimizes the combustion process in the cylinder. Also it has the potential to reduce emissions during sea, transition and maneuvering and can achieve to reduce NO_x emissions up to 25% and PM emission up to 20-40% [8]. The system has been tested by Wärtsilä and shows promise for reducing both NO_x and PM with the co-benefit of CO_2 and fuel consumption reductions.

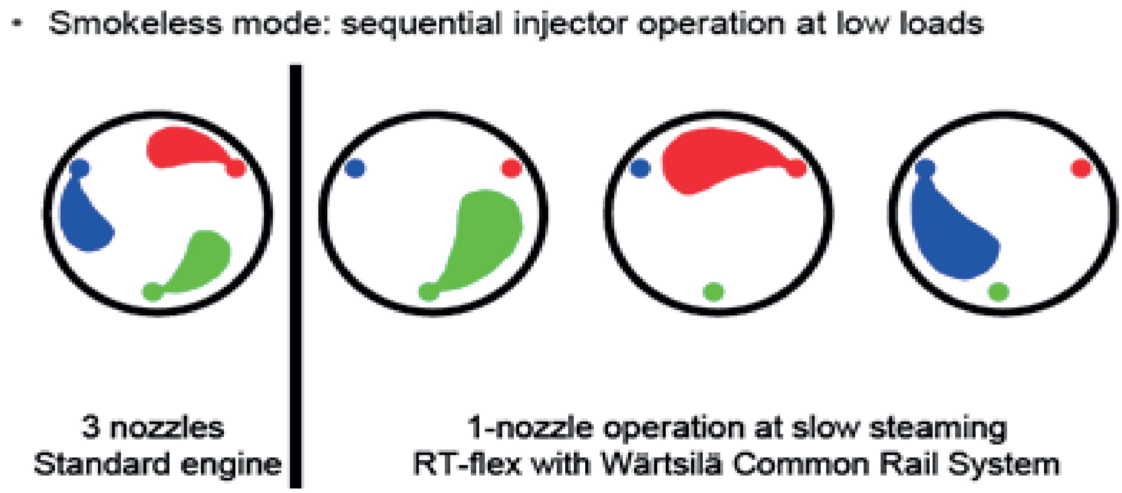

Figure 20: RT-Flex engine low-load nozzle cutout, by Wärtsilä [8].

Electronically controlled lubrication systems

Electronically controlled lubrication systems developed by both MAN and Wärtsilä provide for more efficient cylinder lubrication, reducing the amount of lubrication needed and improving the combustion cycle timing of lubrication oil injection/dosing. The injection rate can be adjusted automatically or manually as load changes, during startup and stoppage, at reduced loads in VSR, based on varying fuel oil sulfur content, as cylinder liner temperature levels change, etc. The systems have electronic controls that can be accessed by the ship's onboard engineering computers. In return, emissions associated with lubrication oil are reduced with the co-benefit of reduced maintenance costs. It can achieve to reduce PM and HC emissions up to 20-30% [8].

Automated engine monitoring/control systems

Automated engine monitoring and control systems that are typically found on electronically controlled engines provide for automatic tuning or adjustment of engine parameters during different operational conditions and engine loads. These systems can control turbocharger shutoff, fuel system equipment, engine fuel efficiency, adjust compression ratio, adjust exhaust valve timing, and adjust fuel injection timing, etc. Engines with these systems can be set to reduce peak combustion temperatures to reduce NO_x (low NO_x mode) and can include low load tuning packages. It can achieve to reduce NO_x emissions up to 25%, SO_x emission up to 3% and CO_2 emissions up to 5% [8]. Dynamic tuning of the engine allows for efficient response to varying injection pressures and timing, which can be optimized for fuel and/or NO_x over all engine loads.

Internal Engine Modifications (IEM)

Basic internal engine modification technique – slide valves

Slide valves are the most wide-spread internal engine modification technique and involve the exchange of conventional fuel valves with low NO_x. Slide valves are specific for MAN two stroke slow speed engines, but the modification of the spray pattern can be implemented on any injection nozzle. Slide valves are used for optimizing spray distribution in the combustion chamber, while the engine temperature is kept constant, which results in somewhat lower heat release than the conventional fuel valves and gives a considerable reduction of NO_x emissions.

According some studies, slide valves reduce NO_x emissions by 20% and also provide considerable reductions in VOC and PM emission [50], [51]. Wallenius Marine reports that measurements on MS Aida indicated 50% reduction of particle emission (PM). This is considered to be, due to the fact that slide valves provide a better control of the combustion process. Nevertheless, like the techniques based on affecting the combustion temperature for the reduction of NO_x, slide valves may increase the CO emissions [46], [52].

Slide valves are already standard on new vessels but constitute a retrofit option on existing ships. Retrofit installations are easy to undertake. The retrofit only entails removing the old valves, and enlarging the fuel injector holes in the cylinder covers. Also the expected life span is around 5 years. Once installed the life time of the valves will be the same as for conventional valves. During their life time they will be effective.

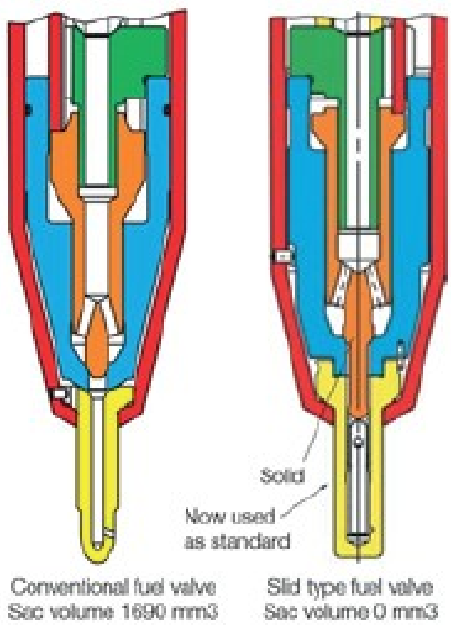

Figure 21: Conventional and slide valve configurations, by MAN [8].

Advanced internal engine modification technique

They are optimized combinations of a number of IEMs developed for particular engine families. They include: retard injection, higher compression ratio, increased turbo efficiency, common rain injection, etc. The most common combination used is increased compression ratio, adapted fuel injection, valve timing and different nozzles [40]. The IEM combinations can reduce NO_x emissions by 30-40% below the IMO NO_x standard [40].

Water injection

Addition of water to the combustion process is a promising approach for NO_x reduction. The techniques using the water injection are continuous water injection (CWI), direct water injection (DWI), use of emulsified fuel and humid air motor (HAM). At these techniques, the water must have good quality to prevent clogging and usually in most methods the fuel consumption tends to increase. At high NO_x reduction rates the emissions of unburned CO, HC and PM tend to increase [53].

Continuous water injection

Continuous Water Injection (CWI) involves the injection of high quality water at relatively low pressures into the hot air stream after the turbochargers. CWI can be installed in either two or four stroke engines as retrofits. Also it has applicability on propulsion and auxiliary engines. CWI operates on the principle that peak combustion temperatures and reduced oxygen results in NO_x reductions during the combustion cycle. The potential emission reductions with CWI are up to 30% for NO_x and 5-18% for PM by [8]. Another study [43] also reports the reduction of 70% in NO_x emissions with continuous water injection technique. However, this high number reduction is achieved when CWI is applied in combination with internal exhaust gas recirculation (EGR) [10].

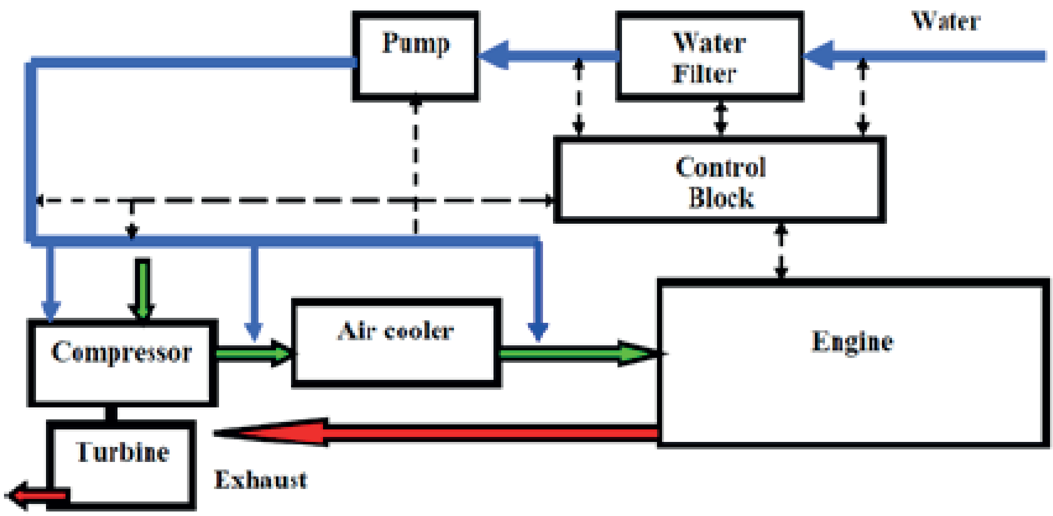

Figure 22: Continuous water injection system schematic [8].

Direct water injection

Freshwater is injected into the combustion chamber in order to lower the combustion temperature. Thus, water is injected into the engine cylinders right after fuel injection when the temperature in the cylinders is optimal for the NO_x reduction process. In direct high pressure water injection, the water is injected into the combustion chamber during the fuel injection. This enables cooler combustion space and hence lower NO_x emission level. The atomized water droplets vaporize immediately in the combustion chamber and the peak temperature is lowered as a combined effect of vaporization of liquid water absorbing heat and increased specific heat of the gas around the flame. If too much water is added the volume of the injected liquid increases leading to too long injection duration, which increases soot formation [54]. The sufficient tank capacity with the necessary fresh water handling system requires some space on board also [23]. The cruise ships have the source of fresh water already since the drainage water for example from showers could be filtered and used in the DWI system.

The technique of DWI can reduce NO_x emissions by 50-60% [8], [10]. The DWI has advantages over the other water injection techniques. The liquid water is close to the flame and away from the wall and the fuel-water can be changed for various operating systems [54]. The possibility to use high water-to-fuel ratio enables a high NO_x reduction potential with DWI.

However, a few disadvantages are also related to DWI technology. Major design changes are necessary for fitting the system on an engine. The system increases the fuel consumption and smoke emissions and it cannot be used at low loads at least at the full efficiency in order to avoid formation of white smoke and increase in black smoke [55]. The costs are higher than with the other water injection techniques because high amounts of fresh water and additional equipment for engine are needed [13]. Also the lifespan of the water injection nozzles is short [55]. The DWI technology is not recommended to use with fuel with high sulfur content (more than 3% sulfur).

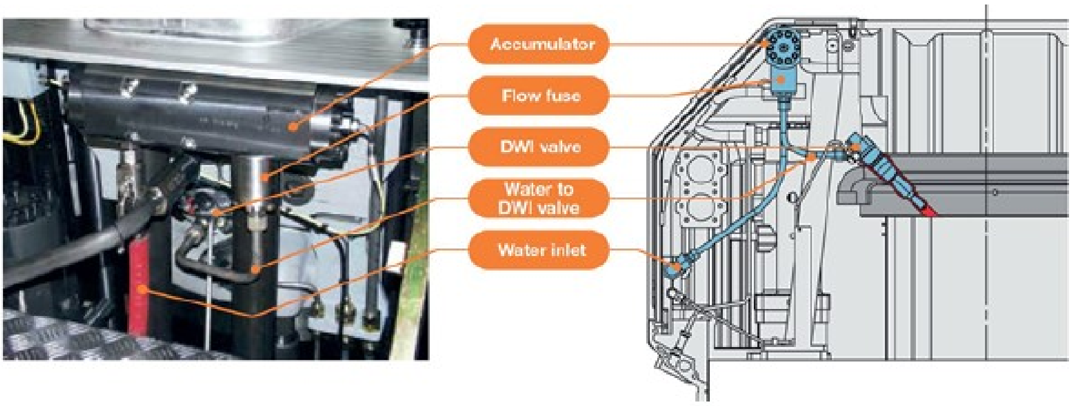

Figure 23: Direct water injection components, by Wärtsilä [8].

Emulsified fuel

In the method of emulsified fuel, water is mixed with fuel oil by means of homogenizer before injecting the fuel into combustion chamber. The injection of emulsified fuel enables effective atomization and good distribution of the fuel in the combustion chamber. This leads to more complete combustion with lower fuel consumption, a cleaner engine and a reduction in the amount of the main ship pollutants. In order to have the optimal spray into the combustion chamber, it is recommended that the water droplets in the fuel oil after emulsification are as small as possible. Moreover, the system requires a water distiller since the water used for emulsification must be clean and without salts [56], [57]. To obtain better reduction rates also at the full load it is fundamental to redesign the fuel injection system, camshaft and its drives etc. Moreover, the injection nozzles have to be adapted to the increased amount of fuel. With the new nozzle design the fuel consumption and temperatures might deteriorate if the engine is used without water. The proportion of water is also limited by the viscosity of the emulsion and the amount of heat required to reduce the viscosity for injection. However, this property of the water fuel emulsion cannot be affected by engine or system design [23].

Generally, a reduction of 10-30% NO_x emissions is possible to achieve with the usage of emulsified fuel [8]. In the report [58], they study about water-fuel emulsion with Caterpillar marine engines using heavy fuel. They were comparing the method to the direct water injection and found out that emulsified fuel system was better method in simultaneous NO_x and soot reduction. Also, Wärtsilä has made some research on emulsified fuel, but used Orimulsion to run the engines. The rate of NO_x reduction has been up 30% compared to normal heavy fuel oils [53].

Scavenging air moistening/humid air motor

The scavenging air moistening (SAM) used for large two-stroke engines, and humid air motor (HAM) used for four-stroke engines. Both of them humidify hot charged air from the turbochargers’ compressor, allowing it to absorb more heat, while at the same time reducing the oxygen content of the air. Specifically, the SAM system reduces NO_x emissions by spraying sea and fresh water into the hot scavenging air for cooling and humidification. The water injection takes place in three stages. First sea water is used for humidification and cooling and then two fresh water stages for removal of any salt from the scavenging. From each of the stages, surplus water will be drained back into three different tanks. The Humid Air Motor technique uses hot charge air to which water vapour is added to cool down and reduce the NO_x formation during the combustion process. The humidified air is generated through heating seawater (unlike CWI) through a heat exchanger in the humidifier and then interfacing the humid air with the charged air from the compressor. The result is a lower combustion temperature in the cylinder, and thus NO_x can be significantly reduced. Co-benefits from the system include: low operational costs, good engine performance via lower thermal loads and also the system requires no additional maintenance. The disadvantage is that HC and PM are increased due to cooler combustion temperatures, and there is a fuel consumption penalty of approximately 3%.

The reduction efficiency of HAM is reported to be 65% of NO_x emissions in IMO 2015. However, another report claimed that HAM technology can reduce NO_x emissions up to 80% down to level of 4 g/kWh. To achieve that about three times as much water vapour as fuel must be introduced into the combustion chamber [13]. Also Entec and other studies report 70-80% reduction for NO_x [46].

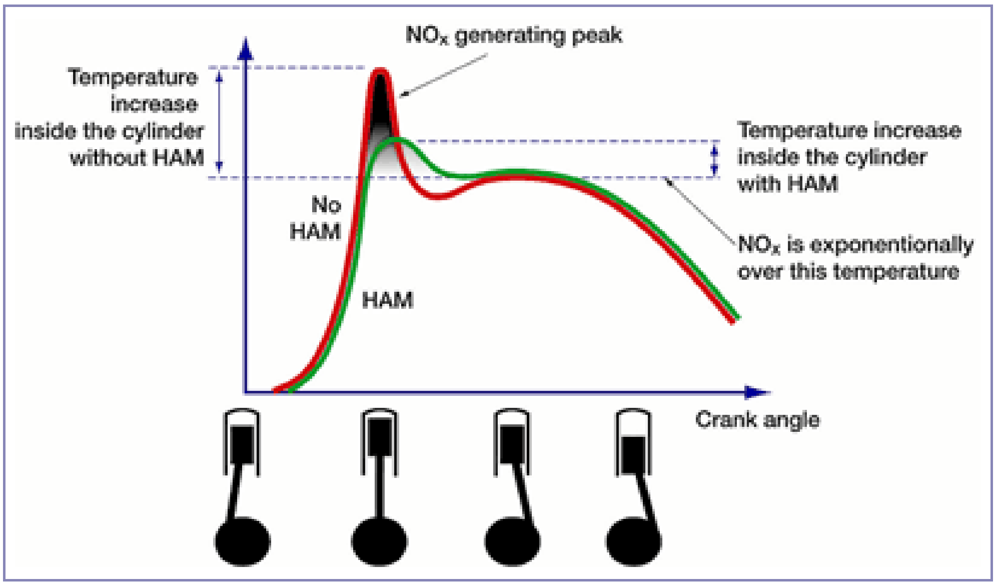

Figure 24: Wetpac humidification system, by Wärtsilä [8].

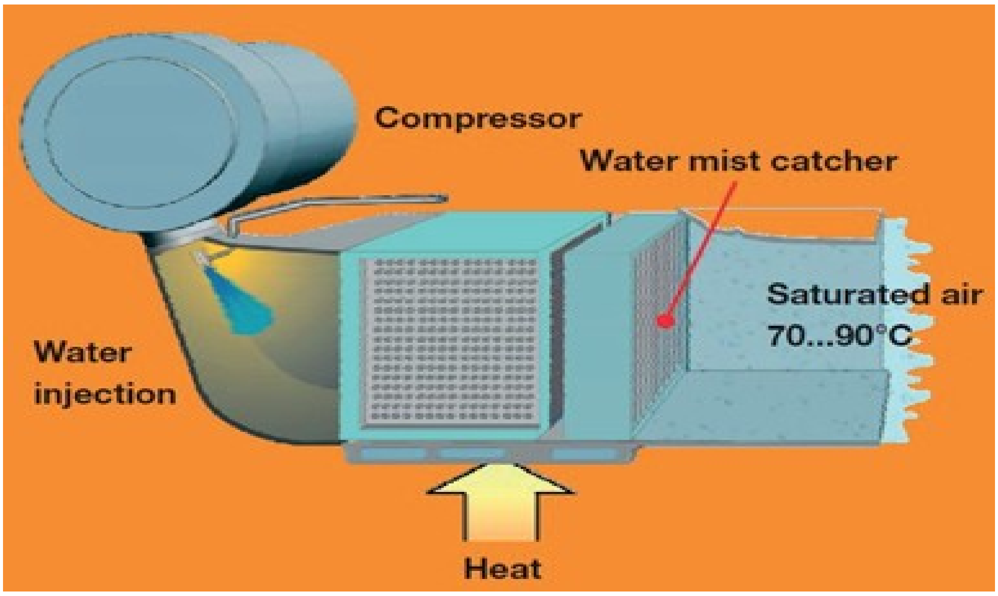

Figure 25: Humid air NO_x reduction by piston position illustration, by MAN [8].

Two stage turbocharging

High pressure, two stage turbocharging combines the use of low pressure and high pressure turbochargers in series to generate increased air pressure, airflow and more efficient turbocharging effect. By using two stage turbocharging NO_x and CO_2 emissions, as well as fuel consumption are reduced and more specifically it can be achieved 40% of NO_x emission reduction.

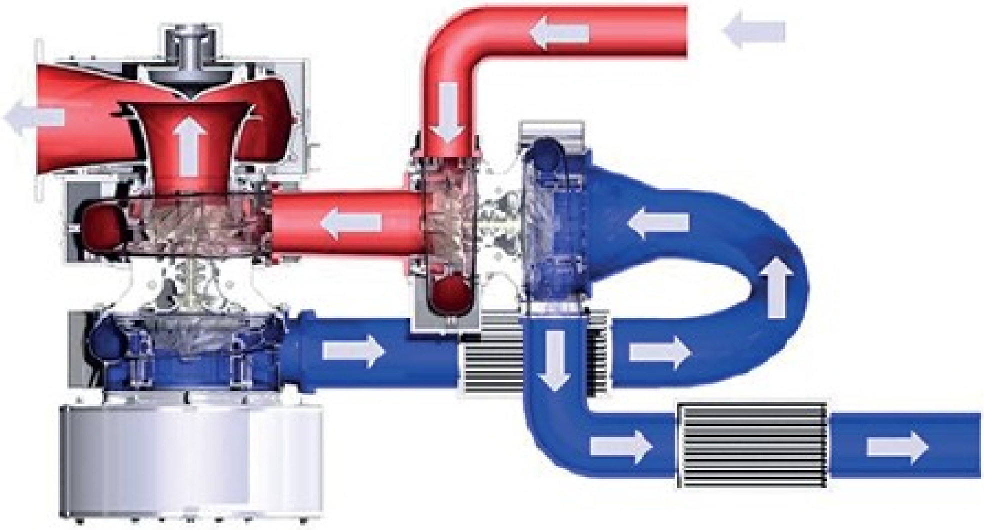

Figure 26: Two stage turbo charger illustration, by MAN [8].

Turbocharger cut-off system

Turbocharger cut-off systems lower fuel oil consumption and improve propulsion engine performance during low load operation. There are two methods in which can be achieved Turbocharger cut-off. The first method is by Installing swing gate valves on the turbocharger air outlet and exhaust inlet and the second by installing blinding plates on the turbocharger air outlet, turbocharger exhaust gas inlet and outlet. By installing a turbocharger cut-off system with swing gates and controls, the ship operator has the option of disabling one of the turbochargers for low load operation. By using two stage turbocharging can be achieved 40% of NO_x emission reduction and fuel saving can be up to 7 grams/kilowatt-hr (g/kWh) [8].

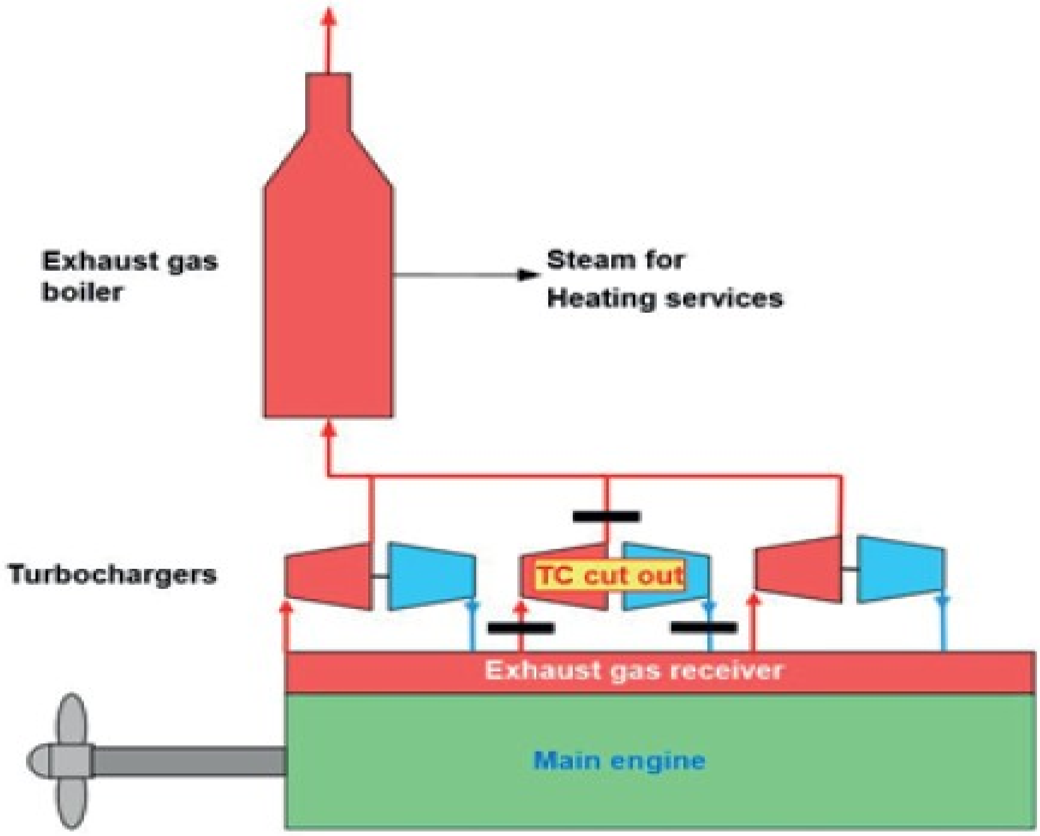

Figure 27: Turbocharger cutout illustration, by MAN [8].

Selective non-catalytic reduction

Selective non-catalytic reduction (SNCR) works similarly to SCR method (referred below) but without use of catalyst. In SNCR a reducing agent (ammonia NH_3) or urea is injected into the engine's combustion chamber or in the exhaust gas and it reacts with nitrogen oxides formed in combustion converting them to nitrogen and water. The reaction requires a high temperature within the range of 900 - 1000 ºC and sufficient reaction time to be efficient. If the process is run above the sufficient temperature range the production of NO_x increases and below it the ammonia emissions increase. Because of the required high temperature the reducing agent must be injected into the combustion chamber or cylinder right after the combustion or into the exhaust gas immediately thereafter.

Using selective non-catalytic reduction system, NO_x emissions can be reduced by 50% [56], [59]. The down side of this system is that it is less efficient that the Selective Catalytic Reduction, because only 10-12% of ammonia react with NO_x and the rest is just burned off. In order to achieve NO_x reduction of 50% is required four times the stoichiometric amount of ammonia. Since the cost of ammonia is about the same as the cost of heavy fuel oil [60] and since the system requires extensive modification to engine, the SNCR don't seems to be competitive. Also another problem of SNCR system is that requires extensive modifications to be made on the engine. Thus, it lowers the overall engine performance and degrade the fuel economy [59].

After-treatment technologies

The after-treatment technologies are systems that are installed to remove pollutants from the exhaust gases that come out of the engine. The after-treatment systems have no effect on engine process and formation of emissions. Table 7 provides a summary of these technologies highlighted in this study with further details for each provided below.

	Retrofittable	% NO_x reduction	% SO_x reduction	% PM reduction	References
After-Treatment Technologies					
Selective catalytic reduction (SCR)	Y	90-99	-	-	[8], [10], [11], [16], [42]–[48], [61]
Exhaust Gas Scrubbers (EGS)	Y	5	75-99	20-80	[11], [16], [31], [47], [62], [63]
Diesel Particulate Filter (DPF)	Y	1-10	-	80-90	[11], [47], [64][48]
Shore/Barge Based-After-treatment Systems	Y	95	95	95	[8]

Table 7: Summary of After-Treatment Technologies.

Selective catalytic reduction

Selective catalytic reduction (SCR) is a technique that removes nitrogen oxides from marine diesel engines. It is done by spraying aqueous urea ($CO(NH_2)_2$) or ammonia (NH_3) as reducing agent into the exhaust gases at a temperature of 290 – 350 Celsius (°C) and the exhaust gases are guided through a catalytic converter. A selective chemical reaction (in minimum temperature of 160°C) takes place in the catalyst that breaks down NO_x to nitrogen (N_2) and water. The reactions are:

$NO_x + NH_3 \rightarrow N_2 + H_2O$

$NO_x + CO\ (NH_2)_2 \rightarrow N_2 + H_2O + CO_2$

The limiting factor for the effectiveness of SCR systems is temperature. If the exhaust temperature is too low, the urea or ammonia forms hydrogen sulfate, which gradually blocks, or "plugs", the catalytic converter. With regard to engine operations in the port area, engine temperatures decrease throughout the transition and maneuvering modes and it is likely that exhaust temperatures could be below the 250^o C level. Further, if combined with scrubber or waste heat recovery systems, the exhaust will be even more likely to drop below the minimum required temperature.

The catalytic reactor is a steal box which contains several layers of replaceable catalyst elements made of some precious metal, a dosing and storage system for the reducing agent and a control system. The injection of urea or ammonia is controlled by nozzles with a feedback loop, which reacts to the amount of NO_x in the flue gases.

The lifespan of the catalyst elements is from three to five years for liquid fuels and longer for engines operating on gas. When the SCR is installed the housing usually replaces silencer in the exhaust uptakes. This reduces noise and also makes the system suitable for both new and retrofit installations. The SCR is an add on system meaning that it does not interfere with the basic engine design and is not dependent on the engine manufacturer [53], [18].

The reduction of NO_x emissions by using the SCR system is more than 90% [17]. According to [13], the SCR system is able to reduce NO_x emissions by 90-99%, HC emissions by 80-90%, CO emissions 80-90% and soot emissions 30-40%. ABB Fläkt had the longest running SCR system in a merchant ship in 2001 with about 50,000 hours in operation. During the whole time the reduction of NO_x emissions have remained in the range 97-98%. Also the HC emissions have been decreased 88% and CO emissions 53% [56]. Kjemtrup (2002) [65] reports a reduction rate of more than 93% in MAN B&W engine deliveries equipped with SCR. Finally, most recent IMO 2015 [8] reports that SCR systems have the potential to reduce NO_x emissions from

80% to 98%. The majority of SCR systems installed on over 500 marine ships over the last 30 years have been on 4-stroke engines [8], although there have been limited applications with large 2-stroke main/propulsion engines. This method is to beneficial, not only because it can achieve NO_x reduction in high level, but also because does not require low sulfur diesel fuels in order to work and it does not require additional maintenance.

One of the drawbacks of the SCR method is that it consists a high cost investment. The volume of the system is equal with the size of the engines and it consumes lots of urea which is needed to store on board and handle by the ship crew [14]. To achieve high reduction rates the size of the SCR system must be increased and more complicated premixing and injection systems are needed. Thus, in order to provide the correct measure of ammonia into the exhaust stream to reduce engine-out NO_x, it requires an elaborate injection or "dosing" mechanism. Also a high number of ammonia compared with NO_x ratio is needed to achieve the high reduction rate. All these reasons increase the initial unit cost is higher and the installation cost. The high NH_3/NO_x ratio may lead to increased ammonia emissions too. Besides being a pollutant ammonia also causes corrosion in the exhaust channel, so it requires a carful injection strategy to avoid 'ammonia slip' [18]. In order to avoid excessive NO_x formation SCR requires a strict monitoring of exhaust temperature. Also, SCR system may require the use of low-sulfur fuel or the low-sulfur fuel at least benefits the application of the system. In the SCR some of the SO_2 in the exhaust gases is oxidized to SO_3, which can form sulfurous acid (H_2SO_3) or sulfuric acid (H_2SO_4). Sulfurous acid combined with ammonia forms ammonia salt, which is a solid with high melting point, leads to increased PM emissions. Furthermore, sulfuric acid in turn causes rapid corrosion in the SCR and in the other exhaust system facilities. Nevertheless, a SRC system combined with usage of a sulfur fuel content of 2.6% , has proved to work without problems [60], [56].

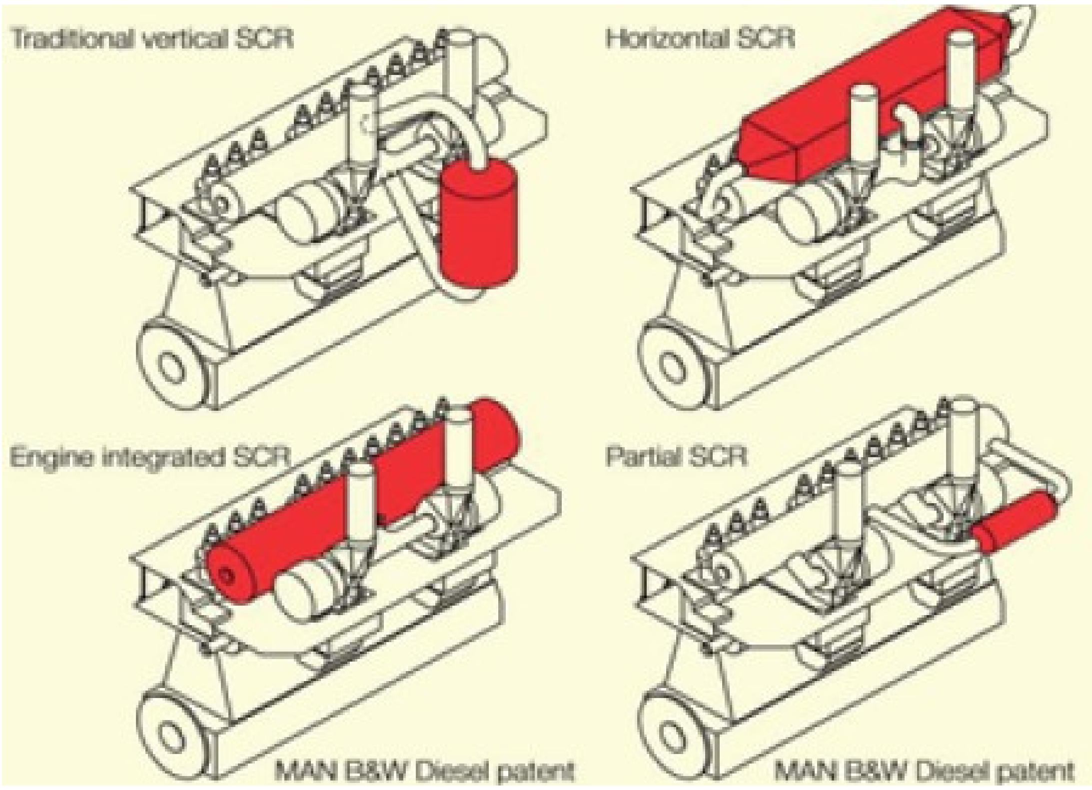

Figure 28: SCR system diagram and SCR placement options, by MAN [8].

Scrubber Technologies

Exhaust gas scrubbers remove sulfur and PM from the engine exhaust stream through a wet or dry interface. One of the major benefits of exhaust gas cleaning are that the ship can use high sulfur fuels and meet IMO and Emissions Control Area (ECA) requirements. Two different scrubber technologies will be described: the Wet Scrubber and the Dry Scrubber. Scrubber systems can be designed for treating both propulsion and auxiliary engines.

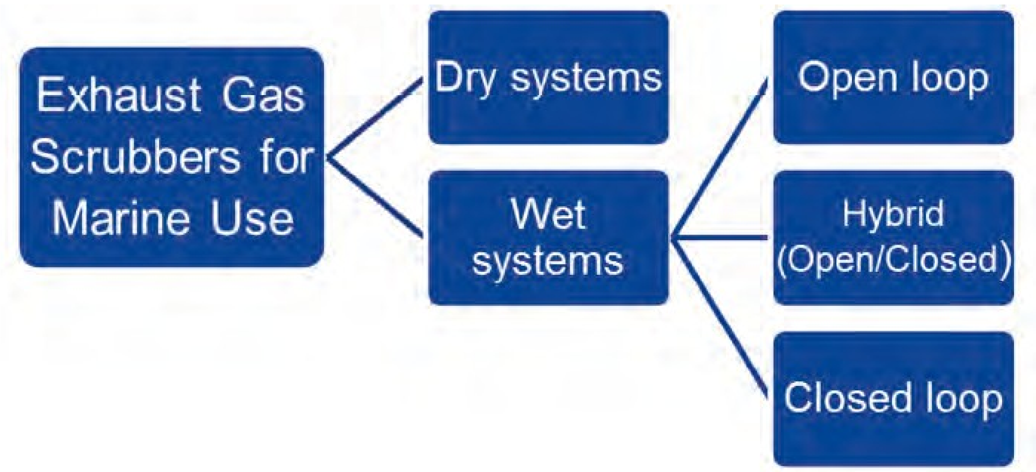

Figure 29: Exhaust gas scrubbers classification [38].

Exhaust Gas Scrubbers – Wet

Scrubbers reduce SO_x emissions coming out from the exhaust gas up to 99% by washing it in different ways. They work with the use of HFO, due to all other fuel types maintain less SO_x, which could be reduced by the engine. The most common are Wet scrubbers and utilize an open loop, closed loop, or hybrid configuration. Specifically, open loop systems utilize sea water, closed loop systems utilize freshwater, and hybrid systems can utilize either, depending on operational mode. Generally, all of these scrubber technologies could even set in as a retrofit model or completed in a new ship building process. Hybrid systems provide the highest operational flexibility.

The first stage in the main scrubbing process is to cool the exhaust gas which is up to 350°C down to 160-180°C. In the second stage, the exhaust gas is treated in a special ejector where it is further cooled by injection of water. There the majority of the soot particles in the exhaust gas removed. In the third and last stage, the exhaust gas is led through an absorption duct where it is sprayed with water and so cleaned of the remaining Sulfur dioxide.

Open loop wet scrubber systems spray the exhaust gases with seawater, which causes reaction between SO_x and seawater and form sulfuric acid. Thereafter, the sulfuric acid is neutralized by the natural alkalinity of seawater. Closed loop scrubber systems utilize fresh water that is generated on board and mixed with caustic soda (NaOH) as wash water, in order to neutralize SO_x. Finally, Hybrid System operates with seawater in an open loop, and freshwater in a closed loop. When the ship is on open sea, the system operates with seawater. In harbours and ECAs, the system can operate with freshwater, without generating any significant amount of sludge to be handled at port calls. The main advantage of hybrid system is, when on open sea the system switches to the open loop, the accumulated water of the tank could slowly be removed back to the sea, having no NaOH consumption. Thus, only the sludge tank has to be removed at the harbours.

Nowadays, there are approximately 30 to 40 ships operating with wet scrubber systems and with the 2015 IMO Sulfur requirements of 0.1% sulfur in the ECA (emission control area) and SECA (sulfur emission control area), orders and installations have rapidly increased over the past two years to well over 300 globally [8].

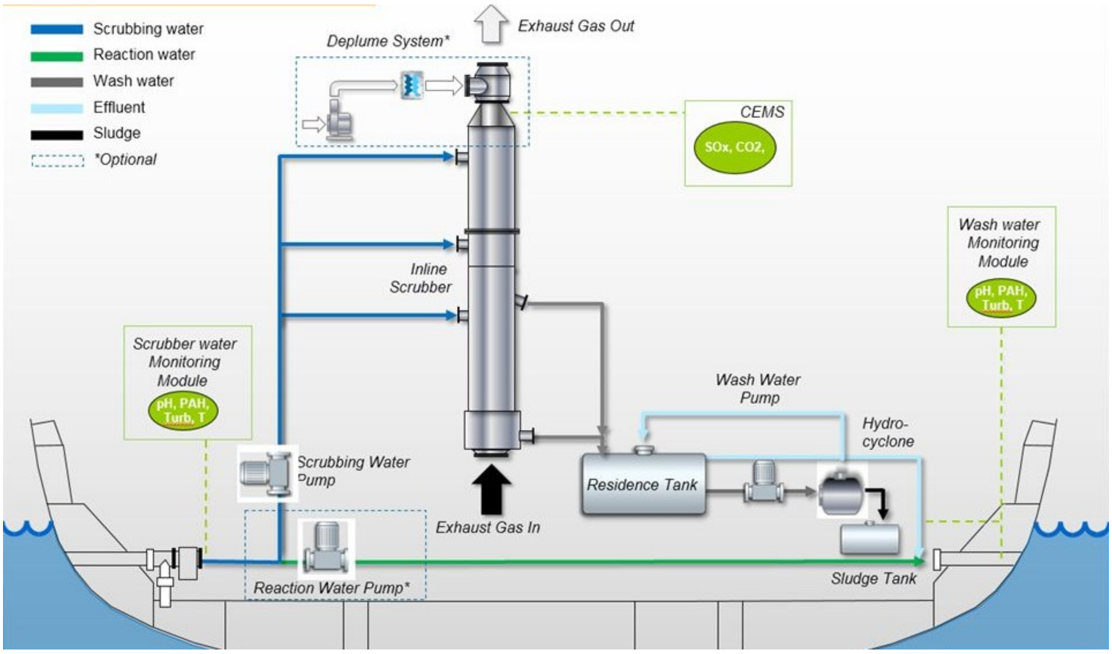

Figure 30: Open loop, by Wärtsilä [8].

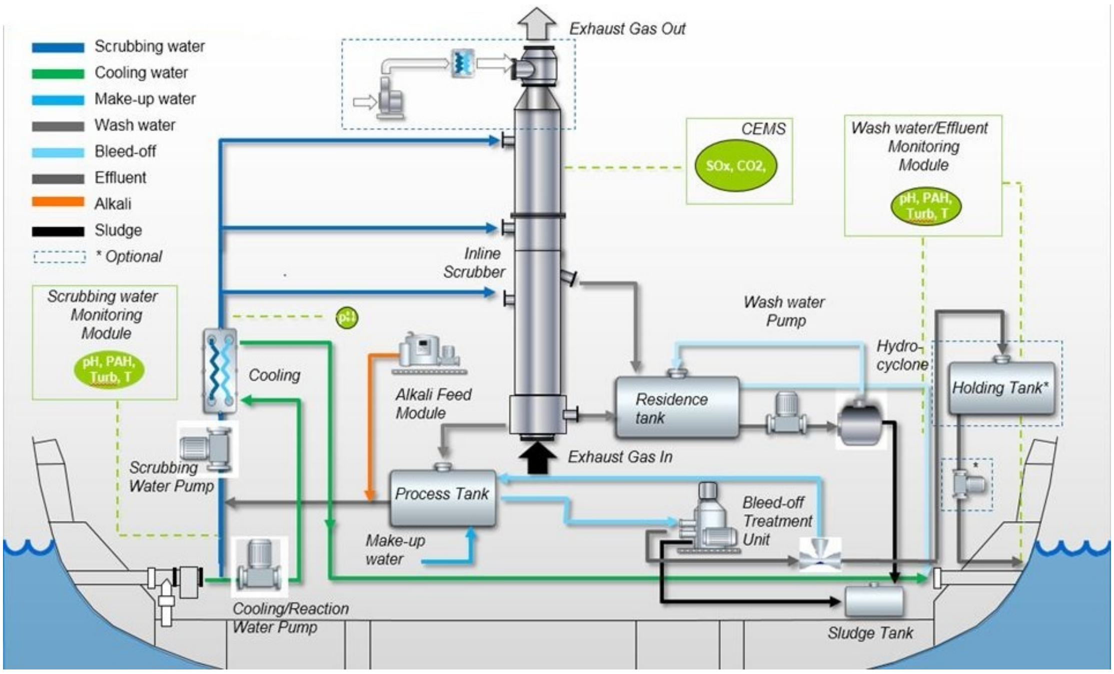

Figure 31: Hybrid system, by Wärtsilä [8].

Exhaust Gas Scrubbers – Dry

Scrubbers remove at least 80% of the Sulfur dioxides (SO_x) contained in the exhaust gas. Dry scrubbers operate with an absorber utilizing granulated pellets of lime ($Ca(OH)_2$). The hot exhaust gases react with the lime to produce gypsum ($CaSO_4$).

During the direct desulfurization process, limestone is used in the combustion chambers at temperatures between 850°C and 1100°C. The Dry EGCS desulfurization is supposed to be operated at approximately 320°C. The lime pellets are moved through the system at an engine load-dependent rate, and the gypsum is removed from the system and stored for removal from the ship. The gypsum pellets are typically sent to land-based power generation stations where they are reused in dry scrubbers. Exhaust Gas Scrubbers work using HFO, since all other fuel types maintain less SO_x, which could be reduced by the engine. An SCR can be located downstream of the dry scrubber. The benefit over a wet scrubber is that the exhaust gas is not cooled by interaction with water and is therefore more effective in combination with SCR [8].

The reduction test for Marine Exhaust Solutions EcoSilencers for auxiliary motors onboard the Pride of Kent (Nov 2004), report that taking all factors into consideration, the final result in their measures was a conservative estimate of 25 % for PM emissions. However, some other studies report that the reduction potential of Exhaust Gas Scrubbers method is 90-99% for NO_x [8], [4], [5], [14], [43] [18] and 60-80% for PM [10], [22], [58]. One benefit of using HFO fuel on this method is that is a low cost fuel. Also, scrubber method has lower CAPEX cost than LNG method and generally is a global available method for many ships. However, it has also some drawbacks. At first, it requires a quite big space to install the equipment. Also, the maintenance of these systems has a considerable big complexity. Finally, from now on are applied IMO Tier III rules that require the installation of SCR or EGR systems in a ship.

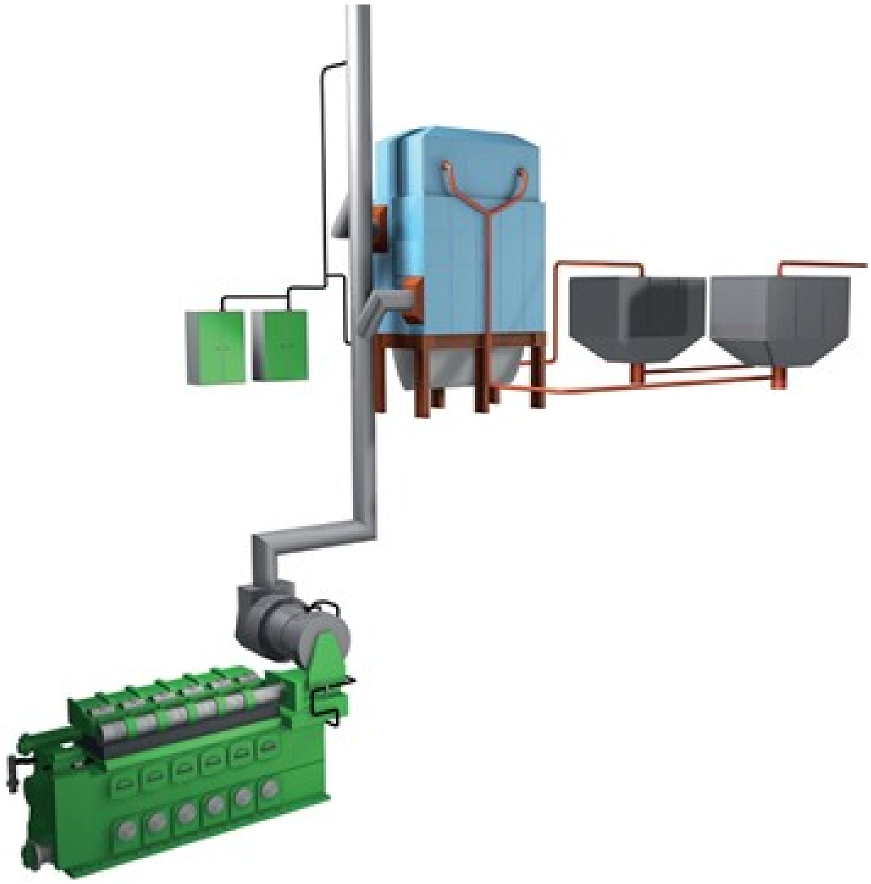

Figure 32: Dry scrubber illustration, by MAN [8].

Diesel Particulate Filters (DPFs)

Diesel particulate filters (DPFs) are one of the most effective emission control technologies to reduce particulate matter on appropriate equipment. Diesel particulate filters have been developed for high-speed diesel engines. This system is comprised of silicon carbide ceramic fibers and a self-cleaning mechanism. The filter collects particulate matter (PM) as exhaust gas is forced through it. Also the self-cleaning element automatically combusts and eliminates particulate matte buildup in the filter. This allows for continual operation without clogging the filter and requires no maintenance. Using diesel particle filters could be achieved NO_x reduction by 1-10%. Also when use in conjunction with a catalyst, DPFs are capable of reducing up to 90% of PM. The DPFs can be divided into two subcategories, on Passive DPFs and Active DPFs. Passive DPFs do not use an external source of heat to promote regeneration. Exhaust temperatures are elevated by the increased backpressure in the exhaust as the DPF fills with PM. On the other hand, on active DPFs the heat is added by one of a number of external means to promote regeneration such as electric heating, injection of diesel fuel into the exhaust, or engine calibration to temporarily raise the exhaust temperature. Active DPFs are mainly used when the engine exhaust temperatures are too low for the use of passive DPFs. Diesel particulate filters are a very attractive retrofit option, but also linked with some drawbacks. Despite their high cost, in order to have DPFs on the engine as an after treatment system, is required the use of Ultra-Low Sulfur diesel fuel. Also, it requires threshold exhaust temperatures in order to ensure regeneration.

Shore/Barge Based-After-treatment Systems

Nowadays, Shore or barge based after-treatment systems are being developed and evaluated at the Port of Long Beach and Port of Los Angeles. These after-treatment systems are based on the concept of collecting ship stack emissions using special ducting and treating the emissions with specific shore/barge-sited emission control units that include exhaust gas scrubbing in combination with Selective Catalytic Reduction. These systems were first attempted when a ship is at the berth (shore-side), although some terminal operations need to be considered when a ship siting on a terminal. Furthermore, ship emissions from the units that power the emission reduction equipment and the barge are also treated in the system. These systems aim to reduce ship emissions to the same level or even better than on-shore power (when considering grid-generated emissions). Shore or barge based after-treatment systems are currently in final testing and are being evaluated by CARB (California Air Resources Board). The barge systems are moved in position on the water near the ship and the ducting mechanism is connected remotely to the ship's auxiliary and boiler stacks. The main advantage of this system is that it doesn't require expensive modifications to the ship, as is required with on-shore power systems. Shore/Barge systems are capable of treating emissions when a ship is at anchorage as well as at berth. Also, the combination of scrubber and SCR technologies that utilized by these systems are already established methods for reducing ship emissions. The key evaluation effort is to demonstrate and quantify capture efficiency and effectiveness at a wide variety of exhaust loads [8]. Due to this method is quite new the reductions rates cannot be quantified at this time. However, IMO 2015 expected that the reduction of the main shipping emissions (NO_x, SO_x, PM) could be above 95%.

Fuels

Fuels have been in the "spotlight" due to a number of requirements including IMO fuel sulfur limitations, recent IMO requirements in ECA and SECA, EU at-berth requirements, CARB marine fuel requirements and many various market based measures that encourage the use of cleaner fuels. Table 8 provides a summary of the different types of fuels and further details for each type provided below.

	Retrofitable	% NO_x reduction	% SO_x reduction	% PM reduction	References
Fuel Technologies					
Switch to low-sulfur fuel (2.7 -> 0.1 % S)	Y	↓ cbc	60-96	80	[10], [16], [42], [44], [46]
Switch to low-sulfur fuel (2.7 -> 0.5 % S)	Y	↓ cbc	60-81	5-20	[10], [11], [31], [42], [44], [47], [63]
Switch to low-sulfur fuel (2.7 -> 1.5 % S)	Y	↓ cbc	44	5-18	[10], [11], [16], [31], [42], [44], [46], [61]
Liquefied Natural Gas (LNG)	Y	80	100	88-99	[8], [64]
Biodiesel	Y	↑	cbc	10-70	[11], [47], [64]
Methanol	Y	↓ tbd	100	tbd	[8], [64]

Table 8: Summary of fuel methods.

Low sulfur fuels

Use of low sulfur diesel fuels instead of fuels with high sulfur content (residual fuel) has been one of the most effective strategies utilized in the port area, not only to reduce PM and SO_x emissions but also to achieve some reductions in NO_x emissions. The reason low sulfur fuels have been so attractive is that it consist the easiest and cheapest method for reducing sulfur dioxide emission and also their use doesn't require significant capital cost to implement in a ship. However, one disadvantage is that the strategy can significantly raise operating expenses, since the major component of ship operating costs is fuel cost. Moreover, since lower viscosity and density of the low sulfur fuel, during fuel switching the ship operators must follow specific operating practices for their engines and other components such as fuel lines and valves. Generally, the rise in operating expenses comes from the cost differential between high sulfur and low sulfur fuels, which can run over $300 per ton. Another quite important aspect is the service and the maintenance guidelines that every ship have to do when it use low sulfur fuels. Thus, both service and the maintenance guidelines, have to be followed by fuel switching crew to avoid damage to fuel lines and valves due to lower viscosity and density of the low sulfur fuel. Moreover, the increased cost of low sulfur fuel may encourage a mode shift from sea to over-the-road for current short sea transportation services. Consequently, careful evaluation is needed while considering fuel switching for short shipping routes.

Generally, many studies have shown the reduction potential of low sulfur diesel fuels. Specifically, the study of Ritchie et al., (2005) shows that a switch from 2.7% to 1.5% sulfur content on fuel will reduce PM emissions by 18% and a switch to fuel with 0.5% sulfur content will decrease PM emissions by more than 20%. Along with this study many others [10], [22], [31], [43], [46], [58], [61] have result the same conclusion about the reduction potential of low sulfur fuels on the main shipping emission pollutants. Furthermore these studies claimed that low sulfur diesel fuels can also reduce SO_x emissions by 44% with the use of 1.5% sulfur content on fuel and by 60-81% with the use of 0.5% sulfur content on fuels. Finally, is reported that a switch from 2.7% to 0.1% sulfur content on fuel will reduce PM emissions by 80% and SO_x emissions by 60-96% [42].

Ultra-Low Sulfur diesel fuel: It is the fuel that contains fewer than 30 parts per million sulfur (0.03%). Furthermore, in this case, capital investments are needed to re-equip the vessel's fuel storage and also the delivery system. In addition, since the ultra-low Sulfur fuel doesn't contain enough sulfur to provide lubrication, a synthetic lubricant additive have to be mixed with the fuel before use [23].

Alternative fuels: Other fuels can be used to replay diesel fuels. Biofuels, natural gas and hydrogen are some of them. Generally, for fuel switching techniques, vessels have the option of either entirely switching to alternative fuels or operating on dual-fuel mode, with separate fuel storage tanks for each fuel. The EU has set a goal of replacing 20% of the fuels used in transport with alternative fuels by 2020.

Liquefied natural gas

Using liquefied natural gas (LNG) as ship fuel has recently gained worldwide attention. Natural gas is generally methane. Wartsila produces a dual-fuel four-stroke engine, which during operation can switch between natural gas and light fuel oil. Thus, an LNG fueled ship might choose to operate continuously on gas or only switch to gas when operating inside an ECA. After 2016, a newly built dual fueled vessel operating in NA ECA will need to operate solely on gas mode if not fitted with NO_x abatement systems [38]. Switching to the diesel mode will be used only in an emergency situation such as gas supply disruption.

One of the major benefits of using natural gas as ship fuel is that will reduce sulfur oxide (SO_x) and particular matter (PM) emissions by 90-95% [8], [64]. Also, NO_x emissions are reduced to below the IMO Tier III limits for Otto-cycle engines without the need for exhaust gas treatment system. LNG technology is available for many types of gas and dual fuel engines, as well for the onboard gas storage and handling systems. Another benefit is that LNG is expected to be less costly than marine gas oil

(MGO) which will be required to be used within the ECAs if no other technical measures are implemented to reduce the SO_x emissions [66].

Generally, LNG fares batter than other technologies economically or technically. The investment cost (CAPEX) for an LNG fueled ship will be higher than a ship operating only on diesel fuel, and the space required for LNG storage tank(s) will for some vessels reduce the cargo capacity. Also, it considered as a high flammability and toxicity fuels.

Biodiesel fuels

Biodiesel fuels considered as cleaner burning fuels and a fuels additive, if mixed in concentration with petroleum diesel that is biologically derived from domestic and renewable sources. Specifically, biofuels are produced from animal or vegetable fat base (palm oil, coconut oil, rapeseeds). During the refining process, glycerol and fatty acids are removed and the residue of methyl or ethyl ester is used as a combustion fuel source.

Biodiesel and its blends have lower particulate matter and hydrocarbon emissions at full load compared with conventional diesel fuel. Thus, many advantages can be reached with the use of biofuels. Reductions of 10 to 70 % in PM emissions have been reported with different blends, engines and test cycles. The reduction potential of CO emissions is 40-45%, but the NO_x emissions may increase up to 10%. Furthermore, the availability of this fuel is limited and the costs remain an issue [58]. Another drawback that appears by using biofuels is the potential to lose some of the engine power (about 2%). On the other hand biofuels have also some benefits, as it consist a renewable source and biodegradable. Also with the use of these fuels can be achieved a better lubricity in the engine.

Methanol

Methanol, similar as LNG, has no sulfur and thus is a capable energy source for ships operating in ECAs and SECAs. Also, similar to natural gas, methanol generates less CO_2 emissions at the stack and at low loads, doesn't have the methane slip like LNG Otto Cycle engines. Bio-methanol can be produced from a variety of biomasses and mixed with methanol produced from fossil fuels. Methanol is liquid at ambient temperature and pressure and used in Otto Cycle engines. Emission estimates for methanol as fuel are not established at this time. It is anticipated that for methanol-fueled engines to meet IMO Tier III, it will be needed additional emission control technologies, such as EGR. Methanol can be used in 4-stroke dual fuel engines and 2-stroke dual fuel engines but EGR would still be needed because they do not have fuel slip. Methanol is toxic if ingested and is miscible in water thus easily degrades in the environment. Also it has nearly the half the energy density of diesel. However, methanol can be used both on land and on ship-side and its cost ranging similar to HFO infrastructure. Finally, is considerably cheaper than LNG since methanol does not need to be cryogenically stored. The reductions rates cannot be quantified at this time for NOx and PM, as IMO 2015 report, but it is capable to reduce SO_x emissions up to 100% [8].

Alternative power systems

Nowadays, the interest about alternative power system is high and many studies occupied with this issue. The most important aspect of these systems is that it reduce the generation of emissions by ships with diesel powered engines while at berth and requires the use of alternative power systems such as solar and LNG which are lower in emissions compared to diesel auxiliary power engines of the ship. These systems can also benefit health as air pollutants are emitted at remote onshore electricity facilities, as opposed to ports near highly populated areas. One good example are cruise ships that consist the main pollutant source in the ports. Thus, 85% of emissions from cruise ships are produced while the ship is docked. For that reason alternative power systems are under great development nowadays. Table 9 provides a summary of these technologies highlighted in this study with further details for each provided below.

	Retrofitable	% NO_x reduction	% SO_x reduction	% PM reduction	References
Alternative power systems					
Shore side power (cold ironing)	Y	95-100	95-99	95-99	[8], [11], [31], [61]
Barge power supply	Y	80	100	98	[8]

Table 9: Summary of alternative power systems.

On-Shore power supply/shore power

On-Shore power supply or Shore Side Electricity consists one of the most recent known methods to reduce ship pollutants while are at berth, since it results in fewer emissions than burning fuel on the ships themselves. Shore Side Electricity involves connecting ships to the port electricity network to supply the ship's power needs, while they are at berth.

There are several challenges that arise in the design of the shore-based infrastructure and electrical equipment. Firstly, it requires investments and some modifications to be made in the ports and on-board, so they can be connected. Another challenges are the frequency of the grid and the ships being shore powered, the voltage system on-board the ship, dynamic or static loading of power, number of connecting points, available power shore-side, cost of electricity and many others. Also, the modifications on retrofit ships are often more complicated than building new ships designed.

Many studies have been made for shore power systems. One of these studies [67] found usage of shore-side electricity to be two to four times more expensive than generating the electricity on-board by heavy fuel oil engines when they only took the direct costs into account. Nevertheless, when the external costs were also evaluated the usage of shore-side electricity proved to be the cheaper option, since the external costs are much lower for vessels connected to shore-side electricity supply. According to IMO's 2015 report, all ship pollutants could be reduced up to 100% at the stack while using grid power [8].

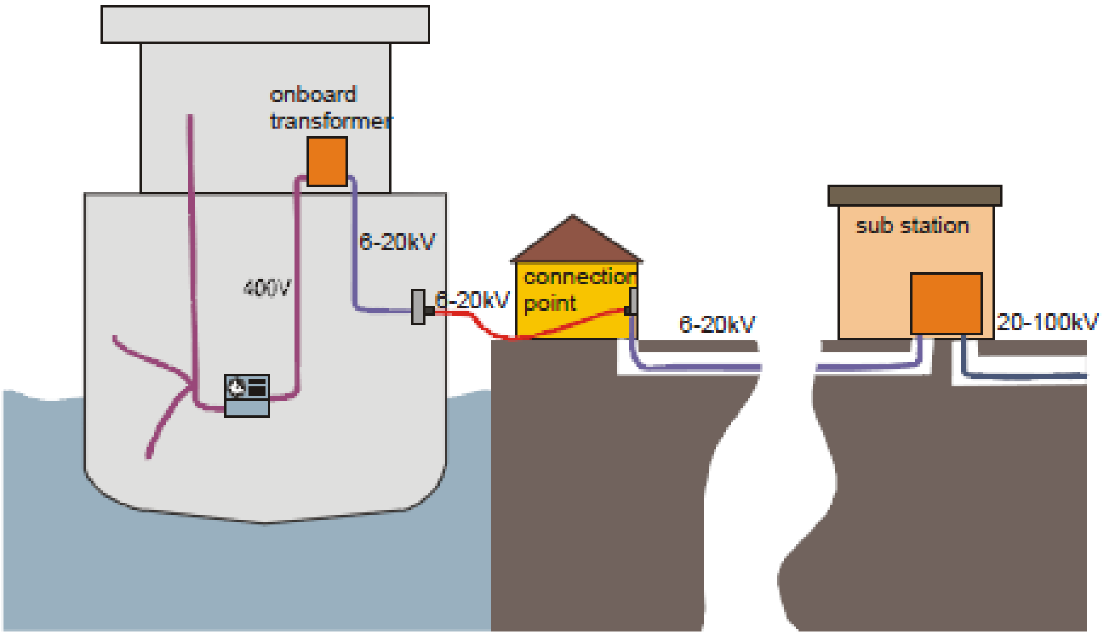

Figure 33: Typical shore-side power connection principles [68].

Barge power supply

Barge power supply provides power to a ship at berth, similar to on-shore power supply. However, the power is generated by a cleaner engine than located on the ship and typically using an alternative fuel, such as LNG. A barge equipped with an LNG Otto Cycle only engine that can provide up to 7.5 megawatts and will be used by cruise ships calling at Hamburg Port Authority [8]. The barge system's advantage compared to terminal-based shore power is that it does not require costly terminal infrastructure improvements and the system can be moved from one berth to another. One attention point is that the mooring infrastructure needs to be constructed depending on port/terminal, so that the barge is secured while in use and not in the way of other ship traffic. In order the ship has the correct power, is needed to have appropriate connection and electrical equipment on board to receive the barge-based power (similar to on-shore power). The potential emission reductions are based on several facts. More specific, the difference in emissions of the engine, after-treatment system and fuel of the power barge supply compared to the on-board power that is otherwise used to generate the ship's power. Assuming a barge equipped with an LNG powered Otto Cycle engine the reduction potential could be up to 80% for NO_x emissions, 98% for PM emissions and 100% for SO_x emissions [8].

Chapter 6: Costs

This paragraph of the study investigates the costs of specific NO_x, SO_x and PM reduction measures on ships. Some of the technologies are well established and have been installed in numerous vessels and others are in an early stage of development. Generally, large uncertainty exists and many costs estimation have been provided, since the costs assessment is depended on the measure. Costs vary with ships size and may differ greatly when the technology is installed in existing vessels (retrofitting). A reduction technology installed on a new ship is generally more appealing than on a retrofit, because dependent systems can be integrated during the overall design process and sufficient space can be allocated for the reduction system. For this reason it is quite difficult to calculate the exactly cost of a reduction technology. Actual overall application costs of emission control and energy efficiency measures (ECEEMs) are a compilation of individual costs that begin with the cost of a specific technology but may expand as other expenses are added. In this report except from the cost of the abatement technologies, also the external cost is calculated and taken into account for the study's final results.

The costs associated with an emission reduction technology can be divided into CAPEX (capital expenses) and OPEX (operating expenses). These two general categories incorporate a range of other cost categories that can be varied based on the technology and the specific application. Capital costs (CAPEX) include the expenses associated with purchasing and installing the equipment on board, so includes the construction, the work, the license fees, the delivery of the installation etc. Operating costs (OPEX) are related to the annual expenditures such as the cost of maintenance and administrative overhead. Also include variable costs, such as the additional labor demand or the increased energy demand for operating the device.

A large number of studies have estimated the total cost of available technologies for reducing ship emissions. The methodologies which have been used in these studies to characterize capital and operation costs vary, as each one do baseline choices and take other key assumptions. The most authoritative and comprehensive evaluation of the abatement costs is a study by Entec (2005) for the European Commission. Generally, this kind of studies are extremely costly and for that reason later reports base their economic analysis on Entec's study [63], [69] (e.g. Cofala et al, 2007, Kågeson et al, 2007). Some of the below figures have also been taken from the Entec report. However, this study reports also cost measurements from more recent studies([63], [70], [71]) in order to take into account a bigger range of values for the final conclusion. The following table has the costs analysis of these recent studies. Again, although these studies are recent, they are using data from older sources-studies.

Tables 10, 11 and 12 present estimates of capital and operational costs, based on recent studies for abatement technologies.

More specific, the table above is mentioned on the abatement technologies that reduce the main shipping pollutants by engine process modifications. One of these studies [43] have taken the cost values from previous studies [13], [41], [57], [72]–[75] and indicates the capital cost and the installation cost for each reduction method. From the Table, we can see that the Retrofitting of the Abatement Measures are more costly compared to Newbuilding, due to the fact that the Fixed Investment Cost of the equipment is approximately 80-90% of the Capital investment.

	Humid air motor (HAM)	Continuous water injection (CWI)	Internal engine modifications (IEM)	Direct water injection (DWI)	Fuel water emulsions (FWE)
Capital cost (USD per kilowatt)	98	3.5	13	30	28
Installation cost (USD)	86000	10000	410	27000	100000
Operating cost (USD) New Build	1400 – 2500	16100	9800	68000	27000
Costs per year for retrofit (USD)	-	-	-	-	328367 – 354367
Costs per year for New Build (USD)	-	-	-	-	148889 – 174889
Sources	[43], [48]	[43]	[43], [47]	[43]	[43], [64]

Table 10: Cost of engine abatement technologies.

The following table (table 11) has the same information with the above table. The only difference is that this table created by Entec 2005 and considered as a more complete study, but not so new.

		New build capex (Euro)	Equipment lifespan (year)	Capex per kW installed (€/KW)	Retrofit capex (€)	Equipment lifespan (year)	Capex per kW installed (€/KW)
Costs of HAM	Small (SSD ME only)	462800	15	131	4628	12.5	131
	Medium (SSD ME only)	1292400	15	113	1392400	12.5	121
	Large (SSD ME only)	2744000	15	95	3244000	12.5	113
Costs of Basic IEM (Slide Valves)	Small (SSD ME only)	1160	2.5	0.39	6060	2.5	2.02
	Medium (SSD ME only)	3120	2.5	0.31	8020	2.5	0.7
	Large (SSD ME only)	7320	2.5	0.29	12220	2.5	0.42
Costs of Advanced IEM	Small (SSD ME only)	107286	25	30	-	-	-
	Medium (SSD ME only)	119.764	25	10	-	-	-
	Large (SSD ME only)	17258	25	6	-	-	-
Costs of DWI	Small (SSD ME only)	135732	25	38	-	-	-
	Medium (SSD ME only)	270.578	25	24	-	-	-
	Large (SSD ME only)	548933	25	19	-	-	-

Table 11: Cost of engine abatement technologies by Entec 2005 report.

Generally, Entec's report and the reports of later studies do not have many significant differences, as the ranges of the values are quite same in all cases.

<u>Humid Air Motors</u>

From price perspective, Humid Air Motors consists one of the most expensive technique instead the other methods, as it has the higher capital cost from all the other techniques. Also HAM has a significant high installation cost than other NO_x abatement measures. One reason for this is the high pre-installation costs, for example the costs related to research and development. However, it has also the least operating cost, which means that the costs of maintenance and administrative overhead are not so high. The main cost involved with HAM is humidifier. Thus, if the humidifier is made out of durable material, such as non-corrosive or galvanized materials, then it is likely the humidifier will last for approximately 25 years. However, if the humidifier is made out of mild steel, the lifespan will be significantly shorter. An approximate lifespan of 15 years is assumed based on information from the MS Mariella. For retrofitting the lifespan will be the remaining ship's average lifespan of 12.5 years.

Continuous water injection (CWI)

Continuous water injection is identified as the best option at this moment when cost related concerns are taken into account, as it has the less Capital cost (USD per kilowatt) than the other methods. Additionally, the recent improvement of the CWI technology in terms of reducing of NO_x from a 30% reduction in 2000, to a 50% to 70% reduction subsequently has clear strengths.

Basic IEM (Slide Valves)

Engine modifications require the least capital investment by Entec's report. Basic IEM includes changing the air injection nozzle to slide valves which allow improved combustion conditions. This change is low cost and simple. Installation costs for a retrofit are not significant, and therefore costs will not vary considerably from installation on new ships to existing ships. Also, there are no operating costs associated with the use of slide valves. There may be some engine service benefits such as reduced fuel oil consumption for lubrication, but these benefits have not been quantified so total costs are assumed to be equal to the capital costs. The lifespan of a fuel valve is assumed to be 2.5 years [52].

Advanced Internal Engine Modifications

Advanced IEM includes a range of engine alterations to optimize combustion, fuel injection and charge air characteristics. IEM costs can be split into two components, firstly fuel injection costs and secondly engine modifications. There are no operating costs associated with the use of advanced IEM. Therefore total costs are equal to the capital costs. As we can see from the above tables, advanced engine modifications are the second cheaper technique from capital cost perspective. The lifespan of IEM Combinations will be up to the life of the engine, assumed to be 25 years for new build engines. In practice, the lifespan will depend on the specific details of the particular IEM combination.

Direct Water Injection (DWI)

The cost premium of retrofitting DWI is likely to be high, since it may require installation of additional cylinder heads (Spencer 2005). Water injectors are likely to have a lifespan of around 4 years, and are routinely changed every four years. The rest of the equipment, including pressure modules, water tank, piping and control unit, is likely to last around 25 years. Direct water injection (DWI) has the higher operation cost from all the other techniques, which means that the costs of maintenance and administrative overhead are high. However, the installation cost of this method is quite less than the operating cost. On the other head, fuel water emulsions (FWE) method has exactly the opposite characteristic; the installation cost of this technique is higher in comparison with the oration cost. All studies finally conclude that Internal Engine Modification seems to be the best technology to reduce NO_x emissions, following the Continuous water injection method and the large vessels results to be the most cost effective both in terms of pollutant abated. This is because a bigger ship has a lower specific consumption per unit of grow weigh than a lighter one. The "size factor" is important on cost efficiency evaluation.

The two following tables (Table 12, 13) are mentioned on the abatement technologies that reduce the main shipping pollutants by After-Treatment Technologies.

	Selective catalytic reduction (SCR)	Seawater scrubbing	Diesel Particulate Filter (DPF)
Capital cost (USD) New Build	60000 - 360000	3199000 - 5840000	40000 - 79000
Capital cost (Euro) Retrofit	-	8149708	-
Capital cost (euro per kilowatt) New Build	100	118	-
Capital cost (euro per kilowatt) Retrofit	-	168	-
Installation cost (USD)	304500	1000000 - 5000000	-
Operating cost (USD) New Build	45000 - 153000	-	40000 - 72000
Operating cost (Euro/MWh) New Build	-	0.3	-
Operating cost (Euro/MWh) Retrofit	-	0.3	-
Operating and maintenance costs (Euro/year) New Build	-	23417	-
Operating and maintenance costs (Euro/year) Retrofit	-	23417	-
Costs per year for retrofit (USD)	-	822927 - 10390927	280618
Costs per year for newbuild (USD)	-	369741 - 9937741	77749
Sources	[43], [47], [48]	[9], [21], [47], [64], [76], [77]	[48], [64]

Table 12: Cost of after treatment abatement technologies by recent reports.

Selective Catalytic Reduction

On Entec's report, Costs for Selective Catalytic Reduction (for main engines) were based on estimations made by the US EPA (2003) [40] and for auxiliary engines are based on estimations from CITEPA (2003, 1). The capital cost for a new built ship is ranged from 60000-360000 USD and the operating cost is ranged from 45000-

153000 USD. The remainder of the equipment, including tanks, piping, wiring etc. and has an estimated lifespan of 15 years.

Seawater scrubbing

The scrubber method is reportedly expanding. The price for installing a scrubber in a ship typically ranges from 1-5 million euro per ship, depending on the size of the vessel. Wärtsilä predicts that the market size will consist of 2,000 vessels over a five years period. However, there are not all vessels suitable for the addition of scrubbers; factors such as the age of a vessel can make the adoption of the technology unfeasible.

Diesel Particulate Filter (DPF)

Diesel particulate filters (DPFs) are one of the most effective emission control technologies to reduce particulate matter on appropriate equipment. As we can see from the table 12 DPF require the least capital investment in comparison with the other after treatment techniques. A paper by Eelco den Boer, "Emissions from the Legacy Fleet" [78], estimates the installation cost of DPF on inland waterway vessels. The estimated CAPEX cost was reported to be EUR 50/kW ≈ USD 63/kW and the CAPEX including installation costs for a typical retrofit case to EUR be 110/kW ≈ USD 139/kW (EUR to USD exchange rate ≈ 1.26).

All studies had the same conclude for after treatment abatement technologies that by reducing the 90-95% of emissions, the Selective Catalytic Reduction seems to be the most efficient technology in environmental terms along with Sea water scrubbers, but the costliest in economic terms.

		New build capex (Euro)	Equipment lifespan (year)	Capex per kW installed (€/KW)	Retrofit capex (€)	Equipment lifespan (year)	Capex per kW installed (€/KW)
Costs of SCR. Ships using RO. Outside SO2 ECA	Small (SSD ME only)	225950	15	64	338925	12.5	96
	Medium (SSD ME only)	525410	15	46	788115	12.5	69
	Large (SSD ME only)	1207403	15	42	1811104	12.5	63
Costs of SCR. Ships using RO. Inside SO2 ECA	Small (SSD ME only)	225950	15	-	338925	12.5	-
	Medium (SSD ME only)	525410	15	-	788115	12.5	-
	Large (SSD ME only)	1207403	15	-	1811104	12.5	-
Costs of SCR. Ships using MD	Small (SSD ME only)	225950	15	-	338925	12.5	-
	Medium (SSD ME only)	525410	15	-	788115	12.5	-
	Large (SSD ME only)	1207403	15	-	1811104	12.5	-
Costs for sea water scrubbing	Small (SSD ME only)	418656	15	118	598080	12.5	168
	Medium (SSD ME only)	1350048	15	118	1928640	12.5	168
	Large (SSD ME only)	3386880	15	118	4838400	12.5	168

Table 13: Cost of after treatment abatement technologies by Entec 2005 report [52].

Table 14 is mentioned on the abatement technologies that reduce the main shipping pollutants by using Shore side power (cold ironing) or Natural gas LNG. This table is created by recent papers that are not too old as Entec's repot.

	Shore side power (cold ironing)	Natural gas (LNG)
Capital cost (USD)	1000000 - 15000000	38850000 - 50000000
Sources	[47]	[38], [64]

Table 14: Cost of abatement technologies by recent reports.

<u>Liquefied Natural Gas (LNG)</u>

There are some main disadvantages that linked in with LNG retrofits. At first, LNG requires at least double the fuel tank volume of fuel oils, which is a challenge for vessels with limited or no deck space. For example container vessels, cruise liners and bulk carriers will need more complicated shapes to fulfill space restrictions. Cost estimates for LNG fuel tanks range from USD 1,000/m3 - USD 5,000/m^3. Second, MAN Diesel advised that an LNG retrofit is not possible on a two-stroke mechanically controlled fuel system, thus a conversion to an electro-hydraulic common rail fuel system (ME-B) is required. If the existing engine is an electronic controlled common rail engine (ME-B, RT-Flex), the cost saving could be up to 20%.

The price of LNG depends for many years on HFO price, but often is cheaper. Taken into account the cost of LNG is about 60% of HFO. On gas carriers the cost of boil-off gas is decreasing due to savings of re-liquefaction process. Natural gas prices (including LNG) have been reduced the last couple of years due to the introduction of shale gas in the US market [64].

Shore side power (Cold Ironing)

Based on the range of recent studies done by ports in the US and Canada, a normal range of costs to provide shore power at a berth can be between 1 - 15 million dollars. However, these costs vary significantly depending on the extent of terminal rebuilding, the proximity to adequate electricity supplies, and the ability to locate the shore-side infrastructure. Many new ships currently being built are including cold ironing systems or implementing designs that would make future retrofits less costly [47]. Generally, capital investments for shore-side power differ from the other methods, because they are highly variable depending on the infrastructure upgrades needed, both to make electric power available dockside and to connect ships to a power supply.

Also, another cost evaluation is made by Entec 2005, Rahai and Hefazi, 2006, Lövblad and Fridell, 2006 and IIASA 2007 and calculated the marginal cost of each abatement measure per ton of pollutant abated. Comparing cost-effectiveness per unit of pollution reduced is often more useful than simply comparing absolute costs.

Entec (2005a, 2005b, 2005c) found that all control strategies to reduce NO_x and SO_x cruising emissions on a large vessel, except for fuel switching, cost less than $700 per ton of SO_x or NO_x. Table 15 presents this estimation of cost-effectiveness of the NO_x abatement techniques, expressed in terms euro per ton NO_x abated.

Technology	Ship type	NO_x reduction measures per €/ton abated		
		Small	Medium	Large
Basic IEM (Two stroke, low speed, young engines)	New	12	9	9
Basic IEM (Two stroke, low speed, old engines)	Retrofit	12-60	9-24	9-15
Advanced IEM	New	98	33	19
Direct Water Injection	New	411	360	345
Humid Air Motors	New	268	230	198
Humid Air Motors	Retrofit	306	282	263
SCR outside SO_2 ECA (ships using 2.7% S resid. Oil)	New	740	563	526
SCR outside SO_2 ECA (ships using 2.7% resid. Oil)	Retrofit	809	612	571
SCR inside SO2 ECA (ships using fuel 1.5% S)	New	543	424	398
SCR inside SO_2 ECA (ships using fuel 1.5% S)	Retrofit	613	473	443
SCR, ships using MDO	New	413	332	313
SCR, ships using MDO	Retrofit	483	381	358

Table 15: Cost effectiveness of NO_x reduction measures per €/ton abated.

Taking into consideration all the related reports, the cost effectiveness of reducing NO_x from ocean-going ships ranges from $9 to $809 per metric ton abated and for SO_x ranges from $320 to 2053$ per metric ton abated.

Generally, the cheapest reduction method for NO_x is the installation of slide valves that consist a part of basic IEM technology. Thus, the costs for emission reduction by introducing slide valves to new or young engine are approximately 12-9 euro per ton NO_x reduced for small, medium and large size vessels, respectively. Also for the older engines the costs are 60, 24 and 15 euro per ton NO_x reduced for small, medium and large size vessels. According to the table below the cheapest reduction method for NO_x is internal engine measures that divided in basic IEM and advanced IEM. The costs of ton NO_x reduced applying a combination of internal engine measures, such as retard injection, common rail injection, increased turbo efficiency etc. are 98, 33 and 19 euro for small, medium and large size vessels, respectively. These costs are calculated for new engines. 'Older' engines require development costs to enable retrofitting of basic IEM. Costs for retrofitting Advanced IEM were not included due to a very high uncertainty in cost estimation.

The costs of the water injection are estimated for DWI and HAM technologies. For Direct Water Injection system the costs for new engines per ton of reduced NO_x are 411, 360 and 345 euro for small, medium and large size vessels, respectively. Costs for retrofitting DWI were not included due to a very high uncertainty in cost estimation.

In HAM technology the costs vary from 198 euro to 268 euro per ton NO_x reduced for new engines depending on vessel's size and for retrofitting engines the costs would be between 263 and 306 euro per ton NO_x reduced.

With the SCR system the NO_x abatement costs depend on the fuel used. The installation of SCR is most expensive for ships using fuel with high sulfur content. Thus, the costs vary between 526 and 809 euro per ton NO_x reduced depending on vessel's size and whether the system is installed on a new engine or retrofitted to an old engine. Also, for ships that sailing in areas where the sulfur content in fuel is limited, the system is cheaper due to the usage of low-sulfur fuel. Specifically, in this case NO_x abatement costs are between 398 and 613 euro per ton NO_x reduced. Moreover, for the case that ships using very low-sulfur marine diesel oil the costs are in the range of 313-483 euro per ton NO_x reduced. These costs do not include the cost of switching between fuels. Also as described in previous chapter, the cost of equipping an existing vessel with SCR may fall in the range of €300 and €809 per ton depending on the size of the ship and the exactly technology that is used.

Technology	**Ship type**	**SO_x reduction measures per €/ton abated**		
		Small	Medium	Large
Sea water scrubbing	New	390	351	320
Sea water scrubbing	Retrofit	576	535	504
Fuel switching: 2.7% S fuel to 1.5% S fuel	New	2053 (1230)	2050 (1230)	2045 (1230)
Fuel switching: 2.7% S fuel to 1.5% S fuel	Retrofit	2053 (1230)	2050 (1230)	2045 (1230)
Fuel switching: 2.7% S fuel to 0.5% S fuel	New	1439 (1690)	1438 (1690)	1434 (1690)
Fuel switching: 2.7% S fuel to 0.5% S fuel	Retrofit	1439 (1690)	1438 (1690)	1434 (1690)

Table 16: Cost effectiveness of SO_x reduction measures per €/ton abated.

Table 16 presents Entec's estimation of cost-effectiveness of the SO_x abatement techniques, expressed in terms euro/ ton SO_x abated.

Also, according to calculations of Entec [23] and other studies more recent, Sea Water Scrubbing for new and retrofit vessels results to be the best technology, in terms of cost-effectiveness, to reduce SO_x emissions. Entec 2005 estimates that for this method the costs range from 320 euro to 390 euro when the system is installed on a new engine and from 500 euro to 580 euro when the system is retrofitted.

However, the cost of fuel switching is strongly dependent on the quantity required of low-sulfuric fuel. A low quantity of low sulfuric fuel, for example, can be produced by re-blending distillate fuels. On the contrary a large quantity of low-sulfuric fuel would require refinery investments. Generally, three different ways can be used to provide low sulfur diesel. The cheapest option is the re-blending. The second one is the processing of low-sulfur crude oil. The last one is the desulfurization of the HFO that is the most expensive [17]. According to Entec's estimation the costs of ton SO_2 abated are approximately 2050 euro when the fuel switching is done between the fuels with sulfur contents of 2.7% and 1.5% and approximately 1440 euro when the switching is done between the fuels with sulfur contents of 2.7% and 0.5%. The table also has the latest published estimates from Concawe that are related with the fuel prices. These numbers are values in brackets ().

Also Nera's study based on information by Entec 2005 create a little different report, that consider the cost of abatement technologies per ton Reduced by Ship Size and Age, by Geography (€/Ton). Thus, focus on emissions in ports or within 12 miles from shore, on the presumption that these nearby emissions are primarily responsible for the environmental effects of shipping emissions. In cases where the geographic area of interest is smaller, the costs per ton of abatement rise significantly because fewer "geographically relevant" emissions are reduced for a given control technology.

Table 17 shows the cost per ton of NO_X reduced for each measure described above, when the reductions are applied to all vessel emissions occurring in the different geographic regions. Also note that costs for the use of shore-side electricity are only shown for in-port emissions.

	Small		Medium		Large	
	New	Young and Old	New	Young and Old	New	Young and Old
All Emissions						
Basic IEM	12	60	9	24	9	15
Advanced IEM	98	N/A	33	N/A	19	N/A
HAM	268	306	230	282	198	263
DWI	411	N/A	360	N/A	345	N/A
SCR	740	809	563	612	526	571
Shore Power	-	-	-	-	-	-
12-Mile Emissions						
Basic IEM	60	300	46	125	48	77
Advanced IEM	489	N/A	166	N/A	96	N/A
HAM	1,285	1,472	1,095	1,351	930	1,257
DWI	920	N/A	669	N/A	595	N/A
SCR	1,125	1,467	838	1,086	777	1,003
Shore Power	-	-	-	-	-	-
In Port Emissions						
Basic IEM	8,220	41,100	6,362	14,929	5,725	8,723
Advanced IEM	8,583	N/A	3,517	N/A	1,942	N/A
HAM	22,311	25,602	22,868	28,271	18,609	25,243
DWI	11,488	N/A	8,481	N/A	6,651	N/A
SCR	9,149	15,211	7,723	12,938	6,846	11,451
Shore Power	9,662	12,086	5,371	6,631	3,847	4,704

Table 17: Cost of NO_X Technologies per Ton Reduced by Ship Size and Age, by Geography (€/Ton) [44].

The cost of basic IEM for young vessels is the same as that for new vessels. Also it is important to note that basic IEM becomes less cost-effective at berth because it is less effective on auxiliary engine emissions.

Table 18 shows similar costs for SO_2 technologies for the same geographical areas. The measures involving low-sulfur fuel have the same cost per ton for all vessel types because is assumed by Entec that vessels are able to use the low sulfur fuels only when necessary without incurring any additional capital costs or fuel-switching costs. Thus, is assumed that vessels can switch entirely from high Sulfur fuel oil to low sulfur fuel, to simplify the cost-effectiveness calculations. Vessels therefore do not need to install additional fuel tanks or modify existing tanks to accommodate multiple fuels, so the fuel switching measures involve no capital costs. Note that the fuel costs alone are not varying across vessels. Again, the costs of measures where the relevant emissions reductions occur only while in port (including the use of 0.1 % MDO and shore power) are only shown in the last section of the table.

	Small		Medium		Large	
	New	Young and Old	New	Young and Old	New	Young and Old
All Emissions						
1.5% Sulphur	1,230	1,230	1,230	1,230	1,230	1,230
0.5% Sulphur	1,690	1,690	1,690	1,690	1,690	1,690
0.1% Sulphur	-	-	-	-	-	-
Scrubber	390	579	351	535	320	504
Shore Power	-	-	-	-	-	-
12-Mile Emissions						
1.5% Sulphur	1,230	1,230	1,230	1,230	1,230	1,230
0.5% Sulphur	1,690	1,690	1,690	1,690	1,690	1,690
0.1% Sulphur	-	-	-	-	-	-
Scrubber	1,850	2,600	1,600	2,500	1,430	2,360
Shore Power	-	-	-	-	-	-
In Port Emissions						
1.5% Sulphur	1,230	1,230	1,230	1,230	1,230	1,230
0.5% Sulphur	1,690	1,690	1,690	1,690	1,690	1,690
0.1% Sulphur	2,326	2,326	2,326	2,326	2,326	2,326
Scrubber	30,060	46,200	36,040	56,800	29,460	45,070
Shore Power	9,889	12,370	5,498	6,788	3,937	4,815

Table 18: Cost of SO_2 Technologies per ton Reduced by Ship Size and Age, by Geography (€/Ton) [44].

Note: 0.1 % Sulfur fuel is also referred to as Marine Distillate Oil ("MDO")

In Table 18 is presented the cost effectiveness of the shore-side electricity technology for ships using 2.7% sulfur that is related with port emissions.

Entec's report assumes that shore-side power is one of the less cost-effective control options, due to the high cost of this method. Nevertheless, from another perspective this method could be very useful if someone accounts the massive energy that consumed when ships are at berth. For example, 85% of emissions from cruise ships are produced while the ship is docked because in order to satisfy their passengers' needs required to consume a lot of energy by activating the auxiliary engines.

Chapter 7: Emissions calculation methodology

The environmental effects of ports to the atmosphere and human health, due to their proximity in densely populated areas, are extremely important. An independent evaluator finds it very hard to access and elaborate relevant emissions data, as in most cases port authorities are not obliged to measure and publicize them. The induced costs of these emissions are practically addressed primarily to the local society, which will have to pay, in due time, the consequences [79].

Generally, the existing approaches for creating ship emission inventories are divided in ‘‘top-down’’ and ‘‘bottom-up’’ (or ‘‘activity-based’’) approaches. The former are fuel-based methods that estimate emitted air pollutants relying on the reported amounts or marine bunker fuel sales, while for the latter fuel consumption-based or ship movements-based methods are employed. ‘‘Bottom-up’’ approaches would generally be more accurate than top-down[35], [80]. In the present study a ‘‘bottom-up’’ method has been used to estimate emissions based on detailed individual activities of cruise ships in selected ports. For each studied port and for all approaching cruise vessels, activity profiles have been created; i.e. a breakdown of a ships’ movements during modes of operation (i.e. maneuvering or at berth), with engines’ types and sizes, engines’ load factors, type of fuel consumed and time spent in each mode. In this context, information required were: rated power of both main and auxiliary engines of each ship, load factors on both types of engines, scheduled arrival and departure times in order to estimate the amount of time spent in different operating modes and engines’ emissions factors.

For every ship call, each of the air pollutants (i.e. NO_x, SO_2 and $PM_{2.5}$) produced during the ship’s activity in the port was estimated through the application of the following expression:

$$\boldsymbol{E_i = \sum_{j,k} (T_j \cdot P_k \cdot LF_{j,k} \cdot EF_{i,k})}$$

where E denotes the amount of ship emissions (tons); i is the specific type of emissions (NO_x, SO_2 or $PM_{2.5}$); j is the ship’s activity stage (i.e. moving–maneuvering or hotelling); k is the engine type, i.e. main (ME) or auxiliary (AE); P is the engine power (kW); LF is the engine load factor during the specific activity; EF is the emissions factor (g/kW h); T is the time spent at each of the ship's activity stages (hours) (for maneuvering T = D/U, where D is the distance traveled by the ship in the port before docking, U is the moving velocity of the ship during moving–maneuvering. The total emissions are calculated for each port by summing for all cruise ships visiting during the selected time period. All necessary data regarding cruise ship calls in Greece during 2013 and 2014 , i.e. vessels' names, date and call duration (arrival and departure time), were carefully collected from local Port authorities and compared with similar data of other sources to harmonize any discrepancies [81], [82].

The IHS Sea-web online database was employed to obtain various technical characteristics and data on main (ME) and auxiliary (AE) engines for all cruise ships [83]. Extensive work on main and auxiliary engine load factors and emission factors of main and auxiliary engines for cruise ships during maneuvering and while at berth has been provided elsewhere [35], [84]–[86]. The load and emission factors applied in this study for the operation of main and auxiliary engines running on specific fuels and load condition, for ships maneuvering and hotelling during summer and the rest of the year were taken from a similar survey that has been conducted for the port of Piraeus [87].

The least possible uncertainty in all adopted values has been maintained during the estimation of the emissions inventories. Cruise ships' hotelling duration and technical characteristics were collected from official local Port authorities and from IHS Sea-web database respectively. The distance traveled by each vessel in the port (for the calculation moving and maneuvering times) was evaluated and a ''generic'' cruise ship path has been created and assigned to each studied port individually. Thus the above mentioned parameters are considered to be as accurate as possible. The dominant uncertainties in all ''bottom-up'' approaches are due to the determination of auxiliary engines' power and the estimation of the average load factors and emission factors of the main and auxiliary engines. In this study, and for almost 30% of the studied cruise vessels, detailed and accurate data regarding their AE power rating were collected from the Sea-web database, while for the remaining the typical auxiliary to propulsion power ratio for cruise ships (0.278) was employed. The employed load factors were based on the most updated recent relevant studies and have taken into account the unique nature of cruise vessels, the ports specific characteristics and local climatic conditions. Emission factors were also determined based on detailed vessel information such as engine and fuel type, but they may also contain uncertainties [79].

7.1 External cost

This report, in order to estimate the total external cost due to emissions to air in studied ports, is using one damage cost methodology named New Energy Externalities Development for Sustainability (NEEDS). NEEDS is the most recent methodology that is an updated version of the EcoSense model, which was used to calculate the damage cost in HEATCO study. In order to cover dominant pollutants and all Member States, the values provided in NEEDS have several features that are especially relevant for the purpose of policy application. First of all, their values cover all European sea territories, which is very relevant for correctly calculating the external costs of maritime transport. Secondly, they associate not only health effects (that correspond to over 90% of the total external effects) but also the side effects of emitted NO_x and SO_2 on materials (i.e. buildings), biodiversity and crops [88]. In this study, we choose to use the values from NEEDS so as to find the total external cost of each port.

7.2 Specific methodology

HEATCO study estimate the health damages linked to PM and ozone exposure. Some of the health effects that considered are: new cases of chronic bronchitis, respiratory and cardiac hospital admissions, restricted activity days, and days of lower respiratory symptoms. This study also distinguishes between chronic and acute health effects, referring to short- and long-term exposure to air pollution respectively. Moreover, when assessing the health impacts, it determines different risk groups affected by the health impacts. The principal risk groups are classified into the following categorize: children below 14 years, adults of age between 15 and 65 and adults older than 65 years, with only small (i.e. one or two years) differences between the studies. In the majority of cases, the risk groups related to the different health effects coincide. Nevertheless, in HEATCO the mortality effects due to PM and ozone exposure is quantified for the population as a whole. About the health endpoint ‘respiratory medication use’, the risk groups in HEATCO are children and adults already suffering with asthma and considers that chronic mortality are exclusively valued based on years of life lost (YOLL) [88].

One of the most active on-going discussions in the specialised literature concerns the relative toxicity of different PM components. However, it is impossible to make a precise quantification with existing tools and data. Consequently, it is recommended that in the impact assessment all traffic-exhaust particular matter (PM) components are weighted as equivalent to $PM_{2.5}$ in terms of their health impacts. Thus, in this study is used the approach with no differentiation of $PM_{2.5}$ toxicity with respect to source (i.e. assume same health effects from fine particles emitted by vehicles or by power plants).

For this study, the damage costs of PM categorized by area on: rural, suburban, and urban, due to the importance of accounting for the actual exposure to health risks when evaluating the impacts of local pollutants (highly correlated with population density).

7.3 Final results

All the final results of the study are gathered in the following four tables. Table 19 and table 20 present the information about the reduction technologies such as, lifespan, reduction rate and the technological cost for each method. Both tables present the same information. However, only the first table includes the technological cost of each method since only these technologies have available information about their cost. In the rest methods these information are not available as well as the lifetime of each method.

Technology	Ship type	Lifetime (years)	% reduction			Cost (€/ton abated)			References
			NO_x	SO_x	PM	NO_x	SO_x	PM	
Basic IEM (Two stroke, low speed, young engines)	New	2.5-5	20-40	-	50	9-12	-	-	[10], [11], [16], [31], [42]–[45]
Basic IEM (Two stroke, low speed, old engines)	Retrofit	2.5	20-40	-	50	15-60	-	-	[10], [11], [16], [31], [42]–[45]
Advanced IEM	New	25	20-40	-	50	19-98	-	-	[10], [11], [16], [31], [42]–[45]
Direct Water Injection	New	4-25	50-60	-	-	345-411	-	-	[8], [10], [11], [16], [31], [43]–[46]
Humid Air Motors	New	15-25	70-80	-	-	198-268	-	-	8], [11], [12], [18], [33], [44], [46]–[48], [50]
Humid Air Motors	Retrofit	12.5	70-80	-	-	263-306	-	-	8], [11], [12], [18], [33], [44], [46]–[48], [50]
SCR outside SO_2 ECA (ships using 2.7% S)	New	15	90-99	-	-	526-740	-	-	[8], [10], [11], [16], [42]–[48], [61]
SCR outside SO_2 ECA (ships using 2.7% S)	Retrofit	12.5	90-99	-	-	571-809	-	-	[8], [10], [11], [16], [42]–[48], [61]
SCR inside SO_2 ECA (ships using fuel 1.5% S)	New	15	90-99	-	-	398-543	-	-	[8], [10], [11], [16], [42]–[48], [61]
SCR inside SO_2 ECA (ships using fuel 1.5% S)	Retrofit	12.5	90-99	-	-	443-613	-	-	[8], [10], [11], [16], [42]–[48], [61]
SCR, ships using MDO	New	15	90-99	-	-	313-413	-	-	[8], [10], [11], [16], [42]–[48], [61]
SCR, ships using MDO	Retrofit	12.5	90-99	-	-	358-483	-	-	[8], [10], [11], [16], [42]–[48], [61]
Sea water scrubbing	New	15	5	75-99	20-80	-	320-390	-	[10], [11], [16], [22], [31], [45], [47], [62], [63]
Sea water scrubbing	Retrofit	12.5	5	75-99	20-80	-	504-576	-	[10], [11], [16], [22], [31], [45], [47], [62], [63]
Fuel switching: 2.7% S fuel to 1.5% S fuel	New/ Retrofit	-	-	44	5-18	-	2045-2053	-	[10], [11], [16], [22], [31], [42], [44]–[46], [61]
Fuel switching: 2.7% S fuel to 1.5% S fuel	New/ Retrofit	-	-	44	5-18	-	1230	-	[10], [11], [16], [22], [31], [42], [44]–[46], [61]
Fuel switching: 2.7% S fuel to 0.5% S fuel	New/ Retrofit	-	-	60-81	5-20	-	1434-1439	-	[10], [11], [22], [31], [42], [44], [45], [47], [63]
Fuel switching: 2.7% S fuel to 0.5% S fuel	New/ Retrofit	-	-	60-81	5-20	-	1690	-	[10], [11], [22], [31], [42], [44], [45], [47], [63]

Table 19: Final results of the study for each method (methods with available cost information).

Technology	Ship type	Lifetime (years)	% reduction			Cost €/ton abated			References
			NO_x	SO_x	PM	NO_x	SO_x	PM	
Increase of Injection Pressure - "Common Rail Technology"	New	-	25	-	50	-	-	-	[8]
Exhaust gas re-circulation	New	-	10-60	75-99	-	-	-	-	[8], [10], [11], [16], [31], [42]
Rotating fuel injection controls	New	-	25	-	-	-	-	-	[8]
Electronically controlled lubrication system	New	-	-	-	20-30	-	-	-	[8]
Automated engine monitoring /control system	New	-	25	3	-	-	-	-	[8]
Continuous water injection (CWI)	New	-	30	-	5-18	-	-	-	[8], [10], [43]
Fuel water emulsions (FWE)	New	-	10	-	-	-	-	-	[8], [11], [31], [42], [43], [47]
Two stage turbochargers	New	-	40	-	-	-	-	-	[8]
Turbocharger cut off	New	-	40	-	-	-	-	-	[8]
Selective Non-Catalytic Reduction	New	-	50	-	-	-	-	-	[10], [11]
Diesel Particulate Filter (DPF)	New	-	1-10	-	80-90	-	-	-	[11], [47], [64][48]
Shore/Barge Based-After-treatment Systems	New	-	95	95	95	-	-	-	[8]
Liquefied Natural Gas (LNG)	New	-	80	100	88-99	-	-	-	[8], [64]
Biodiesel	New	-	-	-	10-70	-	-	-	[11], [47], [64]
Methanol	New	-	-	100	-	-	-	-	[8], [64]
Shore side power (Cold Ironing)	New	-	95-100	95-99	95-99	-	-	-	[8], [11], [31], [61]
Barge power supply	New	-	80	100	98	-	-	-	[8]

Table 20: Final results of the study for each method (methods with not available cost information).

More specific, the first two columns of this table include all the reduction technologies that are described in this study and the ship type of each method. Ship type is very useful because it affects the lifespan of the equipment of each technology as well as the cost of the technology itself. Thus, it has been a separation of ship types, in new and retrofit option. Costs vary depending on ships' size and may differ greatly when the technology is installed in existing vessels. Generally, a reduction technology in a new ship is more efficient concerning cost and equipment's lifespan, as it operates more years than on an old ship.

The method with the highest lifespan of 25 years is Humid Air Motors (HAM) if durable non-corrosive or galvanized material is used. Also the equipment of Direct Water Injection (DWI) estimated to have the same lifespan of 25 years but the general lifespan of DWI system is estimated to around 4 years. We can observe that the lifespan of the technologies in a retrofit ship would have a certain reduction than in a new ship and for that reason the HAM method in an old ship would last approximately 12.5 years. Another case that this happens is on the installation of Selective catalytic reduction (SCR) and the Sea water scrubbers (SWS) where the lifespan ranges from 15 years for the new ships to 12.5 years for the old ships. For the rest of the methods there is either not available information about their life or it cannot be estimated with accuracy. For instance switching to a fuel that contains less sulfur is a reduction method that doesn't have an exact lifespan as it depends on the lifespan of the engine. Moreover, technologies such as shore/barge based-after-treatment systems, shore side power (cold ironing) and barge power supply has the same difficulty in calculating their lifespan as they consist of quite complex methods. The fourth column includes for each pollutant separately the reduction rate that could be achieved by using a reduction technology. For example, we can observe that sea water scrubbers and more specifically Dry scrubbers as mentioned below, can reduce 5% NO_x emissions, 15-99% SO_x emissions and 20-80% PM emissions. The next column involves the marginal cost of each abatement measure per ton of pollutant abated. Through this column we can observe that fuel switching method from 2.7% sulfur fuel to 1.5% sulfur fuel, Selective catalytic reduction (SCR) and Direct Water Injection (DWI) are the most expensive technologies as opposed to Basic IEM (internal engine modification) for new and for old ships which is the cheapest one. Finally the last column refers to the references used for this table. Also important to mention that in the table, when a dash is used, it means that the information for these elements are not yet available.

Table 21 refers to the ports that this study takes into account. The studied Greek ports are Piraeus, Thessaloniki, Santorini, Corfu, Rhodes, Heraklion, Volos, Kavala, Mykonos, Katakolo, Patmos, Argostoli, Kos, Chania, Zakynthos, Lavrio, Igoumenitsa, and Milos. These ports are considered as the most popular ports for cruise ships in Greece. At first, we divided these ports into three categories depending on the number of local residents. So, the first category consists of the urban areas in which Piraeus and Thessaloniki are included. The second category is suburban including Santorini, Corfu, Rhodes, Heraklion, Volos and Kavala and the last category is rural, concerning Katakolo, Patmos, Argostoli, Kos, Chania, Zakynthos, Lavrio, Igoumenitsa, and Milos ports. Table 21 also refers to the emissions data that this study has used, based on detailed individual activities of cruise ships in selected ports for years 2013 and 2014. For the calculations of this study, the sum of these two years has been used in order to estimate the total amount of pollutants (in tons). For each port the value of NO_x, SO_x and PM pollutant for these two years is described as well as the social cost in million euro that these pollutants cost. It is worth recalling that the social cost, due to emissions to air in studied ports, is estimated in this study by using the damage cost methodology named New Energy Externalities Development for Sustainability (NEEDS). Finally, the last column calculates the total social cost by adding the social cost of each main pollutant for the two years.

Below table 21, the first three charts show the elements of the table by mentioning the categories of ports respectively. Thus, they represent the social cost and the amount of the emissions in each area.

	Ports	Total emissions 2013-2014 (tons)			Social cost (Million €)			
		NOx	SOx	PM	NOx	SOx	PM	Total
Urban	Piraeus	1114.10	448.70	55.67	4.29	3.68	11.01	18.99
	Thessaloniki	26.06	9.10	0.88	0.10	0.07	0.17	0.35
Suburban	Santorini	807.06	328.79	43.26	3.11	2.70	2.19	8.00
	Corfu	528.43	214.27	26.21	2.03	1.76	1.33	5.12
	Rhodes	415.32	165.35	19.17	1.60	1.36	0.97	3.93
	Heraklion	231.25	81.08	8.37	0.89	0.67	0.42	1.98
	Volos	38.72	14.54	1.66	0.15	0.12	0.08	0.35
	Kavala	23.39	8.18	0.81	0.09	0.07	0.04	0.20
Rural	Mykonos	659.03	252.17	28.40	2.54	2.07	0.55	5.16
	Katakolo	356.18	150.04	19.29	1.37	1.23	0.37	2.98
	Patmos	55.32	19.32	1.91	0.21	0.16	0.04	0.41
	Argostoli	94.13	35.48	3.95	0.36	0.29	0.08	0.73
	Kos	59.64	21.08	2.05	0.23	0.17	0.04	0.44
	Chania	77.17	32.81	4.27	0.30	0.27	0.08	0.65
	Zakynthos	27.41	9.75	1.00	0.11	0.08	0.02	0.20
	Lavrio	19.44	6.14	0.51	0.07	0.05	0.01	0.14
	Igoumenitsa	6.87	2.19	0.18	0.03	0.02	0.00	0.05
	Milos	16.06	5.82	0.60	0.06	0.05	0.01	0.12
Total		4555.57	1804.80	218.20	17.54	14.82	17.42	49.78

Table 21: The studied Greek ports, their emissions and their social cost for years 2013-2014.

We can observe that in urban ports, Piraeus is more polluted port than Thessaloniki. That is reasonable due to the fact that Piraeus is the largest port of Greece, and one of the largest in terms of passengers and freight in Europe compared to Thessaloniki's port that is not such a tourist destination. The rectangular bar shows the social cost that has been created by cruise ships in Piraeus these two years, that is up to 19 million euro. The most costly pollutant is PM and following are NO_x and SO_x pollutants. Also we can see how emissions values are ranged, with NO_x emissions dominating and following SO_x and PM. Although PM emissions in Piraeus are less than the other emissions, they have the higher social cost due to the health effects they cause. Moving on, the next chart shows the emission rates and the social cost of the suburban ports of the study, predominant being the port of Santorini, as far as pollutants are concerned. Again here we can observe that the NO_x emissions are the highest ones with 807.06 tons for the years 2013-2014, causing 3.1 million euro social cost and PM emissions ranging up to 43.26 tons and causing 2.19 million euro in social cost. The next chart is about rural ports and shows that Mykonos port is the most polluted port in this category, causing 5.16 million euro social cost. Finally, the last chart contains the emission data analysis of all the studied Greek ports, in order to give an overall view of the emissions emitted and the social cost for these two years in Greece.

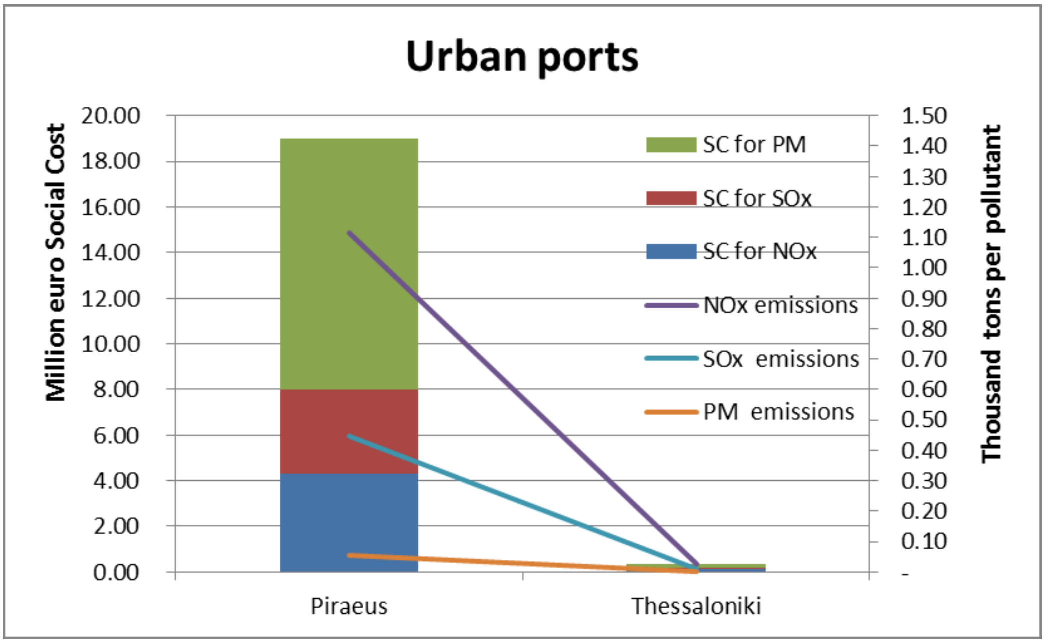

Figure 34: Total amount of social cost and emitted pollutants in the studied urban area.

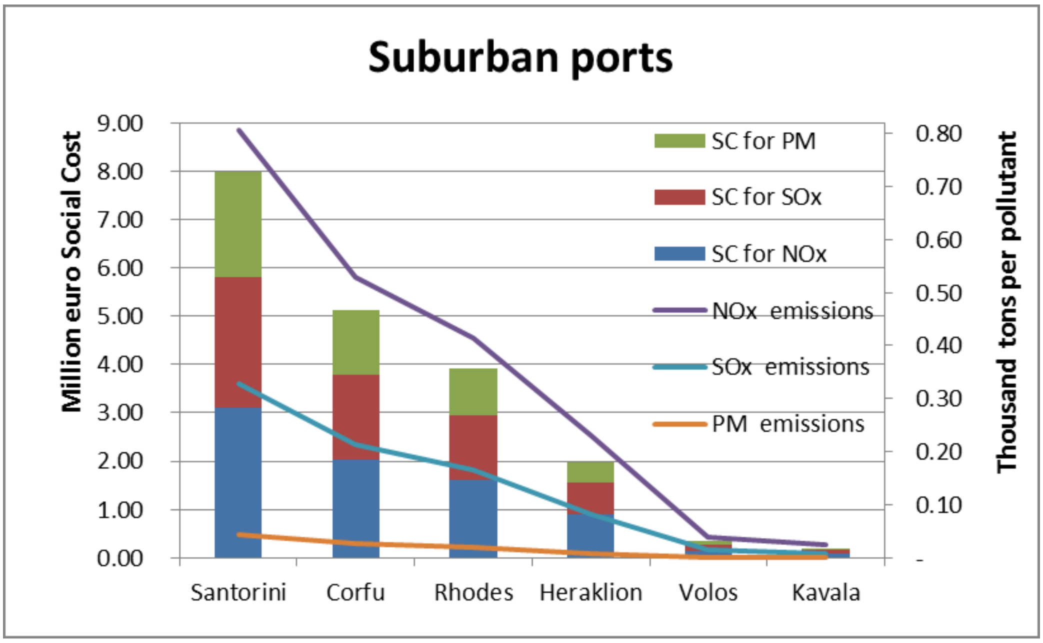

Figure 35: Total amount of social cost and emitted pollutants in the studied suburban area.

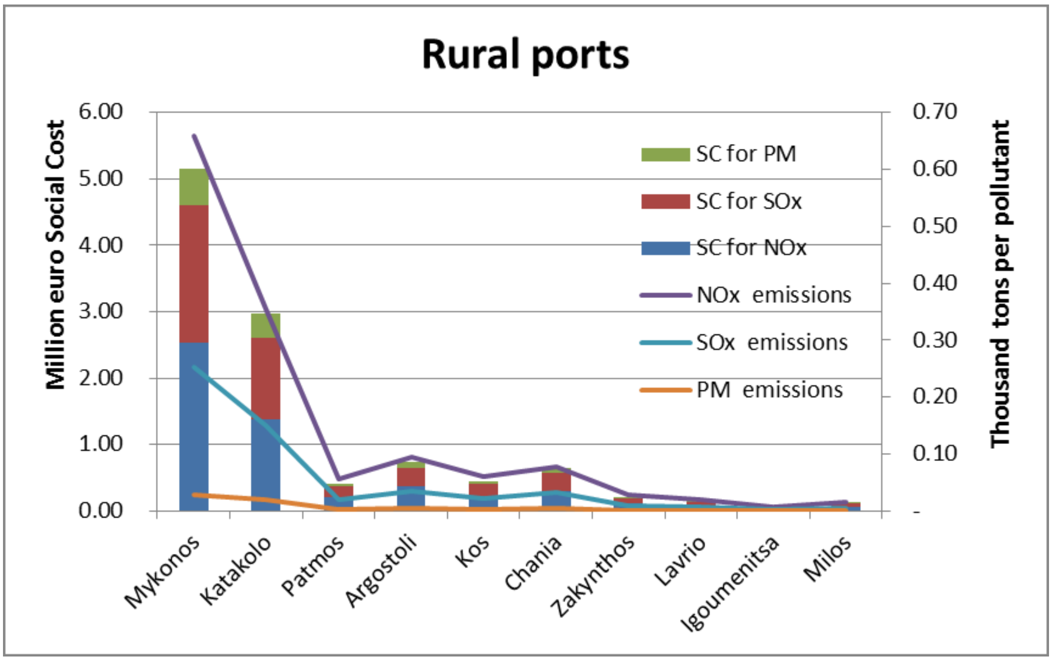

Figure 36: Total amount of social cost and emitted pollutants in the studied rural area.

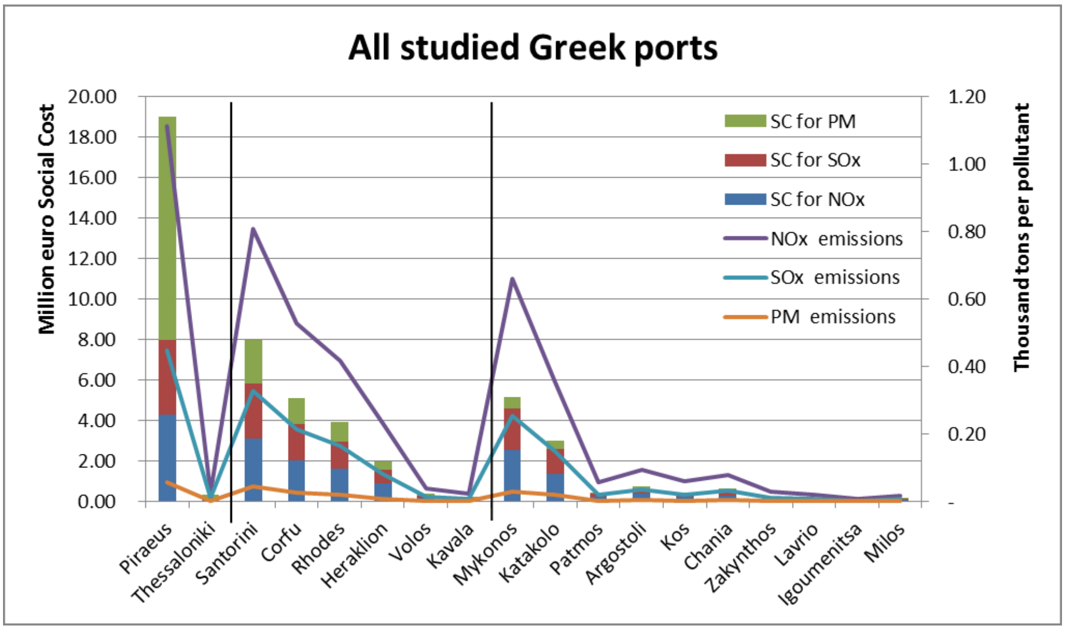

Figure 37: Total amount of social cost and emitted pollutants in the studied Greek ports.

Through calculations and data analysis table 22 was created. This table presents the total results of this study concerning which method is the most beneficial one in order to reduce emissions and the social cost, and at the same time being financially advantageous. The first two columns of this table include all the reduction technologies that are described in this study and the ship type of each method. The second column, as mentioned above, divides the technologies into two categories, based on whether the technologies would be installed on a new ship from the first place or on older ships by a retrofit structure. The next column includes the total emissions of the main pollutants (NO_x, SO_x, PM) in all studied Greek ports, that cruise ships emitted for a two year period (2013-2014). Also the table includes the social cost for the year 2013-2014 that cruise ships created by polluting the port communities with the previous amount of pollutants. Moreover, we can see the abated emissions that could be achieved in each pollutant depending on the reduction rate of each technology. One of the most important information to get a result of which method is the most beneficial to reduce ship pollutants, is to know how much a technology may cost to ship owners. Thus, the following column contains information that was reported by Entec in 2005 and other studies which have been mentioned in an above chapter and contains the cost of each technology expressed in terms of euro per ton pollutant abated. However, this information is limited and is not provided for all reduction technologies. For these methods, when the information is not available, an asterisk (*) is placed in the corresponding position. For this reason, in this study, the reduction technologies are divided into two categories. The first category refers to the reduction technologies for which their cost information is available from older studies by the form that is mentioned above. The second category refers to the remaining emission reduction technologies for which the costs information is not available. The next column contains the social cost after the reduction method for each technology. More specifically, in this column we can see how social cost has been modified by installing some of these technologies, which is calculated by using the emissions of 2013-2014, instead of the initial social cost that is referred to in the fourth column for these two years without the use of the reduction methods mentioned earlier. Finally, the last column includes the net environmental profit of this study that is calculated by subtracting the social cost of an after reduction emissions method and the cost of each technology from the total social cost of the two years for the main pollutants.

Below table 22, are presented the basic results of this table into two charts. These charts (figure 38 and 39) show the minimum social cost that every technology-method can achieve for each main pollutant and the minimum technological cost of each method (if exist). Also, these figures present the maximum and the minimum net environmental profit for each technology that have calculated in this study. These charts was created in order for someone to understand how the costs (social cost and cost of a technology) ranged for each technology in comparison with the total social cost that calculated in this study for the years 2013-2014. Note that all the technologies are illustrated in these two charts with the same turn where are mentioned in tables 19 and 20.

Technology	Ship type	Total emissions (t)			Social cost (million euro)				Abated emissions (t)			Cost of technology (million euro)			Social cost of after reduction emissions (million euro)			Net e pro
		NOx	SOx	PM	NOx	SOx	PM	Total	NOx	SOx	PM	NOx	SOx	PM	NOx	SOx	PM	
e low speed young engines)	New								911-1822	-	109	0.01-0.02	0	-	10.53-14.03	14.82	8.71	
e low speed old engines)	Retrofit								911-1822	-	109	0.01-0.11	0	-	10.53-14.03	14.82	8.71	
IEM	New								911-1822	-	109	0.02-0.18	0	-	10.53-14.03	14.82	8.71	
ter Injection	New								2278-2733	-	-	0.79-1.12	0	-	8.77	14.82	17.42	
Motors	New								3189-3644	-	-	0.63-0.98	0	-	5.26	14.82	17.42	
Motors	Retrofit								3189-3644	-	-	0.84-1.11	0	-	5.26	14.82	17.42	
le SO_2 ECA g 2.7% resid. Oil)	New								4100-4510	-	-	2.15-3.4	0	-	0.18-1.75	14.82	17.42	
le SO_2 ECA g 2.7% resid. Oil)	Retrofit								4100-4510	-	-	2.34-3.65	0	-	0.18-1.75	14.82	17.42	
SO_2 ECA g fuel 1.5% S)	New								4100-4510	-	-	1.63-2.45	0	-	0.18-1.75	14.82	17.42	
SO_2 ECA g fuel 1.5% S)	Retrofit								4100-4510	-	-	1.81-2.76	0	-	0.18-1.75	14.82	17.42	
using MDO	New								4100-4510	-	-	1.28-1.86	0	-	0.18-1.75	14.82	17.42	
using MDO	Retrofit								4100-4510	-	-	1.47-2.18	0	-	0.18-1.75	14.82	17.42	
scrubbing	New								228	1354-1787	44-175	0	0.43-0.70	-	16.67	0.15-3.7	3.48-13.94	
scrubbing	Retrofit								228	1354-1787	44-175	0	0.7-1.03	-	16.67	0.15-3.7	3.48-13.94	
hing: l to 1.5% S fuel	New/Retrofit								-	794	11-39	0	1.62	-	13.41	8.3	14.29-16.55	
hing: l to 1.5% S fuel	New/Retrofit								-	794	11-39	0	0.98	-	13.41	8.3	14.29-16.55	
hing: l to 0.5% S fuel	New/Retrofit	4556	1805	218.2	17.54	14.82	17.42	49.78	-	1083-1462	11-44	0	1.55-2.1	-	13.41	2.82-5.93	13.94-16.55	
hing: l to 0.5% S fuel	New/Retrofit								-	1083-1462	11-44	0	1.83-2.47	-	13.41	2.82-5.93	13.94-16.55	
f Injection Pressure - "Common ology"	New								1139	0	109	*	*	*	13.16	14.82	17.42	
s re-circulation	New								456-2733	1354-1787		*	*	*	7.02-15.79	0.15-3.7	17.42	
uel injection controls	New								1139	-	-	*	*	*	13.16	14.82	10.45	
ally controlled lubrication	New								-	-	44-65	*	*	*	17.54	14.82	12.20-13.94	
d engine monitoring /control	New								1139	54	-	*	*	*	13.16	14.37	17.42	
s water injection (CWI)	New								1367	-	11-39	*	*	*	12.28	14.82	14.29-16.55	
r emulsions (FWE)	New								456	-	-	*	*	*	13.16-15.79	14.82	17.42	
turbochargers	New								1822	-	-	*	*	*	10.53	14.82	17.42	
ger cut off	New								1822	-	-	*	*	*	10.53	14.82	17.42	
Non-Catalytic Reduction	New								2278	-	-	*	*	*	8.77	14.82	17.42	
ticulate Filter (DPF)	New								46-456	-	175-196	*	*	*	15.79-17.37	14.82	1.74-3.48	
ge Based-After-treatment	New								4328	1715	207	*	*	*	0.88	0.74	0.87	
s (LNG)	New								911	1805	192-216	*	*	*	3.50	0	0.17-2.09	
	New								-	-	22-153	*	*	*	13.41	14.82	5.23-15.68	
	New								-	1805	-	*	*	*	13.41	0	17.42	

Table 22: Total information and calculations for all the technologies in the studied Greek ports.

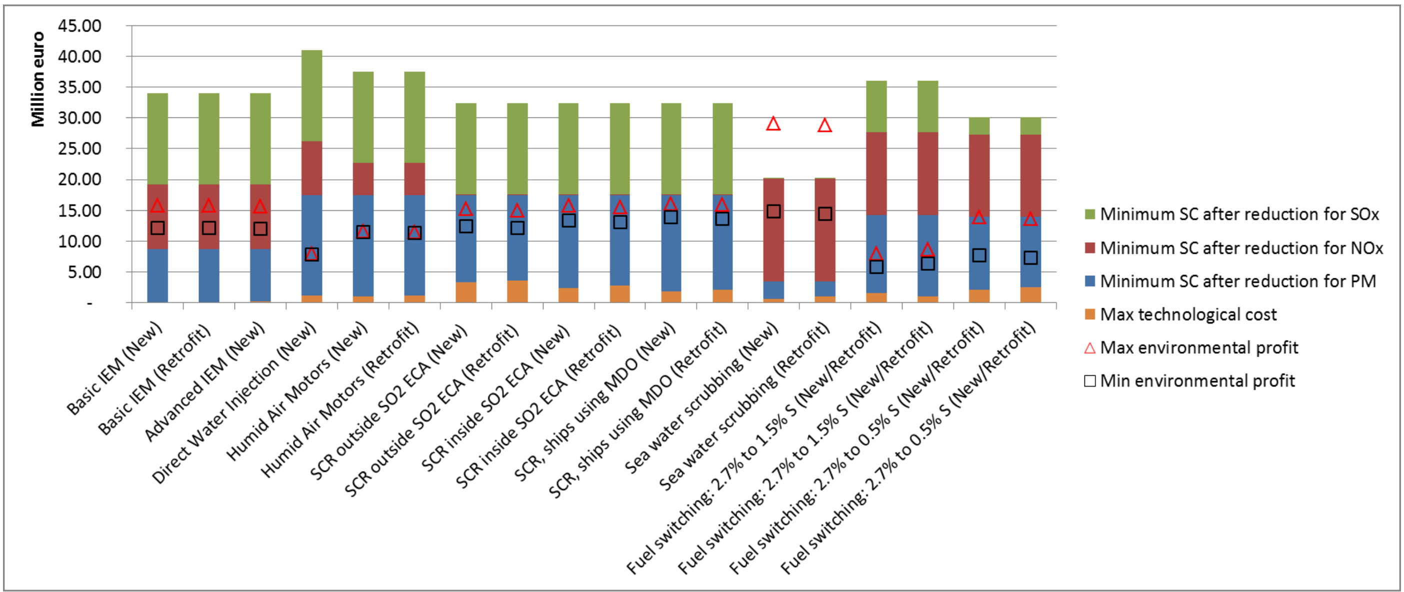

Figure 38: Basic results of table 22 (cost of technologies exists).

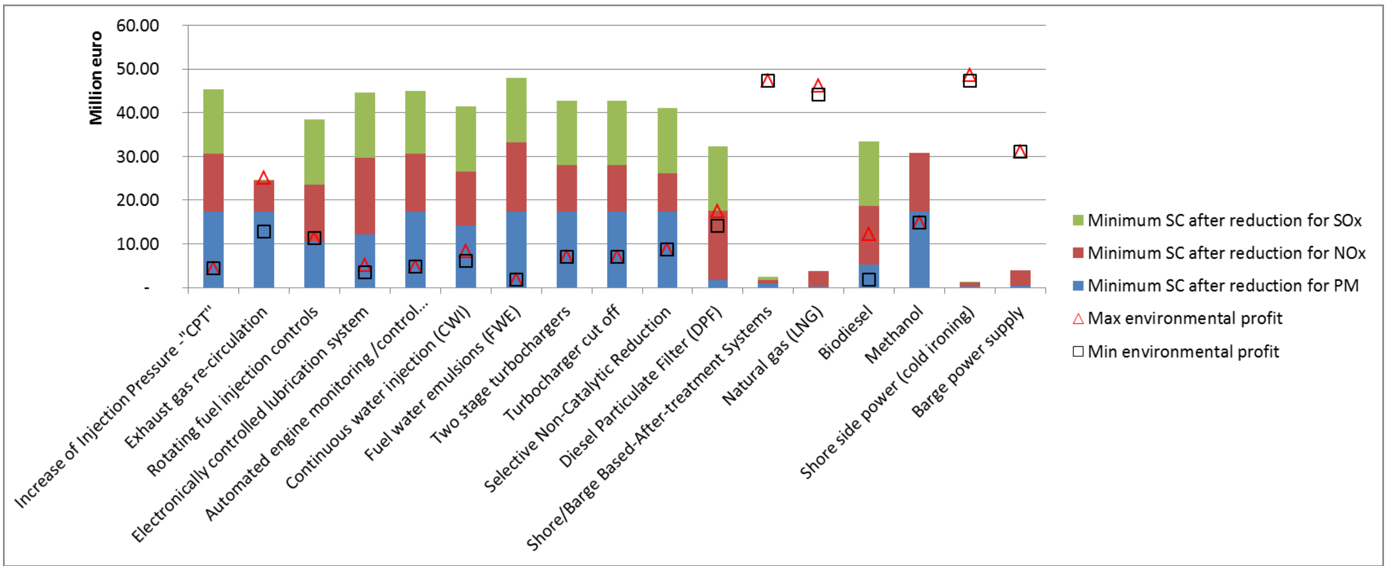

Figure 39: Basic results of table 22 (cost of technologies is not exists).

For the first category of technologies for which we have information about their installation cost, we can see that Sea Water Scrubber technology consists the most efficient method with the higher net environmental profit. Based on the marginal external costs of air emissions, the environmental profit could range from 14.4 up to 29.1 million euro for installing the SWS (new builds and retrofits) for two years. Thus, despite the high installation cost of this method that ranges from 433,153 up to 696,835 it is a highly beneficial method which can reduce the main ship pollutants and increase the profit of the ship owners. Also because of a longer lifespan, the scrubber system on a new- built ship has slightly larger net environmental profit (29.1 million euro) than retrofits (28.8 million euro). Thus, Sea Water Scrubber installed on a new ship is generally more appealing than on a retrofit. An old ship is not suitable for a scrubber installation when its remaining lifespan is less than 4 years. Moreover, the next technology with the biggest net environmental profit is Selective Catalytic Reduction as well as Internal Engine Modification. Specifically, on SCR the higher profit can be reached by using MDO fuel on new- built ships (16.1 million euro) and retrofits (15.9 million euro). The MGO solution is the most appealing in the above example. However, the price of ship fuel is subject to fast changes and is greatly uncertain. The price spread for MDO and MGO instead of HFO is expected to increase due to the sulfur regulation introduced in 2015-2016 as a result of the higher demand in lower sulfur fuels. The lifespan of this method is about 15 years for new builts and 12.5 years for retrofits. IEM follows close, being the second technology with the higher profits. Thus, Basic IEM and even more Advanced IEM have net environmental profit 12.1-15.7 million euro.

This study considers that Basic IEM and the Advanced IEM are reducing both NO_x and PM emissions at the same level; however, the cost of each technology is different. The cost of the Basic IEM for retrofit ships is higher than for new ships; however it does not affect the net environmental profit due to the fact that both methods have low technological cost. Nevertheless, Advanced IEM is more efficient than Basic IEM since the lifespan of this method could be 25 years while basic IEM's that could be only 2.5 years. This is due to the fact that basic IEM is generally a simple modification. In most cases, an installation of slide valves is enough to reduce some emissions, although they have only a few years of life.

On the other hand, Direct Water Injection has the less net environmental profit (7.8-8 million euro). One reason that justifies this result, is that DWI reduces only NO_x emissions up to 50-60% and also the cost of this method is quite high compared to others. Moreover, DWI system's life span is estimated to around 4 years and the rest of the equipment is estimated to have a life time of 25 years.

The other half table is related with the second category of technologies that reduce NO_x, SO_x and PM emissions but their installation cost is not available by the exact way which the previous methods referred above. Thus, although this information does not exist, in this study the capital and installation cost for most of them is mentioned in order to compare all technologies.

More specifically, the most profitable solution is to install a Shore Side Power System on ports. By installing this method a profit of 47.3-48.59 million euro could be achieved. A normal range of costs to provide shore power at a berth can be between 1 to 15 million dollars. Although it can achieve a huge reduction for all emissions, the costs of these systems vary and depend on several facts. Similar to shore power systems are the On-Shore Power Supply and Barge Power Supply Systems. These methods can reduce almost all the main ship emissions that are produced in ports and they can also achieve a high profit of 47.3 and 31.11 million euro respectively. Also one of the most beneficial techniques is the Liquid Natural Gas (LNG) that reached a net environmental profit of 44.19-46.11 million euro for the years 2013-2014. This method could not reduce NO_x emissions but it can almost eliminate all the SO_x and PM emissions. For this fact, using Liquefied Natural Gas (LNG) as ship fuel has recently gained worldwide attention. Also recently, in cruise ship industry, for the first time, four new vessels have been equipped with dual fuel engines that run on clean burning LNG to generate 100% of power while at sea.

On the contrary, Common Rail Technology, Automated Engine Monitoring/Control System and Electronically Controlled Lubrication System have the least net environmental profit as opposed to the other technologies with 4.39, 4.83 and 3.48-5.23 million euro for each method respectively.

From another perspective, the highest NO_x reduction can be achieved by using Selective Catalytic Reduction (SCR) or Humid Air Motors (HAM) for the first category of technologies and by using Shore Side Power Systems or Shore Based-After-treatment Systems for the second category. In particular, the abated emission of NO_x by using SCR is calculated between 4,100-4,510 tons for the two years that this study refers to and for HAM ranges between 3,189-3,644 tons. NO_x emissions can be reduced by engine design systems or after-treatment technologies. Most commonly used techniques are internal engine adjustments, which include several methods for optimizing the combustion conditions and fuel injection and charge air characteristics in terms of nitrogen oxides and particulate matter emissions. With these modifications a reduction of 30% in NO_x emissions can be achieved. For further reduction of nitrogen oxides the most potential techniques are water injection to the engine process by direct injection, water-fuel-emulsion or humid air, exhaust gas recirculation and selective catalytic reduction. With exhaust gas recirculation the NO_x reduction potential is 35-50%, with DWI and fuel-water-emulsion 50-60%, with HAM 70-80% and with SCR 90-99%. Fuel quality and many of the NO_x reduction technologies also affect the emissions of PM, CO and HC.

Furthermore, the highest SO_x reduction can be achieved by using Sea Water Scrubbing Systems with 1,354-1,787 tons of abated emissions both on a new built or on a retrofit ship. However, the cost for this technology differs between new and retrofit option, with the installation cost of an older ship being higher than on a new built ship by 0.68-1.03M and 0.433-0.70M respectively. On the second category of methods, Liquid Natural Gas (LNG), Methanol, Barge Power Supply Systems and Exhaust Gas Re-circulation have the highest SO_x abated emissions with the three first methods being able to achieve 100% reduction with 1.805 tons of SO_x abated emission. EGR system follows with 1,354-1,787 tons of SO_x abated emissions.

Particulate matter (PM) emissions generally can be reduced with the sulfur dioxide reduction measures and for further reduction oxidation catalysts and particulate filters can be used. The highest PM reduction can be achieved by using again Sea Water Scrubbing Systems with the value of abated emissions ranging between 44-175 tons and by using Shore Side Power Systems, Liquid Natural Gas or Diesel Particulate Filter (DPF) with 207-216, 192-216 and 175-196 tons of abated PM's emissions for each method respectively.

7.4 Reduction potential

Large emissions of NO_x, SO_x and PM are a cause of major environmental problems in the sea area and most importantly in the port areas. Ships account for a large and growing share of these emissions. For that reason organizations like IMO try to diminish this issue by applying very stringent rules, with the most recent of these applied from 1 January 2016. However, a problem in the context of the new rules is that they will apply to new ships only, and the turnover of the fleet is slow.

This study is associated with social emission effects and private abatement costs in order to provide a cost-benefit analysis of main reduction measures for shipping. This could be achieved in two ways. When a ship operator needs to choose a new technology in order to comply with the shipping regulations, it is essentially a matter of balancing high investment costs for retrofitting of new equipment or in new built ships against long-term operational costs depending on the type of fuel selected. Also it has to find if it is more efficient to invest only in one new technology or invest in a combination of technologies. In addition to these basic calculations there may be other factors that also need to be considered, such us the space that the new technology may require or the lifespan of the equipment that will be needed.

The most feasible and cost-effective technologies may be found among Sea Water Scrubbing, Selective Catalytic Reduction or LNG and Shore Side Power (cold ironing). But Basic Internal Engine Modification is also a relatively simple method to reduce emissions with a reasonable cost-effectiveness. Also, several of the abatement technologies may be used in combination with one another in order to increase efficiency or to reduce more efficient the main pollutants for shipping.

Many studies have made researches in order to examine this issue and find out which combination of methods are the most efficient. For example, some studies found out that Exhaust Gas Re-circulation systems work very well with Diesel

Particulate Filters. DPFs not only function to reduce PM but are also very important to the functionality and effectiveness of an EGR system. Since EGR systems require a clean exhaust supply before the exhaust gases are directed back to the engine, the use of a DPF fulfills this process while reducing PM at the same time. Diesel Particulate Filters are a very attractive retrofit option, but are also linked with some drawbacks. Despite their high cost, in order to have DPFs on the engine as an after treatment system, the use of Ultra-Low Sulfur Diesel Fuel is required. Also, it requires threshold exhaust temperatures in order to ensure regeneration.

Moreover, significant results can be gained by combining an EGR system for NO_x removal with an exhaust gas cleaning Scrubber (EGCS) system for SO_x removal. The purpose of the Exhaust Gas Recirculation (EGR) scrubber is to remove sulfur and PM from the engine exhaust gas so that this gas can be re-introduced to the engine without damaging the cylinder liners or other engine components. This process removes a big amount of sulfur and PM that does not have to be removed again in the EGCS, as well as the total exhaust gas flow is reduced. For that reason, the EGCS can be made smaller in comparison with the size it would have had for a similar sized engine without EGR scrubber. However the reduced scrubber size requires some operation changes of the EGR system or fuel switch to a low sulfur fuel at engine loads above approximately 80% outside NECA [77].

The study showed that EGR and EGC scrubber can be combined in a beneficial way in order to reduce the main pollutants and almost eliminate them. This way, they can work together to reduce 10-60% NO_x emissions, 75-99% SO_x emissions and 20-80% PM emissions. Also both of their net environmental profit is quite high, due to the high social cost that would be able to save. Also, another study [77] has shown that the benefit of installing EGR and EGC scrubber as a combined system is a potential reduction in CAPEX around 20% if the EGC scrubber is reduced according to the reduced exhaust gas flow when operating with EGR. If the full EGC scrubber size is kept, the saving in CAPEX is around 5%. The OPEX savings by operating on HFO with EGR and EGC scrubber systems compared to operation on MGO/MDO is around 20% to 30% giving a payback time below two years [77].

MGO is considered to be an attractive strategy with quite low investment costs for actors who believe that LNG may have a breakthrough sometime in the mid-term future. However, if many use that strategy, the MGO demand, and hence price, may increase further in the near future.

Another beneficial combination of shipping reduction techniques is SCR with biofuels. As far as PM is concerned, the use of biodiesel in combination with a catalyzed such as, continuously regenerating trap and Selective Catalytic Reduction System (CCRT-SCR) would avail to further remove the solid PM component from the exhaust in order to achieve a reduction up to 90% of PM. Alternatively, operation of engines on high quality fuels, in combination with DPFs will produce significant SO_x and PM reductions, although both of these options come with a cost penalty.

Another perspective regards the use of different combination of methods by using a shore side system. A Shore-Side emission treatment system could be demonstrated as an alternative to shore-side power at ports. This system could be connected to the ship exhaust stack and the exhaust respectively could be funneled to a combined SCR and scrubber system installed on a barge or on a dock. These kinds of systems are expected to reduce NO_x emissions by 95% and SO_x emissions by 99%. However, they could be two to four times more expensive than generating the electricity on-board by heavy fuel oil engines if someone takes the direct costs into account. Nevertheless, when the external costs were also evaluated, the usage of shore-side electricity proved to be the cheapest option and the most efficient, since the external costs are much lower for vessels connected to shore-side electricity supply systems.

7.5 Conclusions

In the present study after taking into account the emissions from maritime for the years 2013-2014 in the main Greek ports tried to find out which reduction technology that already exist is the most beneficial. The results after the study show that there is a great reduction potential in NO_x, SO_2 and PM emissions from ships. However, reduction in emission levels is not the same in all kind of ships. For that reason each ship has to decide which technology is the most beneficial in order to cover its needs and also have the maximum profit. In this study, the used pollutants referred in cruise vessels that generally are a particular form of vessels. Cruise ships require a lot of space for the amenities of the passengers. Thus, a reduction technology with big installation system that requires specific facilities and plenty space, perhaps is not acceptable in this case.

In order to estimate emissions based on detailed individual activities of cruise ships in the selected ports a ‘’bottom-up’’ method has been used. For every ship call, the emissions were calculated through a specific application. The total emissions are calculated for each port by summing for all cruise ships visiting during the selected time period. All necessary data regarding cruise ship calls in Greece during 2013 and 2014, i.e. vessels’ names, date and call duration (arrival and departure time), were carefully collected from local Port authorities and compared with similar data of other sources to harmonize any discrepancies.

In this study in order to make the final conclusion required to have the technological cost of the reduction methods. The information about the technological cost of each method in this study was evaluated based on already related studies. The most authoritative and comprehensive evaluation of the abatement costs that have been used also in this study, is a study by Entec (2005) for the European Commission.

In this report except from the cost of the abatement technologies, also the external cost is calculated and taken into account for the study's final results. The total external cost due to emissions to air in studied ports is estimated by using one damage cost methodology named New Energy Externalities Development for Sustainability (NEEDS). For the calculation of the total external cost are used the pollutants in the main studied Greek ports for the years 2013-2014. Also, in order to find out which technologies are the most beneficial, the social cost of after reduction emissions is calculated. Finally, the net environmental profit of this study is calculated by subtracting the social cost of an after reduction emissions method and the cost of each technology from the total social cost of the two years for the main pollutants. This net environmental profit shows us which method is the most beneficial from cost perspective, in order to make our final conclusions. The conclusion of the study not only presents the better solutions for maximum profit, but also presents combinations of different technologies that could be used in order to achieve better results in emission reduction and in increase of profit.

There are several techniques to reduce the shipping emissions. The level of SO_2 emissions is mainly depended on the sulfur content of fuels used. Another possibility to diminish SO_2 emissions is by using Sea Water Scrubber to clean the SO_2 from exhaust gases. In this study totally found out that Sea Water Scrubbers are the most beneficial method as it has the highest net environmental profit and also can be used during the free sailing of a ship. However, this technique requires too much space inside so some passenger cabins need to be removed. The only solution that can be installed in cruise ships is the closed loop system because of the space that it requires and due to the fact that utilizes sea water that is generated on board. The other scrubber system, the dry system although is not polluting, is not a possible solution for the cruise ship, because it needs a higher than two car decks and there would be a significant loss of ship capacity. The highest SO_x reduction can be achieved by using Sea Water Scrubbing Systems with 1354-1787 tons of abated emissions both on a new built or on a retrofit ship. This range in abated emissions is relates with the fact that SWS can reduce SO_x levels up to 75-99%. Sea water scrubbers are also recommended due to the fact that except from SO_x it can reduce as well PM emissions up to 80% and NO_x emissions up to 5%. Nowadays, more and more ships operating with wet scrubber systems and with the IMO Sulfur requirements in the ECA (emission control area) and SECA areas (sulfur emission control area) that increase, installations are expected to have rapidly increased over the next years. However, the cost of this technology is quite high as it requires large equipment to be installed and also has high maintenance cost. The cost for this technology differs between new and retrofit option, with the installation cost of an older ship being higher than on a new built ship by 0.68-1.03M and 0.433-0.70M respectively. Despite that, in this study the SWS system seems to be the most beneficial method. Together with this technology goes also selective catalytic reduction system. The exhaust gas, produced by the engine with the use of HFO, goes directly to the boiler, from where it is led to the SCR and then to the silencer. The scrubber is the last part, where the exhaust gas is going through. Thus, SCR is also a technology that it is recommended in this study in order to minimize NO_x emissions is Selective Catalytic Reduction. The reduction of NO_x emissions by using the SCR system is more than 90%. Also, as we saw earlier the capital cost for a new built ship is ranged from 60000-360000$ and the operating cost is ranged from 45000-153000$ instead scrubber technology that cost much more.

A method that every day is getting more and more renowned is Liquid Natural Gas (LNG). LNG has also a high net environmental profit, so it is the second method that this study recommends. LNG is not considered as a technology, however, using LNG as ship fuel promises less emissions and given the right circumstances, less fuel costs. In some conditions the emission reduction can be up to 100% for SO_x, 80% for NO_x and 88-99% for PM emissions. Actually, very recent was made the world's first cruise ship which can be operated with liquefied natural gas (LNG) while docked in port resulting in major reduction in emissions. As mentioned earlier it requires also a lot of space to store it which is a challenge for vessels with limited or no deck space. This problem can be solved by using specific tank systems that hasn't so high investment cost as scrubber tanks. Also, the price of LNG depends for many years on HFO price, but often is cheaper. Taken into account the cost of LNG is about 60% of HFO. Furthermore, for larger vessels such as cruise ships the LNG system has the shortest payback time as some studies have shown.

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