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Title CO_2 emission reduction measures in shipping

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Abstract

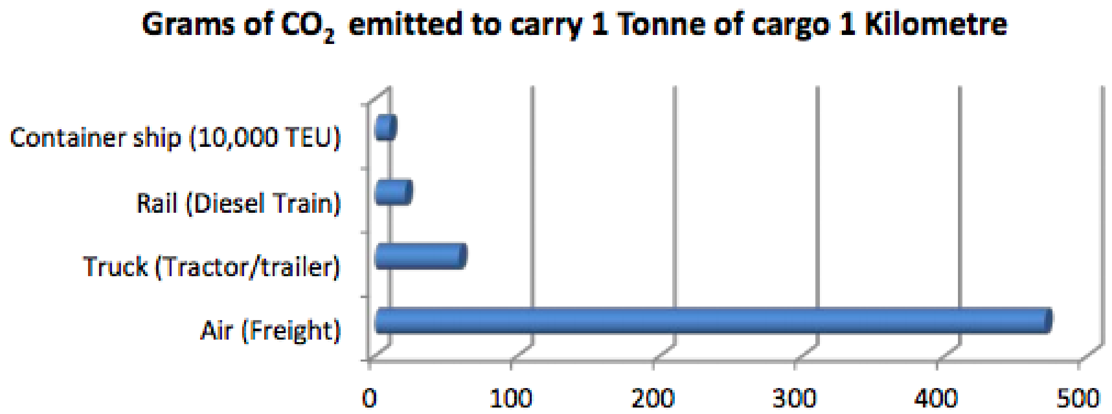
As the dominant source of global trade and transport, the shipping industry contributes overwhelmingly to the environmental deterioration compared to other modes of transportation. Stakeholders - from consumers, shippers, cargo owners, governmental institutions, suppliers to international community – have consistently been raising their concerns in addressing the environmental hazards and resource depletion. The shipping industry with 90% of the international trade mobilization has a lot to contribute to deteriorating global environment as the volume of trade is accelerating globally with increasing population. To help protect biosphere and environment and address the societal concerns about environment while be profitable in their operations, many shipping firms have been investing in different operational and technological measures to curtail the GHG emissions from shipping. This paper aims to review the existing body of literature on the available measures that can be undertaken for fuel efficiency and/or emission reduction, along with hurdles and policy implications for future.

Keywords: green shipping, operational measures, technological measures, sustainable shipping, marine development, eco innovation, environmental regulations, Climate change, CO2 abatement measures, GHG emissions.

Introduction

With accelerating population and increasing trade mobilization globally, there is need for more to meet the needs of the society than ever before. In pursuit of this quest, the industries and businesses often becomes oblivion to their role as responsible citizens. As the international community is becoming more concerned about the climate change and environmental protectionism, there is mounting pressure on all industries to play their role and implement certain policies and measures to meet the climate challenge (Paris agreement). The aim is to keep the global temperature below 2 degree Celsius (UN, 2015).

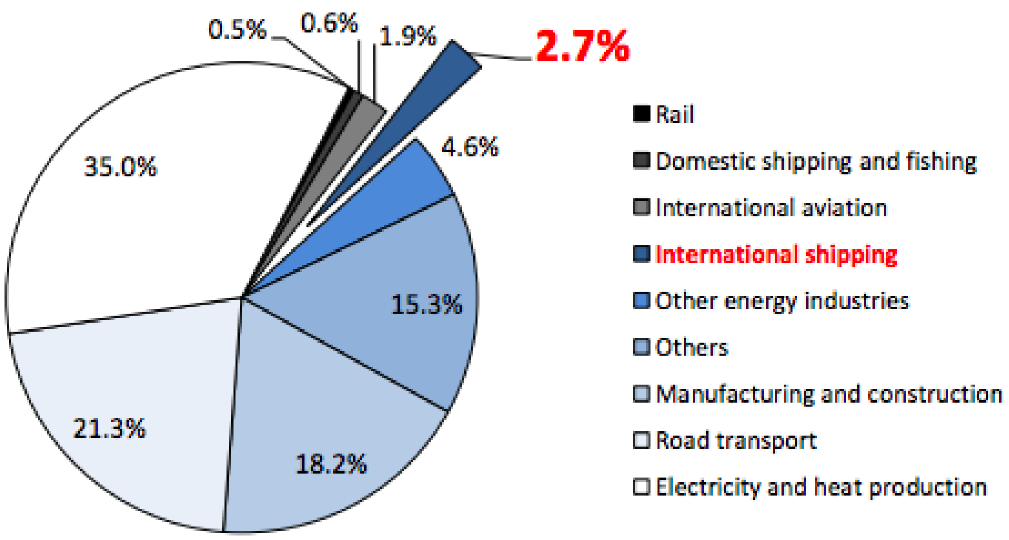
The maritime industry is considered to be one of the main contributor of GHG emissions globally (Eide et al., 2009), although it is often claimed that the sea borne trade, compared to other modes of transport, is the most environmental friendly form of trade (WSC, 2009). A container vessel emits almost 10 grams of CO2 per tonne-km compared with 470 grams of CO2 to air borne trade. The marine vessels emit hazardous emissions, mainly CO2, from the burning of heavy fuel oil (Crist, 2009). Approximately, 80% of the marine vessels use HFO due to it being cheap and economical (IMO, 2007), (Lee, 2010). The shipping CO2 emissions contributes over 3% (around 1 Gt) of global CO2 emissions in 2007, that comparatively renders lesser emissions to other modes of transport, like air, road and rail and makes it more efficient (Buhaug et al., 2009). Presently, the estimated statistics of the global CO2 emissions of the sector accounts to approx. 2% of global CO2 emissions (Smith, 2014) that could probably surge to approx. 17% of CO2 emissions due to greater business demand for shipping industry by 2050 (Cames, 2015).



Co2 emission for different transports (Maersk, 2010)

There is a growing pressure on the shipping industry to regulate GHG emissions and implement policies to address it. The industry relies on IMO and other organizations for policy construction and implementation. The United Nation's International Maritime Organisation (IMO) works under the auspices of United Nations Framework Convention on Climate Change (UNFCCC) for pursuance of Kyoto protocol. The Energy Efficiency Design Index (EEDI) as defined by IMO sets mandatory CO2 reduction targets for all the new built ships built as of 2013. These reduction targets are made stringent after every five years up to 2030, making sure that the ship owners order energy efficient ships. The amendment established the Ship Energy Efficiency Management Plan (SEEMP) asking the ship owners to have a plan on-board for ships enhancing operational efficiency.

The International Maritime Organisation (IMO) came up with technological, operational and market measures that maritme industry can adopt to curtail GHG emissions and achieve energy efficiency (Buhaug, 2009) (IMO, 2010a). The most important study on this was done by CE Delft et al (2009), included 29 operational and technical energy efficiency measures for 14 ship types (tankers, bulkers, containers etc.) for different ship sizes.



Shipping CO2 emission comparison with other industries (Buhaug et el., 2009)

Global trade via shipping delivers both advantages and disadvantages due to rising globalization. Shipping firms are expanding their operations while, at the same time, resource depletion and increase in GHG emissions is also observed due to it. Ships are contributing around 3% of total (GHG) emissions. This level can to 18% by 2050 if proper measures are not taken. This renders international efforts counter-productive to check the global warming temperature increase at desired levels i.e. below 2 °C.

Keeping in view the importance of global maritime industry and the share of seaborne trade, it is important for the shipping sector to implement measures for carbon reduction and fuel efficiency.

Several studies and reports (Tillig, Mao, & Ringsberg, 2015), (Eide, 2011), (Heitmann & Peterson, 2012), (Paul Gilbert, 2014), (CCNR, 2012), (Wang & Lutsey, 2013), (Buhaug et el., 2009), (N.Psaraftis & A.Kontovas, 2010), (Rehmatullaa, Calleyab, & Smith, 2017), (Hoffmann, Eide, & Endresen, 2012), (Faber et al., 2011), (Lindstad, 2015), (Maddox consulting, 2012), (Wärtsilä. 2009), (Harrould & Savitz, 2010), (Miola., 2011), (Lin, 2012), (ICCT, 2011), (Crist, 2009), (Eyring et al., 2005), (Endersen et al., 2008), (Longva et al., 2009) by or to the organizations like the IMO have been conducted to address the increased marine environmental deterioration caused by the marine vessels and how certain measures can be taken to remedy it. Some of these studies takes a holistic approach and includes all the CO2 reduction measures that shipping industry has taken to achieve energy efficiency and minimize the environmental hazards while other studies address adopting one or two measures about a specific part of the ship (e.g. using alternate source of energy like LNG, solar or wind power). The studies further divide these measures either into operational measures (improving and maintenance of certain parts of the ships without having to highly invest), technical measures, and/or structural measures. Some of these measures can either be applied to the existing ships or new-builds or both depending on the complexity of the structure as well as other issues. Furthermore, some studies concentrate on the green practices that the shipping sector can adopt and speculating the effects of these measures and what results it can yield in terms of energy efficiency and CO2 emission reduction while other studies implement one or two measures (e.g. weather routing, speed optimization measures, hull and propeller adjustments, economies of scale etc.) on to ships and measures the results with either the previous available data or compare with other ships. Depending upon the capital investment cost and easiness or complexity of applying these measures on the ships, the studies show the amount of fuel efficiency and emission reduction that each of these measures result in relative to others. Furthermore, some studies discuss the barriers and limitations in implementing these measures while other studies explore the regime regulations and policy implications for emission reduction.

This study aims to review the academic literature on efficiency measures for CO2 reduction that shipping industry has undertaken, what drives it, what measures are being implemented and their implication in the maritime industry. The remainder of this thesis is structured as follow. Section 2 defines the research question, purpose and scope along with the drivers for CO2 reduction. Section 3 presents the research methodology. Section 4 reviews the literature in detail on CO2 reduction measures that have been implemented, and their implication for the shipping industry. Finally, Section 5 discusses the challenges and policy options and offers useful recommendations and future directions.

Research Question

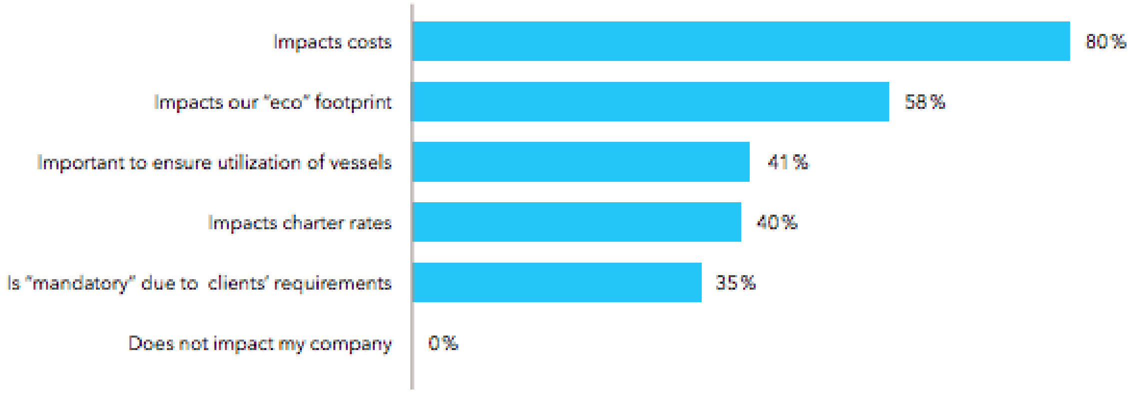
What are the CO2 emission reduction measures in shipping?

Purpose and scope

The purpose of the study is to review the literature and get into the details of all the measures that the shipping sector is familiar with in mitigating the CO2 emissions, thus achieving operational efficiency. The study will evaluate the barriers in implementing these measures and further recommendations about the position that the shipping industry should take vis a vis CO2 emission reduction measures.

Drivers for reducing CO2 emissions

The history of environmental regulations shed light on the importance of environmental protection. Shipping firms opt for application of various approaches to reduce CO2 emissions. There are numerous impulses for shipping firms to adopt these measures. According to (Armstrong & Banks, 2015), the drivers toward addressing these practices and initiatives can be divided into three main driver groups: economics, compliance, and customer requirements. The institutional theory states that firms use such measures due to desire of shippers for fulfilling the legal requirements.



How the energy efficiency measures impact the shipping companies
(DNV GL, 2014)

While there is increasing pressure from the regulatory bodies and governments on shipping firms to become green in some, if not all, of their operations and activities, there is significant evidence that firms, instead of succumbing to external pressure, would themselves like to adopt GHG reduction measures for being cost and energy efficient.

Companies adopt regulatory requirements for energy efficiency. The international maritime organisation is responsible for implementation of various protocols for preventing maritime pollution.

Another prevailing mechanism in the shipping industry towards green practices is the enforcement of **regulations** by governments and other organizations. Improving the role of the maritime industry in emissions reduction from ships is a serious concern. The maritime sector, the IMO, and different governments in several countries collaborate to minimize these emissions (McKinnon, 2007). The Kyoto Protocol of the UN Framework Convention on Climate Change (UNFCCC) asks the shipping countries to take the responsibility to mitigate shipping emissions based on Common but Differentiated Responsibility (CBDR) principle. However, due to the hurdles in determining emissions discharges in deep waters, it is complex to report on this (Gilbert & Bows, 2012). The IMO, a United Nations body in collaboration with maritime industry, has developed International Convention for the Prevention of Pollution from Vessels (MARPOL). This body covers all the areas of shipping sector with details. It emphasizes the technology to be used to lessen SOx and has established a new vessel design benchmark for ship energy efficiency. The United Nations Convention on the Law of the Sea (UNCLOS) outlines the sources of marine pollution and responsibilities of the shipping states in this area. Besides IMO, there are other organization working to regulate the marine environment. While we analyse the articles on the role of regulatory authority towards green practices, it is noteworthy that the regulatory framework in place to address the emission problem is inadequate, since this regulatory framework is state centric and hardly shipping corporations are included in the framework. Also, most of the shipping corporations prefer not to disclose detailed information of ship emissions, and there is hardly any transparency on the data reported by shipping firms on their annual reports (cited (Mia, Islam, & Kuruppu, 2016).

The updated version of IMO 2012a which was amended in 2013, is used for achieving the goal of energy efficiency. This regulation requires that a certain design according to energy efficiency has be used. UN efforts like promulgations of KYOTO protocol are also bounding companies to comply to international standards of reducing carbon emissions.

The emission of CO2 will boost up in the upcoming decades. The figures will jump from 50 percent to 250 percent till 2050. The studies (i.e. smith, 2014) has found that awareness regarding the issue has brought a little change in carbon emissions.

EU has also started complying to Monitoring Reporting and Verification for removing the obstacles in the way of using energy efficiency methods of carbon emission reduction.

The Environmental Protection Agency of USA has also proposed regulations because legislative measures are mandatory for environmental protection.

In the second group, Porterian hypothesis says that the cost incurred on environmental regulations can be offset by the innovation it brings. Environmental regulation results in innovation due to low cost material and efficiency in the process of material utilisation. The study further argues that Prescriptive based policy like technology controls, standards of performance are weaker as compare to non-prescriptive market based innovation policy like taxes and cap and trade (tradable permits).

The third group is customer requirement, as huge organisations are enlisted with stock exchanges so they follow the vessel chartered for sustainability initiative and for claiming the corporate social responsibility. The main concern of the customer is low carbon emission supply as it contributes to climate change. Similar finding are found in (Florida, 1996), (Hemel, 2002) research studies.

Methodology

The methodology in this paper uses the qualitative assessment by reviewing the previous peer reviewed studies, reports and conference proceedings regarding energy efficiency and CO2 reduction measures are undertaken or being considered in the maritime industry. The review of the studies, beside important efficiency measures, focuses on the intensity and the percentage of decline in CO2 these measures result in. Reviewed studies apply different methodologies for measuring the CO2 reduction potential ranging from surveys and interviews with the important maritime stakeholders, implementing the operational measures to using the simulations and computer aided programs for some of the technical measures.

To search and analyse the results from the previous literature, we use online sources, various research websites that have peer reviewed articles and the university's online database with the following search strings: CO_2, GHG emissions, green innovation drivers, green shipping, sustainable shipping, marine development, eco innovation, green technology, environmental regulations, CSR, ship energy efficiency measures, CO2 reduction measures. Furthermore, leaving aside the methodology employed by the reviewed articles, we focused mostly on the abstract, introduction, discussion and conclusion parts to fetch the relevant information regarding the nature of measures employed (operational, technical or otherwise) and whether they yield significant results curtailing CO2 from the ships.

This exact number of reports and articles that we analysed is unknown but we included as many articles as we could find, based on the search strings and relevant reduction measures, to include in this study.

Literature analysis

To achieve the global climate target, maritime industry, like other sectors, should play its role in limiting the carbon footprint. It's more challenging considering the increase in maritime trade volume in the coming decades, likely exacerbating emissions further if proper measures are not taken. This section highlights and reviews the studies to identify the measures for potential CO2 emission reduction from shipping. Curtailing the emission in absolute terms in the long run requires a combination of measures to be implemented. There are few detailed studies and reports on how collectively implementing measures can reduce the emissions. Further these studies differentiate between various categories of measures and under each category, different measures that are undertaken. The major studies classify these measures into either technical/technological, operational and/or structural or alternate fuel measures. For the sake of convenience, all these measures are shown in the table 1.1. GHG emissions can be curtailed in three ways. Through technical measures, market based measures & operational changes (N.Psaraftis & A.Kontovas, 2010). (Balcombe et al., 2019) highlights the use of alternate energy sources (LNG, solar, wind, nuclear) along with some technical measures to decarbonise shipping. (Rehmatullaa, Calleyab, & Smith, 2017) identifies four ways to implement energy efficiency measures to mitigate shipping carbon footprint: a) Implementing operational measures in shipping that could reduce fuel consumption, hence emissions. b) Using renewable energy like wind and solar power, kites etc. c) Using biofuels that have lower emissions content. d) Using green technologies for new build ships.

	Operational	**Technical**	**Power sources**	**Structural**
Purpose	Maintenance	Optimizing engine power	Alternate fuels	Improved performance via interaction bw charterers.
Example	Slow steaming, hull & propeller maintenance, weather routing, voyage optimization	Reducing power to the engines, Optimizing hulls	Renewable energy (solar, wind), LNG,	Better fleet and logistics management, port efficiency, charter contracts
Investment cost	Low	High	High	Moderate
Emission reduction	Low	High	High	

Application	All ship types	Mostly new ships	Lack of on-board infrastructure, suitable for niche market	Hard to implement

From the studies by (Hoffmann, Eide, Faber, Heitmann)

Similarly, (Hoffmann, Eide, & Endresen, 2012) calculated the emission reduction potential from 25 measures that are applied to 59 shipping segments over a period of 20 years from 2010 up until 2030. The author divides the emission reduction measures into four categories: **Technical** measures include optimising the hull, propeller and rudder arrangements, hull coating, effective waste heat recovery system. These measures reduce the power required by the main and auxiliary engines. Most of these technical measures are limited to new ship designs and thus have substantial investment and moderate operating costs and hence yield reduction in emission and raises fuel efficiency. Similarly, **operational** options include the slow steaming, weather routing, engines tuning and maintenance, hull and propeller cleaning, optimised trim and ballasting. The investment and operational costs is very low for these measures and they give small reduction in emissions. These measures can be implemented on all ship types and training of the personnel and other educational measures to implement it. Using LNG, wind and solar power as an **alternate fuel**. Measures such as speed reduction due to increase in the fleet and port efficiency, reducing ballast journeys constitute the **structural change** that is part of this study.

Many of the cost effective measures are operational in nature. The author concludes that 19% of the baseline emissions for 2010, 24% for 2020 and 33% for 2030 can be mitigated cost effectively. By increasing the costs level to 100 USD/t gives a reduction potential of 27% in 2010, 35% in 2020 and 49% in 2030. Also by increasing the cost level more than 100USD/t yields less emission reductions, meaning emission reduction potential is achievable at low or moderate cost.

In a report submitted by (Buhaug et el., 2009) to IMO about the GHG emissions from shipping and measures taken to mitigate the carbon footprint, the author identified certain measures that can be undertaken for fuel efficiency and GHG emission reduction. Four categories were identified for reducing emission.

Firstly, by improving the energy efficiency, more useful work could be carried out in design and operational areas without having to consume extra energy and to incur major cost. Secondly, by using the renewable energy, like wind and the sun. These energies can be used on ships as additional power but the total share of energy that could be created is limited as it depends on the intensity of solar energy and direction of wind. Thirdly, using alternate fuels like LNG and biofuels, with less total fuel-cycle emissions per unit of work done. Lastly, using technologies by mitigating emissions through chemical conversion, capture, storage etc.

The author concludes that by using the above-mentioned technologies, shipping could generate 25 – 75% energy efficiency up til 2050.

Similarly, (Faber et al., 2011) presents fifty technical and operational efficient energy related measures but details analysis of twenty-two of these measures only due to availability of data.

The methodology is designed to estimate each of these measures for fuel efficiency and CO_2 abatement. Their study validated cost data and other estimates from naval architects and engineers, service providers and with the users of these technologies. The study first evaluates, then calculate cost effectiveness of these measures and the constraints to adopting these measures in the shipping industry. The study estimates that the fuel efficiency can be improved up to 45% by 2030.

The following table lists all the measure's the study enlists:

Technical Measures	Operational Measures
Lightweight construction & Design speed reduction	Operational speed reduction
Optimisation hull dimension	Optimization of ballast and trim
Wind power (kites), Hybrid and auxiliary power & Solar panels	Efficiency scale
Hull coating and Optimizing hull openings	Weather routing
Propulsion upgrade, Scrubber & Fuel-efficient boilers	Autopilot adjustment
Optimization propeller hull interface & Air lubrication	Increasing energy awareness
Waste heat recovery, Reducing on board power demand, & Speed control of pumps and fans	Propeller maintenance
Alternative fuels & Main engine adjustments	Hull cleaning

Source: DNV GL, (CE et al., 2009), (Faber, 2009)

Other similar studies include (Eyring et al., 2005), (Endersen et al., 2008) and (Eide, 2011), (Longva et al., 2009) who employ the same measures as discussed before and includes world merchant fleet above 100 GT to calculate the future (2020, 2025, 2030, 2050) shipping emission scenarios. International Council on Clean transportation (ICCT, 2011) along with Society of naval Architects and Marine Engineers (SnAME) identified 50 ship efficiency measures. Out of these 50, 22 measures were applied on 53 ship types to calculate cost effectiveness emission reduction potential.

Operational Measures

These measures involve operating and maintenance improvements that result in immediate CO2 emissions reduction. These measures are about the way ship is maintained and operated like speed reduction, weather routing/voyage optimization and optimising of trim and ballast. They have the same purpose; to mitigate CO2 reduction thus achieve fuel efficiency without having to make greater physical changes to the ship and without having to invest heavily for implementing the measures. They give less results in terms of Co2 reduction potential compare to technological measures but their results are immediate.

Measures	Fuel/CO2 reduction	Studies reference
Slow steaming / Speed Optimization	15 – 30%	(CE Delft, 2010), (Lindstad et al, 2011), (Corbet et al, 2009), (Faber & Jasper, 2011), (Psaraftis & Kontovas, 2010), (Chang & Wang, 2014), (Tai & Lin, 2013), (Cepeda, Assis, Marujo, & Caprace, 2017), (Tillig, Mao, & Ringsberg, 2015), (CCNR, 2012), (Crist, 2009), (Wang H, 2009), (Stepford, 2009), (Bond, 2008)
Speed reduction (Port turnaround time reduction)	8 – 20%	(Bazari & Longva, 2011), (Johnson & Styhre, 2015), (Shneerson & Lavon, 1981), (Eide, 2011), (Faber, 2011), (CCNR, 2012), (Cooper, 2003)
Bulbous Bow	2 – 12%	(Guerrero et al., 2018), (Tillig, Mao, & Ringsberg, 2015), (Watle, 2017), (Bray, 2009), (Chang et al., 2016), (Leonhardsen, 2017), (Faber, 2011), (Mahmood & Huang, 2012).
Trim optimization	6.8 – 11.3%	(Xujian, 2018), (Jianglong, 2016), (Wärtsilä, 2009), (Faber, 2011), (IMO, 2000). 0.6% saving in fuel (DNV GL, 2009), (Tillig, Mao, & Ringsberg, 2015), (Arwa W. Hussein., 2015), (Huang, 2015), (Sun, 2012), (CCNR, 2012)
Economies of Scale	Up to 30% or more. (depending upon the ship type)	(Lindstad et al, 2012), (Wärtsilä, 2009), (Lindstad & Eskeland, 2015), (Christa et el, 2008), (Cullinane & Khanna, 2000), (Notteboom & Vernimmen, 2009),
Voyage optimization / Weather routing	4 – 18%	(Lokukaluge P., 2017), (Zacconea, 2018), (WANG, 2018), (Ruihua et al., 2015), (Tillig, Mao, & Ringsberg, 2015), (Buhaug et al, 2009), (Crist, 2009)
Auto-pilot adjustment	0.5 – 3%	(Buhaug et al, 2009), (Crist, 2009), (Tillig, Mao, & Ringsberg, 2015), (Wärtsilä, 2009)
Propeller and hull maintenance	0.6 – 8%	(Faber, 2011), (Buhaug et al, 2009), (Tillig, Mao, & Ringsberg, 2015), (Wärtsilä, 2009), Crist, 2009)

Combined CO2 reduction from operational measures

Numerous studies have been conducted on operational measures that the shipping industry has undertaken with a view to achieve fuel efficiency and curtail the CO_2 emissions. The reason being obvious that operational measures require low investment cost since there is no change in physical form or design of the ships but slight improvements.

Slow steaming

Speed reduction is perhaps one of the most researched and implemented operational measure for energy efficiency and hence emission reduction. Many shipping companies have adopted this measure as they face the high volatility of fuel price. Normally, fuel consumption and ship speed are related by a third power function, meaning a 10% reduction in speed will result in 27% lower emissions (CE Delft, 2010). When ships sail at lower speed, it reduces the power required by the engine to sail. But while the power is curtailed, it now takes more time for the ship to cover the same distance. There is another issue with the adjustment of the engine load if the ships were to sail at lower speed and most engines as we know it are made to operate at a specific speed, and changes, if any, could damage the natural working of the engine. Automatic engines in such cases are more flexible to operate on slow steaming compared with mechanical. This measure can be adopted in all ship types but suitable for those that don't have fixed schedules like cruise and ferries.

According to (Lindstad et al, 2011) some shipping firms motive for speed reduction is to be cost efficient and be profitable (Bausch et al., 199), Fagerholt, 2001) and (Christiansen et al., 2007). For that, they find the optimal routes (fleet scheduling) and specific type of vessels for maximum cargo transport or only the profitable cargo on board (fleet size mix). Others consider the speed reduction with the aim to reduce GHG emissions.

(Corbet et al, 2009) studied the relationship between speed optimization and emission reduction of container vessels entering and leaving US ports. They studied 2 cases, on where the speed is reduced but no additional vessel is hired to maintain service frequency while in the other, speed reduction with extra vessel. Their findings concluded that the emission reduction in the second case are twice that of the latter and that taxing based on fuel consumption (150/t) leads to substantial decrease (30%) in the CO_2 emissions. (Wang H. , 2009) calculates the optimal speed for container ships and finds that at a bunker cost of $300/t, a 10% and 25% speed reduction results in $20/t and $50/t of emission reduction. Similarly, (Delft, 2010) report about container vessels, dry bulk and tankers showed reduction in CO_2 emissions and speed by employing extra goods on the fleet (overcapacity). (Lindstad et al, 2011) included the sea state (water and wind resistance) to claculate the CO_2 emissions reduction and found out that upto 19% can be mitigated but increase in cost due to the bunker price and additional ships required to cover the same amount of goods transported.

(Faber & Jasper, 2011) explains that relationship between speed, engine power and fuel consumption. Speed optimization means more time sailing and less transport work per unit of time, which can be compensated by increasing the vessels in the fleet. He assumes that keeping the port calls constant, the extra cost in adding the vessels to fleet can be offset by saving from the non-recurring costs of speed reduction (fuel savings) annually. He concludes that at a design speed of 100%, 90%, 80% and 70% and engine power 75%, 55%, 38%, 26%, the fuel consumption is 100%, 73%,52%, and 35% respectively.

Another situation, according to (Faber, 2011), is reducing the speed because of the port congestion. Instead of waiting for loading/unloading operations at the port due to congestion, the charterer can come to an agreement with the owner about speed reduction at sea, so to arrive at the port when they believe it's ready to load/unload. Based on the demurrage calculations, fuel efficiency of about 10% can be achieved.

(Psaraftis & Kontovas, 2010) concluded that up to 15% reduction in emission at 10% lower speeds but that reduces the profit for the container shipping because additional ships required to cover the transport capacity. (Chang & Wang, 2014) under four speed scenarios argued that that the decision to attain optimum speed depends upon the charter rates and the bunker cost and that instead of hiring new vessels to meet transport capacity, alliances with other firms can be pursued to attain the benefit of speed reduction. (Tai & Lin, 2013) examines GHG emission reduction in container shipping and found that around 23% reduced emission when the speed is slowed down to 4 knots less from the design speed. (Cepeda, Assis, Marujo, & Caprace, 2017) studied bulk carriers and found that even though there is reduction in transport capacity due to slow steaming due to just in time arrivals, but an additional vessel could help in to meet the transport quantity and 22% reduction in emission meets the IMO targets.

Up to 20% and greater fuel savings for speed optimisation (Tillig, Mao, & Ringsberg, 2015). Engine power is a cubic function of speed and hence a speed reduction of 1, 2 and 3 knots will curtail fuel use up to 11%, 17% and 22% (Crist, 2009).

Important to consider here is that container liner services are optimized for the operation. In case they lower speed, they will gain in fuel saving but render additional costs related to longer voyages and will affect their competitive position in the market (by lowering the service quality as well as the time required to transport). (Stopford, 2009) in his book shows calculations of two scenarios, one in which vessel sailing at normal speed while another vessel at 20% reduced speed. The ships operator in the latter scenario would still save $31 million, even though he employed an additional vessel to maintain the service frequency.

Optimal ship speed (the speed at which operator thinks he can save fuel) doesn't necessarily have to be the lower speed. Fuel saving could be 25% more at optimal speed compared to real speed due to the variation in travel speed and this gap could be reduced to 4% if properly monitored (Crist, 2009), (Bond, 2008). The decision to reduce fuel consumption by lowering speed is not easy as all these studies suggest. The vessels carrying high value time sensitive products might not avail the speed reduction option even if the oil price is high. Also, a ship at lower speed might reach the port at the weekend or off job time for which it might render additional costs.

Speed Reduction (port turnaround time reduction)

Ports, as part of the global transport network, play an instrumental role in the promotion of global trade. Although neither production centres nor goods processing or consumption hubs, ports, however are the hubs for distribution of large amount of good via shipping and hence add to the pollution (Chen, 2009), (Chang and Wang, 2012). Besides, since these vessels in the port contain pollution causing materials as well, so any accident would damage not only the port environment and the population nearby but an increase in global warming as well due to the GHG emissions (Ma, 2014). However, port authorities and other relevant stakeholders still overlook the environmental damage caused by the ports (TS Wang, 2014). Due to this negligence, the notion of green port was recommended in 2009 in the UN climate change conference (Wu and Ji, 2013). So, green ports are basically those that encompass better ecology, economical use of resources and less energy or fuel consumption in the port (Chen, 2009).

Many studies (Gupta et al., 2005), (Cai, 2010), (Wan, Zhang, Yan, & Yang, 2018), (Lu and Hu, 2009) and (Liu, 2004) have been done on green port development with the aim of sustainable development in the broader sense and GHG emission reduction. E.g. in Italy, where power was supplied to the harbour through shore resulted in 30% CO_2 reduction and 95% NO_x reduction in the port (Cai, 2010). In the construction and development of green ports, environmental aspect should not be ignored, rather both should go hand in hand (Liu, 2004).

Port productivity/efficiency is one of the operational/structural measures used for fuel efficiency and emission reduction. The first of such studies on port efficiency was done by (Shneerson & Lavon, 1981) after the oil crises during 1970, in which the author argues how to offset cost at sea with optimal speed against port time operations, i.e. minimizing the port time operations and optimizing the speed at sea so to achieve fuel efficiency as well as reduction in emissions. Similarly, in a detailed report assessing the IMO regulated measures, (Bazari & Longva, 2011) concluded that around 10 to 20% energy efficiency could be obtained via port productivity.

Earlier studies (Eide, 2011) & (Faber, 2011) show high potential for mitigating emission economically by optimizing speed at sea and less time in ports. (Johnson & Styhre, 2015) discusses optimizing the speed at sea by cutting unproductive time in port. He argues based on one year observation of 2 ships that around 40% of the time ships spend in ports and 20% is unproductive. The author cites several issues that leads to unproductive time in ports. These include limited port open hours, especially during the weekend when the ship is berthed and can’t load/unload, early arrival at the port during which stevedores can’t perform their operations, delayed time in port clearance procedures and waiting time for the arrival of pilot to take ship in or out of the port. The author concludes based on the observed data that around 2 to 8% energy efficiency can be obtained by optimizing speed at sea and properly managing the port operations. Furthermore, by improving the cargo handling speed (not part of the study), would allow further efficiency in port time.

A great deal of potential to achieve energy efficiency via port operations is possible from just-in-time arrival practices, efficiency related to working hours, removing communication gap between the office, ship-port management, port agent and third party agents.

The cost of Efficient port infrastructure for reducing the time in ports can be passed over to the charterers in the shape of taxes or harbour fees or it can be the cost of efficient equipment’s on board (Faber & Jasper, 2011)

Bulbous Bow

In naval shipbuilding, the bulbous bow shape is considered to mitigate the ships wave resistance. To reduce the underwater hull resistance, it’s a common practice to fit ships with bulbous bows. Less resistance means the ship consumes less power and fuel and hence less emissions.

Numerous studies have been done on how to optimize the bulbous bow to reduce the hydrodynamic resistance. (Guerrero et al., 2018) used computational fluid dynamics (CFD) model to run simulations for optimized bows which resulted in 6% less fluid resistance. Up to 2% fuel savings by optimising hull shape and bulbous bow (Tillig, Mao, & Ringsberg, 2015).

(Watle, 2017) studies different bulb designs at various speed scenarios. However, the reduction in the engine power due to less wave resistance was too less to account for the costs incurred to design a flexible bulbous. Around 12 to 15% energy efficiency can be achieved because of bulbous bow (Bray, 2009) but that too on ships sailing at their design speed while any variation in design speed will result in lesser efficiency from the perspective of bulb, according to (Faber, 2011). Different design variants of bulbous bow are applied to a container ship resulting in 2.8% less hydrodynamic resistance (Chang et al., 2016). Between 5 to 10% fuel savings from reconfiguration of the bulbous bow (Leonhardsen, 2017)

Although, there are numerous studies (Mahmood & Huang, 2012), (Chen et al., 2002), (Lua & Lan, 2017), (Zhang et al., 2006), (Özdemir et al., 2007), (Huang & Wang, 2016), (Bolbot & Papanikolaou, 2016), (Fonfach & Soares, 2010) on how to find the optimum bulb shape using CFD and other mathematical and statistical programs but the main emphasis of all these studies is the reduced underwater resistance and hence fuel saving and hardly any studies on the amount of CO2 reductions because of this measure. But the fact remains, that less fuel consumption mean less CO2 emissions.

Trim/hull optimization and ballast system

Trim optimization in shipping is an effective operational measure for fuel efficiency and for reducing GHG emissions. The workings are based on the notion that, depending on the trim, ship experiences different hydrodynamic resistance for the same speed and draft. It means choosing a trim condition that has minimum resistance. The hydrodynamic resistance is directly proportional to the required power. Therefore, less resistance implies less power and fuel burn and fewer CO2 emissions.

When it comes to fuel efficiency, one of the main concerns about ship hydrodynamics is to mitigate the underwater resistance faced by the ship. By modifying the trim and hull lines during the design stage for low hydrodynamic resistance is an excellent measure but its costly at the same time (Huang, 2015) & (Sun, 2012). So, without making modification to hull design, another method is to optimize the hull to reduce resistance.

Previous literature is concentrated on the influence of trim on the hydro resistance. (Iakovatos et al., 2014) researched the effect of different trim conditions on the resistance of six ship models. (Lv et al., 2013) used a panel method to calculate the underwater resistance of ship under various trim conditions and found the optimum trim for low underwater resistance. (Xujian, 2018) studied the relationship between trim condition and wave resistance and made a comparison between an optimized trim and worst trim condition and found that 6.8 to 11.3% of the total wave resistance is reduced. (Sherbaz & Duan, 2014) employed the computational techniques by obtaining resistance values under various trim conditions of a container vessel and found that instead of taking ballast water, by shifting weights within optimum trim can be achieved. (Jianglong, 2016) conducted a trim optimizing program on a container ship and analysed different trim conditions for resistance during the sea trial.

By means of performance monitoring systems, the optimal trim can be determined. Certain measures can be undertaken to reach an optimized trim like adjusting the cargo on-board, arranging the bunkers or by managing the ballast water treatment (Faber, 2011).

According to (Wärtsilä, 2009), around 5% fuel efficiency can be achieved by optimizing the trim. Reducing the ballast water will result in less resistance and less propulsion power required by the ship but enough water required to keep the propeller underwater for overall stability of the ship. 8.5% energy efficiency in terms of less propeller power can be achieved by reducing the ballast water and enlarging the bean to 0.25 meters. 0-1% fuel saving by optimizing the ballast and trim (IMO, 2000). 0.6% saving in fuel (DNV GL, 2009)

Up to 5% fuel saving potential for trim, ballast & rudder control optimisation (Tillig, Mao, & Ringsberg, 2015). (Arwa W. Hussein., 2015) conducted a study of trim optimization for minimum fuel consumption of bulk carrier at three different load conditions and found that the resistance is reduced by 14%.

This measure is applicable to both new builds and retrofitted and can be applied to all ship types.

Economies of scale / Fleet management

In shipping, economies of scale refer to economic benefits reaped by replacing larger vessels with smaller ones. Other papers of economies of scale in shipping have focused on the economic benefits of building larger vessels within one specific segment, e.g. container vessels (Cullinane & Khanna, 2000), (Notteboom & Vernimmen, 2009).

The common knowledge is that as the vessel sizes increase, its emission decreases. According to the EEDI baseline requirements, the emission reduction for a container vessel is 14%, 33% for car carriers (ro-ro vessel), 31% for an oil tanker, 20% for a general cargo vessel and 30% for a dry bulk carrier.

(Lindstad et al, 2012) investigated the reduction in shipping costs and emissions using the economies of scale**.** They compared shipping emissions from the existing fleet (2007), with that of increasing the vessel size. Examples of such increases are the new Chinamax dry bulkers (400,000 dwt) which is double the size of bulk carrier; the Capesize vessels (172,000 dwt). Also, the new Maersk's triple-E class container vessels (216,000 dwt) which are double the size of today's largest container vessels. The data was taken from the world fleet in the Lloyds Fairplay database (IHS database). Their results show that emissions can be reduced up to 30% by replacing the existing fleet with larger vessels. To replace the whole fleet may take up to 25 years, so the reduction in emissions will be achieved gradually as the current fleet is renewed.

Large ships can transport more cargo at the same speed with less power required per cargo unit. Regression analysis results of new build ships show that a ship 10% larger in size will give around 4% higher transport efficiency (Wärtsilä, 2009).

In a study done by (Lindstad & Eskeland, 2015), the author identifies 3 measures, namely, the economies of scale, speed optimization and slender hull design to achieve energy efficiency and thus low carbon emissions. The author cites earlier studies (Cullinane & Khanna, 2000), (Notteboom & Vernimmen, 2009), (Stott and Wright, 2011), Lindstad et al., 2012; Lindstad, 2013) where big ships tend to be more energy efficient per freight unit (per ton mile of goods transported) than smaller ones. The author observes that when the ship's cargo-carrying capacity is doubled, the required power and fuel consumption increases by approx. two thirds, so the fuel consumption per freight unit is reduced. Based on the data, the author observes that large crude oil carriers when operate at a speed of 16 knots, the fuel consumption is lowered approximately 34% and the cost saving is around 25% less compared to small crude carriers, the Aframax.

Previous research studies give an insight into economies of scale in shipping but exclude the costs associated with cargo handling, port infrastructure and other and larger ships will have fewer port calls and access to limited ports because of low draught (Heaver, 1968; Jansson & Shneerson, 1987; Cullinane & Khanna, 1999; Ham, 2004)

In their studies, (Christa et el, 2008) concluded the economies of scale for large containership but at the same time identified several limitation factors that needs to be addressed to have economies of scale. E.g. the specialized ports and terminals needing higher investment for big containerships, fewer port calls, high feeder cost for loading and unloading etc.

Except for the offshore support vessels, the applicability of this measure is for all those ships that transport huge amount of loads like cargo, passenger, ro-ro, tankers and containers.

Voyage optimization / Weather routing

Voyage optimization is one of the many methods employed by the maritime industry to enhance energy efficiency and mitigate the Green House Gas (GHG) emissions. In this approach, ships tend to find the optimum routes for sailing based on certain weather forecasting data, taking into account the currents etc. This is called weather routing.

According to (Lokukaluge P., 2017) weather routing techniques (pre voyage planning) play a critical role in several modes of transportation (Motte et al., 1987), (Burnett, 2000), (Vettor and Soares, 2016), (Stratton, 1974). Routing optimization issues in shipping has been discussed by many researchers in the past and most were related to minimum time that a ship takes to arrive at the port (Zacconea, 2018), (James, 1957), (Papadakis & Perakis, 1990), (Zoppoli, 1972) but most of these authors didn't include other factors into account like the sea behaviour etc. Recent studies however include several factors including the fuel consumption.

(Zacconea, 2018) used a 3D program for optimal route based on weather forecasts and found considerable savings in fuel. (WANG, 2018) used hybrid voyage optimization algorithm's and found that it provides not only accurate estimated time of arrival but fuel savings as well. (Grifoll, 2018) ship routing system based on pathfinding algorithm and found the economic benefits of up to 18% saving of the total cost. (Ruihua, Osman, Evangelos, Charlotte, & Atilla, 2015) conducted a semi empirical ship operational performance analysis using the (Kwon, 2008) model to predict the extra resistance caused by the wave and wind for two oil tankers, Suezmax and Aframax. The model they used could accurately observe the operational performance under varying ship draft, speed and angles to help find the relation between fuel consumption and different voyages. The result of their study show that the fuel consumed during the selected optimal voyages (five in total) can achieve 10% less than the recorded route. However, the one limitation in the study was the increase in fuel consumption due to the hull and propeller fouling and engine degradation, which couldn't be considered due to the lack of ship dry docking and engine maintenance reports, and that remain a future challenge to work on to have accurate operational efficiency.

To optimize the voyage a ship undertakes, there are many weather routing system that can be installed on the ship and many ships already have this feature on-board, so the operational efficiency of this measure is less. Around 4% can be achieved (Buhaug et al, 2009). Up to 10 fuel savings for weather routing and voyage optimisation (Tillig, Mao, & Ringsberg, 2015).

Autopilot adjustments
Self-tuned and adaptive auto-pilots keeps the ship on course and reduces the unnecessary use of rudder. Poor Autopilot adjustments causes the ships directional instability (yaw motion) and result in more drag and increased fuel consumption.

By using an auto-pilot, the power required is curtailed by controlling drift and reducing the use of rudder, meaning less drag and less energy consumption (Nikitakos & Fikaris, 2009). Finding the optimal autopilot adjustments will reduce the load on rudder and drag and gives a fuel efficiency between 1-5% (Wärtsilä, 2009).

According to (Buhaug, 2009), the energy efficiency between 0.5 - 3% is achieved but since most of the ships already have this measure on board, so the actual reduction could be less. Up to 2% fuel savings for autopilot adjustments (Tillig, Mao, & Ringsberg, 2015).

Propeller and hull maintenance (cleaning, polishing and coating)

With ships sailing on regular basis, it’s obvious that the underwater parts of the ships accumulate organic materials and thus increases the underwater resistance over time. For smooth sailing, it’s necessary for ship operators to polish the inner and outer surfaces of propeller on regular basis or when required.

Source SCUBA: Underwater propeller cleaning.

Similarly, increased hull frictional resistance due to the accumulated aquatic material (algae) on its outer surfaces increases the consumption of fuel and CO2 emissions. Different anti-fouling methods like anti-foul paints and coatings are adopted for smooth working of the hull and hence less frictional resistance, fuel consumption and less hazardous emissions.

Around 2 – 5% (Buhaug, 2009) and 2.5 – 8% (Faber, 2011) energy efficiency can be achieved by polishing the propeller on regular basis or when required. Similarly, around 1 – 10% fuel reduction potential is achieved for hull cleaning and polishing (Buhaug, 2009). According to (Wärtsilä, 2009), 0.6 – 3% can be achieved for different ship types. Comparison after 4 years for saving in fuels with a modern hull coating compared with the conventional is between 0.6 (for the OSV), 3 – 5% for ferries and ro-ro to a maximum 9% for tankers and container (Wärtsilä, 2009). Up to 5% fuel savings for optimised ship maintenance schedule, hull and propeller cleaning (Tillig, Mao, & Ringsberg, 2015).

This measure is applicable to all ship types.

Technical / technological Measures

The measures under this category can be divided into main engine adjustments, hull shape improvements, auxiliary power systems, propulsion system and aerodynamics of the ships structure (Crist, 2009). Most of the measures are being implemented for new build ships because retrofitting such measures in existing ships could be too costly. High Upfront investment is required and it takes a long duration to realize the benefits in fuel and GHG reductions since most of the measures are for new builds and existing vessels have life of up to 25 years. We discuss some of the technical measures here but prior to that, its important to know that most of the technical measures are being pursued to reduce resistance between a ships structures and water/air. We identify three kinds of resistance:

Frictional resistance that occurs due to the interaction between the underwater hull area of the ship and water. This resistance is more for the bulk and tanker (up to 70%) compared to the containers (40), as the latter moves with high speed (MAN Marine, 2007). Algae and other aquatic materials increase this resistance because of which anti-fouling methods are preferred over the lifetime of the ship.

Residual resistance caused because of how the waves behave at the fore and aft parts of the vessel. This resistance is low for the slow-moving vessels and increase with the vessels speed (Crist, 2009).

Air resistance is caused by the ship structure above the waterline. Since container vessels have a massive structure in terms of the container on the deck that are exposed to air, so they experience air resistance much more than any other vessel.

All these resistances together effect a ships speed, as the speed is related to the engine power and propulsion, hence why most of the technical measures are pursued to curtail one or more of these resistances. We now discuss in brief some of these measures.

Lightweight construction

By using the lightweight materials (aluminium, glass or carbon fibre etc.) while building the ship can reduce the weight of the ship and hence fuel consumption. This measure has already been in practice (Buhaug, 2009). Its applicable to all ship types and this high tensile stretchable steel as an alternate to the conventional steel is a bit costly (Faber, 2009) but it does yield energy saving benefits due to less weight.

According to (Wärtsilä, 2009), reducing steel weight up to 20% will result in reducing half the propulsion power and a quarter of energy savings. Up to 5% fuel saving for high strength steel and other composite material (Tillig, Mao, & Ringsberg, 2015). Arroximately 9% less energy with 20% reduction in weight (Crist, 2009).

Optimizing the hull dimension

All the ship characteristics (like the ship type, its deadweight tonnage, its speed, draft, length etc.) are determined during the design phase of the ship. Ships length and hull ratio determines the frictional resistance ship will have during voyage. In the case of too large or too less ratio will increase the resistance. An optimum hull dimension will decrease the resistance and hence will result in fuel savings. A detailed study is done by Larsson and Raven (2010) about how the hull resistance faced by the ship is dependent upon the hull form,

(Elizabeth & Ingebrigtsen, 2018), (Kristensen, 2010), Lindstad, 2013, 2015) and (Stott & Wright, 2011) have researched the optimal hull designs for efficiency by changing the structural specifications of the hull (length, beam, width, draught). The conclusion of their findings provide evidence that slender hull designs minimizes hull resistance and ship drag, thus lowering power and hence saving in fuel and reduced CO2.

(Elizabeth & Ingebrigtsen, 2018) investigated the slender ship design (increasing hull length and beam) and concluded that at general design ship speed (15 knots), the power required for propulsion is significantly reduced compared to either in the calm waters or rough sea condition, which offers no significant advantage. Between 5 – 20% in fuel saving can be achieved by optimizing hull (Buhaug, 2009). Maximum saving potential is around 9% (Wärtsilä, 2009) (Crist, 2009).e

This measure is applicable on all ship types and is implemented during design phase of the ship (Faber, 2009).

Hull Coating

Aquatic material that stick to the hull of the ships increases the frictional resistance because of which the it takes more bunker fuel. To reduce such resistance and to let the hull work efficiently and smoothly, one method is to coat hulls.

(Algae and aquatic material under a ship's hull)

(Faber, 2009) extracts the data for panamax vessel and applies two types of hull coatings and fuel savings lie between 2 – 5% depending upon the ship types. These coatings are applicable for all ships types and are very expensive as well. The surface of these hulls also deteriorates quickly.

Optimizing the hull openings

For reducing the water flow disturbances, the hull openings are designed accordingly, i.e. by installing a scallop or grid behind hull openings. Another way could be closing the hull openings bow thruster permanently by installing welding plates on top of it. Tug boats can be used then.

By designing the hull opening efficiently, up to 5% less power is consumed (Faber, 2009) & (Wärtsilä, 2009). It can be applied to all ship types during the design stage. Up to 2% fuel saving for hull optimization (Tillig, Mao, & Ringsberg, 2015).

Design speed reduction

In operational speed reduction, there are few problems that ship operators face like operating at lower than design speed may result in less efficiency because engines are not designed to operate at the tuning. In design speed reduction measure, the engines can be de-rated or less powerful engines can be used for low speed.

This measure is applicable for all ship types and is not much costly since small engines are used that also occupy less space on board thus paving the way for more cargo. One draw back of this measure is that vessels moving slower will result in less transport work per time but this can be offset with other benefits.

The abatement potential is much more than the operational speed reduction (Faber, 2009)

Optimizing the interaction between hull-propeller

Using computer simulation techniques, the interaction between hull and propeller is quantified based on the water resistance. According to (Faber, 2009) & (Wärtsilä, 2009), by redesigning the propeller, hull and appendages, up to 4% efficiency can be achieved. Up to 5% fuel saving for optimisation of stern bigle, rudder & propeller for inflow considerations and better propeller balde design) (Tillig, Mao, & Ringsberg, 2015).

Air lubrication

To reduce the frictional resistance between a ship's hull and the water underneath, air cavity system can be used to pump compressed air at the bottom. Air compressors delivers the air to the cavity and its ensured that the air stays there below the hull so that there is less resistance for propeller.

This measure can be applied to new builds to vessels with flat bottoms and length of 225 m (Faber, 2009). The important thing is the smoothness of the hull to realize the fuel savings. Due to other technicalities, vessels with certain draft and length specifications can avail this technology.

The potential fuel saving, according to (Crist, 2009) (Wärtsilä, 2009) is between 10 – 15% for tankers and bulk carriers and up to 9% for containers. Up to 5% fuel saving (Tillig, Mao, & Ringsberg, 2015).

Propeller adjustments and upgrades

Numerous technical measures are applicable in this category. E.g. CRP, in which a pair of propeller rotate in the opposite direction. Without mentioning the technical workings, the efficiency reported for Counter rotating propellers is around 10 – 15% (Wärtsilä, 2009), 6 – 20% (Faber, 2009) and up to 6% (Buhaug et al, 2009). Propeller adjustments can reduce fuel consumption by up to 10% (Kollamthodi et al., 2008)

Similarly, by installing wing thrusters, between 8 – 10% energy savings achieved because of less resistance from hull appendages (Wärtsilä, 2009). Up to 5% fuel savings for propulsion improving devices can be achieved (Tillig, Mao, & Ringsberg, 2015).

Rudder can also be adjusted to reduce the drag on ships resistance. Designing the rudder and propeller with a rudder bulb can help achieve between 2 – 6% energy efficiency (Wärtsilä, 2009).

Similarly energy efficiency between 2 – 5% for advance propeller blades, winglets and installing nozzles instead of an open propeller (Wärtsilä, 2009).

Main Engine adjustments

Multiple adjustments can be done under this measure. E.g. Engine tuning is optimized at specific loads that gives maximum efficiency, up to 0.8% (Buhaug, 2009). Diesel electric propulsion systems can be used to provide power to the propeller through the electric motor.

Efficiency up to 20% (Wärtsilä, 2009).

Waste heat recovery

This system recovers the otherwise waste thermal heat from exhaust systems and coverts it into the electrical drive. Boiler and steam turbines are used to recover the heat. The energy recovered can be used for on board ship services like lighting up the ship and air conditioning or it can be used for engine power as well. Efficiency of up to 15% is feasible while its more if the system is installed on new builds (Wärtsilä, 2009). 8 -10% (Siemens 2009). Up to 10% savings for Waste heat recovery system (Tillig, Mao, & Ringsberg, 2015).

Alternate Fuels and renewable source of energy

GHG emissions can be curtailed by using alternate to diesel fuel. E.g. Liquefied natural gas (LNG) and bio fuels are associated with less CO2 emissions. Since LNG is cold, so by using it will result in reduction of CO2 emissions due to less heating. According to (Tillig, Mao, & Ringsberg, 2015), up to 5% fuel savings can be achieved for Alternative fuel for power. Between 1 – 10% CO2 reduction per ton mile for renewable energy and 5 – 15% for low carbon fuels like the LNG (Buhaug et al., 2009).

According to (Elizabeth & Torstein, 2018), since hydrogen emits no GHG emissions, so it's a very attractive option for many (Bouman et al., 2017) and other energy sources like wind power (Perkins et al., 2004), (Clauss, 2007), (Teeter and Cleary, 2014), (Traut, 2014), (Psaraftis, 2016) and solar panels (Sjöbom & Magnus, 2014).

Similarly, there are other studies (Gilbert et al., 2018) on the use of alternate fuels with the aim of mitigating the local pollutants to comply with the international policies and to curtail the GHG emissions to meet the climate challenge.

Auxiliary hybrid engines

As we know that it's the main engine that provides the required power for propulsion and electricity and auxiliary power to the rest of the ship. Hybrid power generators include fuel cells and batteries that provides the power to the shipping internal network. The hybrid batteries provide enough power to boost propulsion. In case the main engine fails, these batteries along with auxiliary engine have the enough power to take the ship to the nearest port. When the ship is static and berthed at night, the hybrid engines provides the necessary power. It can receive and store energy from other sources as well like solar and wind.

These batteries run generators provides fuel efficiency and reduces NOx up to 80% and CO2 up to 30% (Wärtsilä, 2009). Up to 2% savings for Hybrid auxiliary power generation (Tillig, Mao, & Ringsberg, 2015). (Elizabeth & Torstein, 2018) conducted an experiment by installing a small engine along with the batteries for storage and found that the fuel consumption is significantly reduced. The potential fuel saving using hybrid technology was investigated by (Turnock et al., 2011) on dry bulk carrier and concluded potential saving between 2 – 10%.

LNG

Although, LNG has its limitation in terms pf accommodating the big gas tanks on decks, especially for ferries (cited by Faber (Hoogma, 2009), piping for cooling and compressing, and due to its availability), yet it is not only fuel efficient as it has higher hydrogen-CO2 ratio compared with traditional diesel fuel resulting in lower emissions (Kg per fuel or carbon) but also its SOx free. Since its cold and compressed at around -1620C, the energy can be sued in places where cooling is need like for AC's. It emits some methane but the damage is offset against the reduction of other harmful emissions. Efficiency of up to 15% (AEA, 2008).

While we consider the economic and CO2 reduction benefit of LNG, there are certain limitation as well that needs to be considered by the industry before its potential is realized. The hurdles are the limited LNG bunkering option, volume of LNG energy content compared with diesel is 3 times higher and its feasible for new build ships because of modifications to the engine and deck space for storage.

Wind power

Shipping operators can take advantage of this renewable energy source in different forms like making use of kites on board, traditional sails and flettner type rotors but the use of wind power on board ship largely depends upon the region in which the ship is sailing (Buhaug et al, 2009). (Tampier B., 2008) conducted a study of two ships (tanker and bulk carrier) over a period of five years, using different wind assisted technologies on board ships, taking different routes while using European weather forecast. Their study found that up to 15% can be saved in energy due to low propulsion but it come at a cost of increased operational and capital cost.

Solar system

Although solar cell technology is instrumental in giving a portion of the backup power and energy but its application is extremely limited because it could be installed and cover the deck area of tanker only (not for other vessels because of the structure) and because the solar energy depends upon the time and place and is not always available, especially at night (Buhaug et al, 2009).

To meet the on-board power demands, solar panels can be installed on ships deck. Applicability is limited, since few vessels like ro-ro and tankers have the enough space to accommodate solar panels on deck. Efficiency up 3.75% (Faber, 2009). According to (Wärtsilä, 2009), 3.5% for tankers, 2.5% for car carriers, 1% ferries.

Combined potential saving from operational and technical measures

Second IMO GHG study (2009) concludes up to 40% emission reduction depending upon the combination of different measures implemented, the economic growth of the maritime activity and bunker cost. CE Delft study of 29 operational and technical measures of 14 ship types concludes up to 35% reduction potential til 2030. DNV GL study of 28 combined measures concludes 50% less fuel consumption by 2050. The ICCT put the fuel saving to 33% by 2020.

A report by Clean North Sea Shipping (CNSS, 2011) which aims to mitigate air and GHG emissions in the North Sea region also proposes operational, technological and alternate fuel and power sources. Operational measures like hull/propeller adjustments and polishing & trim and ballast optimisation that are linked to a ships resistance can realize fuel saving from 0.5% - 10%. Approximately, 19% fuel saving per tonne-km via speed reduction, 25% by using LNG, 10% - 35% for using wind energy, and 4% for solar power.

Operational measures can reduce up to 40% while technological retrofitting can mitigate emissions between 4% - 20% (Crist, 2009) (Hobson, et al., 2007). Both combined measures can potentially mitigate emissions up to 42% /t-km by 2020 and more than 60% /t-km by 2050 (Berrefjord, et al., 2008).

An important point to consider here is that the economic life of vessel is around 30 years. So, by 2020 or 2030, only a small portion of vessels in the world fleet would have been replaced. This means that most of the measures prevalent in the maritime sector in the short to medium term would be operational in nature as they require low investment and less time while the technology related measures will be implemented in the long run between 2030and 2050 with the increase in turn-over of the world shipping fleet.

Critical factors regrading implementation and cost effectiveness

Barriers in implementing CO_2 reduction measures

While in the earlier section, we discussed measures from different research findings that could be implemented in the shipping industry for fuel efficiency and CO_2 emissions reduction, it's vital to consider why most of the shipping firms are hesitant and don't want to realize the potential of these technologies. Some of the comprehensive studies on energy efficiency barriers are done by (Fleiter et al., 2011), (Faber et al., 2009), and (Jafarzadeh et al., 2016) in the Norwegian fishing fleet.

Researchers have cited different reasons for this. Some of the reasons identified by (CE e al., 2009) are, the organizational barriers, e.g.

the **mismatch of priorities**. Instead of focusing on the fuel efficiency measures, the shipping firms consistently focused on the low labour (crew) for efficiency because the oil prices were relatively stable back in the past and there was little priority given to fuel efficient measures. But as the bunker cost has accelerated in the past 2 decades, the focus is now shifting to fuel efficient measures (Faber, 2011), (Tillig, Mao, & Ringsberg, 2015). Similarly, the focus on the part of shipyards and owners on sticking to traditional measures and values instead of gradual improvement for fuel efficiency is another hurdle cited by (Devanney, 2010).

The short **lead time** for the new ship to operate could be another hurdle, e.g. there is increase in demand for general cargo, oil, LNG or any other product, then the decision by the ship owner to order a standardized vessel as quickly as possible to enter the market to realize gains will exclude any operational or technical related changes to the vessel as it would take time.

Then, there is the problem of **split incentive**, since in charter contracts, the owner, who decides the capital to be invested for fuel efficient measures in the ship, is not always the operator, the one who pays for the fuel only (Eide et al., 2010), (IMAREST, 2010). So, the owner is reluctant to implement measures because the benefits of savings in fuel will be reaped by the operator only. The ship operators hedge themselves against any fluctuation in fuel cost through bunker adjustments, thus making the high investment in fuel efficient technologies less attractive.

The **transaction cost** associated with testing the fuel-efficient measures could be high (CE e al., 2009), (IMAREST, 2010).

The **information** barriers include the insufficient data or the lack of transparency in the available data about the fuel saving measures from the makers of these technologies as these technologies are not tested for how much fuel efficient they are, they are only claims (Tillig, Mao, & Ringsberg, 2015). The artificial condition of model testing cast doubts in the minds of the shipping firms that these models might overestimate the reduction potential of CO_2 emissions (Lin, 2012) (Lockley & Jarabo-Martin, 2011).

The investment or **financial** barriers includes the high cost of capital investment in such technologies. While big shipping firms can manage the finance from internal or external funding, for small firms raising funds is a challenging task (Faber et al., 2009). Some of the measures that yield maximum abatement potential are also very costly. Ship operators are also concerned about uncertain return on investment and longer pay back periods for such measures (Lin, 2012)

Measures	**Barriers to implementation**
Hull Design	Standardized design by shipyards
Hull Coatings, Waste heat recovery	Expensive, difficult to quantify saving potential
Air Lubrication	Uncertainty, complexity and unsuitable for specific ships
Engine related measures	Low awareness amongst the ship stakeholders about the technology.
Fuel oil treatment	Low saving potential, lack of knowledge.
Light weight construction	Applicable to specific ship type, safety issues, lack of suitable material.
LNG	Lack of space, infrastructure. Low availability.
Wind energy (kites, fixed wings and sails)	Dependability on wind direction, difficulty in handling and durability issues.
Fuel Cells	Expensive and lack of implementation.
Solar	Low yield power per installation, specific ship types (ferries and ro-ro)
Speed reduction	Dependency on charter contracts, design speed inflexibility.
Weather routing	Dependency on specific routes.
Trim, voyage and ballast optimization, auto-pilots, hull propeller cleaning.	No specific barriers.

Operational and technological barriers (Faber, 2009), (Buhaugh, 2009)

While the above-mentioned barriers are general in nature, there are barriers associated with **technology and infrastructure**, either the incompatibility for the use of technology on the ships or the fear in the mind of the ship owners about the technological failure or that the attained technology might not yield the desired results in addition to the high level of investment (IMAREST, 2010). Additional cost could be associated with the use of new technology or the training needed for the ship operators to avail it. These barriers, according to (Faber et al., 2009) relate to the operational, technical and alternate sources of fuel and energy measures.

E.g. most of the ships are already optimized for hull design for efficiency or the shipyards because of their standardized design for vessels are reluctant to change hull designs and hence constitute a major barrier. Similarly, besides being costly, the anti-fouling hull paint to reduce algae constitute a barrier as it is difficult to quantify the saving potential arising from this measure. So, most of the ship owners stick to the traditional hull coatings.

It is important to note that there are few barriers that ship owners face when it comes to operational measures, hence why these measures are most prevalent in the shipping industry.

Another barrier is the route specific vessels that is hardly mentioned in the other studies and discussed by (Crist, 2009) and (Faber, 2009) in his interviews with multiple shipping stakeholders was the efficiency measure for the route that a ship undertakes or for a specific ship type. That implies that a measure might or might not be effective on a specific shipping route or to a ship type. E.g. a ship has undergone the optimum ballast treatment measure for fuel efficiency but the ship hardly takes any routes on which benefit of this measure could be realized because of the nature of cargo on the ship.

Cost effectiveness, Implementation and abatement potential

The general perception is that the ship operator will prefer to implement those operational and technical measures that yields maximum abatement potential for CO_2 emission reduction. Principally, such a scenario means high level of implementation. We analyse this based on the study by (Lin, 2012).

The findings of the study show that the level of measures implementation is inversely proportional to the abatement potential. E.g. the operational measures (such as weather routing, engine adjustment, ballast, trim and hull optimization) have higher level of implementation even though the abatement potential for CO_2 mitigation is low compared to a technical measure (waste heat recovery, cold ironing) and alternative fuel which has a higher level of CO_2 reduction potential. This implies that there are other factors (cost effectiveness) that the shipping firms consider beside Co_2 reduction potential of a measure. The study provides credence to the notion that from the perspective of the ship operator, the level of implementing a measure is dependent upon the cost effectiveness of that measure, as opposed to the abatement potential. Higher a cost-effective measure, higher will be its implementation.

These factors are of a critical importance for the policy makers when formulating strategies for the maritime sector. Most of the operational measures are already implemented within the shipping sector and are easily retrofitted because of their cost effectiveness and relatively low level of risk associated in terms of investment. Technical measures, on the other hand, incudes high investment risk, besides income uncertainty and low pay back and hence shipping operators are reluctant to implement it albeit they have high abatement potential.

Overcoming barriers and choosing the right measure

Selecting a proper measure that is cost effective and has a high abatement potential is paramount when formulating a CO2 reduction strategy. To achieve this, the ship operators needs to overcome some of the general barriers associated with information and cost. They can use their own sources or hire independent experts for evaluating a measure that they want to implement and gather credible information before arriving a final decision. Similarly, they can get support from international organizations or form their own government subsidies to overcome the cost barriers if they want to implement green technologies. For the technological barriers to overcome, an optimum mix of cost effectives and abatement potential should be considered to realize a win-win situation that is equally beneficial to both the firm and the environment.

Further discussion

International regulatory and regional bodies

Growing climate awareness requires urgent measures to be undertaken to mitigate GHG emissions from shipping. IMO GHG study highlighted some of these operational, technical and market based measures but there was a lack of regulation regime for monitoring and implementing these measures (Buhaugh, 2009). The EU implemented its own regulations for emission control (Eide et al., 2009) because of the lack of enforcement from IMO. Compared to 1990 and 2005, the EU committed to a reduction of 20% and 50% by 2020 and 2050 (CNSS, 2011). The report 'Strategy to reduce atmospheric emissions from seagoing ships' by the EU climate mission and the Swedish climate institute commits to 20% energy efficiency improvements, at least 10% use of the renewable energy (coal, solar, hybrid) and 40% GHG emissions by 2020.

The International Maritime Organization (IMO) has made some legislation regarding the shipping energy efficiency measures. MEPC is IMO's main body for addressing shipping pollutions and meets every nine months to develop plans regarding maritime environmental issues. The key regulation for limiting the carbon footprint in shipping is the Maritime Agreement Regarding Oil Pollution (MARPOL). In 2001, Energy Efficiency Design Index (EEDI) was added to MARPOL, which requires obligatory technical measures from the shipping sector regarding the efficiency standards on those new ships that are built 2013 onwards. This measure put the limits on the percentage of GHG emission per tonnage of transported items. They have set the target of reducing emission 10%, 20% and 30% relative to the years 2015, 2020, 2025 by implementing innovative changes in ship design and other technical areas and focus on to tighten the policy every 5 years (ICCT, 2011). Since these are recent developments from IMO but these limitations will become strict with the passage of time as the volume of global transport increases, due to the increase in global climate and GHG. Here it is important to consider that the economic life of s ship is 20 to 25 years, so it might take decades for the policymakers to look for any effects of GHG reductions on the maritime sector (Faber, 2011). Similarly, Ship Energy Efficiency Management Plan (SEEMP) is another policy instrument that requires ships to make a proper plan and monitor the changes that come about due to the efficiency measures undertaken. This measure is specifically for the fuel efficiency of ships by focusing on operational measures and doesn't include the emissions reduction.

However, there are two challenges for the IMO. One is to accurately find the aggregate emissions from the maritime sector, which the second IMO GHG study by (Buhaug et al.,

2009) has provided and the other is to allocate these emission to their respective users (nations), which is yet to be done although several proposals have been given. Further adding to the complexity is the fact that two third of the world fleet is registered in countries (Flag of Conveniences) having no allocated targets for GHG emission reduction. So, if IMO comes up with a global GHG policy, this will not turn out to be workable. Interestingly the owners of these two third of the world fleet are nationals of countries who have set emission targets in the Koyoto protocol (Crist, 2009) but have registered their vessels under FOC's

Despite all these measures undertaken or being considered and the percentage of emissions they reduce, it is estimated that global emission will increase 250% up til 2050 (Eyring et al., 2005) (3rd IMO GHG study). That means it will be difficult to maintain the global climate temperature below 2°C pre-industrial level (Buhaugh, 2009). A temperature increase up to 6°C above pre-industrial levels will mean the end of life on earth in few years. The only way to address this climate challenge is to mitigate the global GHG emissions. The report by Intergovernmental Panel on Climate Change (IPCC, 2007) concluded that GHG emissions need to be 50%–85% below current levels in 2050 to reach this target. Last year, IMO agreed to reduce the emission to 50% by 2050 compared to 2008 level.

Different reports have suggested that if proper measures are not undertaken, carbon emissions from vessels will increase twofold by 2050. The European Union (EU) and the United Nations Framework Convention on Climate Change (UNFCCC) are using their influence to regulate the shipping emissions and allocate them to relevant stakeholders (Oberthur, 2003). The International Maritime Organization (IMO) is working to regulate GHG emissions for shipping sector through technical, operational, and market-based policy measures. It's very likely that CO2 emissions from shipping will be regulated by the IMO within a few years. The maritime sector is conscious of its role regarding CO2 emissions and knows that proper remedial actions are necessary. The efforts undertaken by the IMO for regulating emissions will materialize in the coming years.

To make the climate change policies effective, it's important to work collectively and make a global policy that should include more sectors and more countries to make it cost effective (IPCC 2014). By doing so, there will be less financial burden on the sectors and countries that have already pledged to reduce global GHG emissions from shipping.

Policy implications for decarbonizing shipping

Based on the previous discussion about the operational and technical measures, here we explore in depth the policy implications for the maritime sector. While we recognize that the shipping industry has potential to reduce emissions to achieve energy efficiency and environmental gains (keeping in view the overall climate change target), the challenge is how to make a uniform global policy that is acceptable and implementable across all maritime sectors and maritime nations.

While the threats of climate change remain uncertain in the long term, for the policy makers, it's a challenge to formulate a policy that appeals to all stakeholders since taking environmental precautions require high investment. Some researchers (Miola, 2011) (Tietenberg, 2003) believe that monetary benefits outperform any fixed or rigid rules to address climate challenges while others (Underdal, 2010) believe a consistent long term policy should be in place that could be transformed into sustained activities. (Miola, 2011) highlights four points to address climate change policy concerns regarding emissions reduction: ambitious and consistent long term goals for GHG reductions, monetary benefits to motivate the relevant stakeholders, sharing of knowledge, expertise and technology amongst the stakeholders and ensuring transparency for the compliance of policy.

In the maritime sector, while there are policies and legislations already in place to comply with CO2 emissions reduction, but there seems to be lack of commitment to comply with the regulations and the pace of implementing GHG reduction measures seems to be very steady (Lindstad, 2013), (Gilbert et al., 2014) And this could be because of the hurdles that the shipping sector face as we discussed in the earlier section.

(Balcombe et al., 2019) identified three policy options for reducing emissions. First, price control mechanism which includes environmental and port taxes and dues. A fluctuation (increase) in the price of purchasing fuel based on the nature (quality and type of fuel used) and quantity of the fuel used or price setting on the amount of emissions discharged. This approach is vulnerable to the fact that the ships might take fuel outside the area where fuel taxes are regulated and hence escape the fuel tax. Ships can escape the carbon tax by flying the flag of convenience (FOC) and become legally bounded under those countries jurisdiction whose flag they sail under and most of these FOC have mild regulation and favourable tax treatments.

Secondly, Quantity control mechanisms are like cap and trade approach (government projects to limit emissions to a certain level and allowing the firms to trade while imposing tax on the firms crossing that emission level) in which the credit and other monetary incentives are given to those green projects that have the potential to reduce emissions to a targeted level. Implementing emission control programs like marine emission trading scheme (METS) could be effective, in that it is flexible to vary the cap on the emissions based on whether the emissions exceeded or not beyond the cap. A challenge, however, for the maritime authorities would be to pursue an optimal cap on the emissions. A cap too high would exert burden on the shipping firms and nation states and they might be discouraged and find it hard to meet the emission target. A cap too low would imply less seriousness in tackling the emission target and thus will increase the emissions.

Lastly, providing subsidies and other financial support by the state or maritime authorities in the form of favourable tax treatment, low interest credits to those who participate in the reduction of GHG emissions through employing green technologies or other efficient measures.

Similarly, a report (Shipping, 2009) by the national shipping owner’s association of Norway, Australia, Sweden, Belgium and UK provided proposals on how, beside technical and operational measures, emissions can be reducing from shipping through a global emissions trading system (ETS), i.e. cap and trade system. Under this, each shipping firm would purchase emission credits or carbon allowances under a specific compliance period, at the end of which, if the carbon allowances are more than the level of verified CO2 emissions, then, it can retain or sell them to the market and the profit can be invested in sustainable technologies. The report further details on how carbon credits will be bought and cap and trade system works and proposes that instead of Kyoto Protocol principle of ‘common but differentiated responsibilities’ (CBDR), the implementation of the IMO’s ‘No more favourable treatment principle’, is imperative, meaning that port states should impose the rules regarding CO2 emissions mentioned in the IMO conventions on all vessels entering their territory for loading and discharge, irrespective of where a ship is flagged. Nonetheless, the main challenge under cap and trade would be how the emission trading system works in allocating the exact emissions to the respective users (Port states, flag states, vessel owner, ship operator).

To add to the discussion of 'differentiated treatment' as the non-annex (developing countries like the BRICS) nations argue for favourable treatment and 'no more favourable treatment, (Anderson, 2012) analyses both the positions and argue that considering the growth of emissions from 2000 onwards and the budget allocated to it, it is vital for non-annex nations to start taking precautionary steps towards climate commitment of remaining below the target. The author suggests treating the shipping as a 'sovereign nation' and allocating carbon budgets to reduce emissions as he believes that the challenge to meet the climate requirement of reaming below 2c is not in the allocation of emissions amongst the annex (developed) and non-annex (developing) nations but from the reducing budget.

(Longva et al, 2009), (Lin, 2012) proposes to consider the cost effectiveness of operational and technical measures to reduce GHG emissions and fiscal measures like fuel levy and cap and trade system enforced by the IMO.

Recommendation and conclusion

This purpose of this paper was to highlight the importance of climate challenge, the impact of carbon footprint associated with the shipping sector and different operational and technical measures that are being undertaken by the shipping industry to reduce the CO2 emissions. We analysed different research papers and reports to find the what type of measures prevail within the shipping industry, the percentage of energy efficiency and CO2 reduction each of these measures result in and the hurdles faced while implementing these measures.

The shipping sector is aware of its role in GHG emissions and environmental issues. It is also sensitive to the fact that shipping emissions could double by 2050 if no preventive measures are taken. IMO in 2018 agreed to curtail up to 50% by 2050, the total GHG emission from shipping compared to 2008 level. The IMO is working on regulating shipping emissions, and shipping emission regulations are expected to materialize within a few years. The (IMO, 2014) GHG study shows 15% reduction in CO2 emission compared to 2012 level. Still significant effort is required at the global level to contribute to the achievement of overall climate target.

While all these efforts look promising, there is hardly any effective mechanism to quantify the progress made so far or in the coming years towards carbon clean shipping transport. Policies regulating emission are yet to be implemented by IMO besides baseline targets against which emission can be compared (Harrould & Savitz, 2010). Consensus amongst the nation states about the allocation of emissions is another challenge for IMO (Miola et al., 2011).

Keeping in view all these efforts undertaken and the challenge they pose, it is imperative that a range of options should be considered to reduce GHG emissions from shipping and contribute to the overall climate target.

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