Wind propulsion optimisation and its integration with solar power

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Wind propulsion optimisation and its integration with solar power

By

Mphatso Nsanjama Nyanya & Vu Ba Huy
Malawi & Vietnam

A dissertation submitted to the World Maritime University in partial fulfilment of the requirement for the award of the degree of

MASTER OF SCIENCE
In
MARITIME AFFAIRS
(Maritime Energy Management)

Year of Graduation
2019

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature):...
(Date): 24 September 2019

Supervised by: Dr Alessandro Schonborn

Supervisor’s affiliation: Maritime Energy Management (MEM) World Maritime University
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Abstract

Research Topic: Wind Propulsion Optimisation and its Integration with Solar
Degree: Masters of Science

The renewable energy capture of a ship was optimised for a combination of rigid
wind sail and photovoltaic power. Two models were developed, to optimise the wind
propulsive system and its integration with the photovoltaic system. The first model
optimises the rigid wind sail angle under varying wind conditions, while the second
model optimises the available deck area of the ship with installations of wind and
solar system. The deck area of the ship is distributed among wind and solar power
installations in order to maximise total power production. The optimisation models
assessed a full factorial design of possibilities, and used the option yielding the
highest power output. Thereafter, optimummum power obtained from the results were
applied in the Energy Efficiency Design Index calculation formulae in order to
evaluate carbon dioxide emission reduction. The results showed that sailing at
optimal sail angle and optimising the available deck area with combined installation
of solar and wind system were able to maximise power production. Furthermore,
maximum power from the renewable energy technologies lowered fuel consumption
and also reduced carbon dioxide emissions at the same time reducing operation cost
and air emissions.

The tool is aimed at stakeholders in the shipping industry, in particular ship
designers, to make decisions on the best way of utilizing the available deck area for
installations of renewable energy technologies, such as; solar and wind systems.
Furthermore, the sail angle optimisation model can act as a tool for both design and
operational measures. As an operational measure it can be used as a tool for
operating a rigid sail system in the most efficient manner, and it can be integrated in
the process of planning weather routing.

KEY CHARACTERISTICS: Optimisation, Wind power, Solar power, Emission
Reduction.
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<table>
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<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Networks</td>
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<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<tr>
<td>EEDI</td>
<td>Energy Efficiency Design Index</td>
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<tr>
<td>GA</td>
<td>Genetic Algorithms</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>GloMEEP</td>
<td>Global Maritime Energy Efficiency Partnerships</td>
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<tr>
<td>HES</td>
<td>Hybrid Energy System</td>
</tr>
<tr>
<td>HOMER</td>
<td>Hybrid Optimisation Model of Electric Renewables</td>
</tr>
<tr>
<td>HRES</td>
<td>Hybrid Renewable Energy Systems</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>LCE</td>
<td>Levelised Cost of Energy</td>
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<tr>
<td>MARPOL</td>
<td>Maritime Pollution</td>
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<tr>
<td>MCR</td>
<td>Maximum Continuous Rating</td>
</tr>
<tr>
<td>MEPC</td>
<td>Marine Environment Protection Committee</td>
</tr>
<tr>
<td>MOCO</td>
<td>Multi Objectives Combinatorial Optimisations</td>
</tr>
<tr>
<td>MPPTS</td>
<td>Maximum Power Point Tracking System</td>
</tr>
<tr>
<td>NACA</td>
<td>National Advisory Committee for Aeronautics</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrogen oxide</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<td>---------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>NPV</td>
<td>Net Present Cost</td>
</tr>
<tr>
<td>NYK</td>
<td>Nippon Yusen Kabushiki Kaisha</td>
</tr>
<tr>
<td>PCU</td>
<td>Power Conditioning Unit</td>
</tr>
<tr>
<td>PM</td>
<td>Particulates matter</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>SECA</td>
<td>Sulfur Emission Control Areas</td>
</tr>
<tr>
<td>SEEMP</td>
<td>Ship Energy Efficiency Management Plan</td>
</tr>
<tr>
<td>SO\textsubscript{x}</td>
<td>Sulpher dioxide</td>
</tr>
<tr>
<td>TFSC</td>
<td>Thin film solar cells</td>
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<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
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CHAPTER 1: INTRODUCTION

1.1 Background information

The shipping industry has evolved from dependency on one form of energy to another since the ancient times. During the ancient times, shipping was relying on human power using oars as its source of energy. Later, due to the growth of sea borne trade there was a shift from human labour to wind sails (Button, 2008). In the 20th century as a result of further growth of international trade, modern energy conversion technologies were realised resulting into switching from sails to combustion engines. Since then shipping sector has been heavily relying on fossil fuels as its main source of energy (Button, 2008).

The continued use of fossil fuel makes international shipping to be among sectors contributing highly to climate change through emissions of greenhouse gases. According to Third IMO GHG study (IMO, 2014), international shipping is contributing to approximately 3.1% of annual carbon dioxide (CO2) globally and if no measures are put into practice this trend is expected to increase by 50 - 250% by 2050 due to growth of international trade.

As the result of the growth of emissions from shipping and other sectors, many scientists started exploring the larger context of the impacts of GHG emissions. For instance, Intergovernmental panel on Climate Change (IPCC) (Change, Intergovernmental Panel On Climate, 2014) reported the impacts of global warming of temperature rise by 1.5 °C above pre industrial level and its associated measures in order to reduce them. (Djalante, 2019), also reported that by 2100 century the temperature is expected to continue rising to up to 2°C and further impacts will be caused, such as; global sea level rise expected to reach 10 cm, diminishing of arctic sea ice, droughts, floods and decline of Coral reefs by 70-90 percent.

In response to this situation, in December 2015, during the meeting of the paris agreement member states under the United Nations Framework Convention on
Climate Change (UNFCCC) pledged to take on increasingly ambitious targets which were aimed at peaking and then drastically reducing GHG emissions to ensure that the global temperature rise is kept below 2°C and preferably limit it to a safer 1.5 rise above pre-industrial levels (United Nations, 2015). Following the Paris agreement, the International Maritime Organisation (IMO), a specialised organisation for shipping was tasked with introducing regulations to reduce GHG emissions from shipping. In order to achieve this, the IMO revised MARPOL and introduced annex VI with regulations aimed at improving energy efficiency (IMO, 2015). These new regulations which were introduced included Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) as technical and operational measures respectively. The EEDI is a technical measure that requires new ships to have energy efficient designs. SEEMP is a regulation that requires that operational measures are introduced on board old and new ships in order to improve energy efficiency.

Apart from CO₂ as the major Greenhouse gas, other emissions which result from use of fossil fuel, includes; Sulpher dioxide (SOₓ), Nitrogen oxide (NOₓ), and Particulates matter (PM). These emissions are harmful to humans health and the environment, and can cause acid rain and eutrophication. Sulphur oxide (SOₓ) is produced as a result of the oxidation of sulphur present in the fuel during the combustion process. Fossil fuel oils are among the type of fuels which produce high sulphur dioxide emissions (Ahlgren, 2018). As compared to road sector, marine sector uses large amounts of heavy fuels, as a result contributes to higher amounts of SO₂ emissions. The average sulphur content in residual fuel was approximately 2.9% in 2007 compared to the maximum allowed sulphur content of 10 ppm in road fuels (IEA, 2013). The contribution from shipping represents about 4-9% of the total anthropogenic emissions (EC, 2016). Therefore, in order to reduce SOₓ, IMO introduced SOₓ regulations. Currently, some areas were designated as sulphur emission control areas (SECA). These are ports where ships operating in these areas are required not to emit SOₓ equivalent to that coming from fuel having a gravimetric
sulphur content of more than 0.1%. In 2020 a new regulation will come into force where all areas will be required to use fuels with sulphur limit of 0.5% (IMO, 2014). NOx is produced as a result of high combustion temperatures in the engines. Since high combustion temperatures typically lead to higher efficiencies in engines, there is a trade-off between engine efficiency and engine NOx emissions. In order to control NOx emissions, IMO introduced regulation where ships built from 2000 should improve their efficiency depending on type of category, Tier I, II and III. Tier 1 are all those vessels built from 2000 and their engines are supposed to reduce emission by 10%, Tier II are those vessel built from 2013 where their engines are supposed to reduce NOx by 20% while Tier III are those built from 2016 which are required to reduce emission by 80% (IMO 2018). Currently, approximately 15% of global anthropogenic emissions of NOx were estimated to originate from international shipping. In Europe, shipping contributed to approximately 20-40% of the NOx emission in the year 2010 and emission from shipping may potentially exceed emission from land based emissions by 2020 (IEA, 2013).

Therefore, to meet the need for the growing demand for these regulations and to reduce the operational cost, many approaches are currently being explored, such as, technical, operational and market based measures. Recently, technologies which are becoming popular include use of renewable energy technologies, such as; solar and wind power systems (Rehmatulla, Parker, Smith, & Stulgis, 2017). These technologies are becoming popular because they are readily available energy resources and contribute to almost zero emissions. However, the availability of wind and solar power depends on the position of the ship and the local weather conditions it is sailing in, and are thus variable in time (Brynolf, 2014). Therefore, it is high time that current energy systems must be hybridised and optimum measures applied in order to improve their performance. These hybrid systems include; solar and wind or combination of more renewable energy systems.
In order to solve this, this thesis is aimed at developing two optimisation models which will be used to determine the best sailing angle for the wind propulsion system and another model to determine the best configuration for the hybrid system of wind and solar power system. These optimisation models will help to improve efficiency through maximisation of power and minimisation of fuel consumption. Therefore, low fuel consumption will result into low GHG emissions and low operating costs hence making international shipping economically and environmentally friendly sector.
1.2 Problem statement/motivation

The over-reliance of fossil fuel as the main source of energy in the shipping sector contributes to increased levels of greenhouse gas emissions a factor which causes climate change (Tillig et al., 2015). In addition, over-reliance on fossil fuels is affecting the operating cost of the industry, because of the fluctuating fuel price on the market. Furthermore, the growth of international trade contributes to high demand for consumption of energy resources resulting into pausing a threat of energy security.

In order to reduce over-reliance of fossil fuels there are many emerging technologies which are being explored, of which the most popular ones includes the use of renewable energy technologies, such as; wind and solar energy systems, (Sundaramoorthy, 2017). However, the efficiency and intermittent availability of solar and wind energy is a disadvantage over the current practice of burning a fuel.

In order to solve these problems, in this thesis two optimisation models have been developed. The first model optimises the wind sail angle of a rigid sail in order to maximise propulsive force. The second model optimises wind and solar power installations onboard a ship in order to find the best combination which will produce maximum power. Therefore the optimised sail angle and best combination of solar and wind will help to improve the efficiency of the ship, hence helping to lower fuel consumption at the same time reducing emission and operating cost.

1.3 Aims and objectives

The aim of the study is to maximise wind and solar power for onboard ship application. The study will achieve the following specific objectives;

I. Creation of an optimisation model for calculating the optimum sail angle in all the wind directions and speeds to maximise wind propulsion power from a rigid sail,
II. Calculate the available effective power of a wind propelled ship on the global trade routes,
III. Determine optimal combination of wind and solar power by optimising the available deck area for solar and wind energy capture,
IV. To determine the fuel saving and emission reduction.

1.4 Research questions or hypothesis
I. How much propulsive force can be produced from a rigid sail at the optimal sail angle?
II. How much propulsive power can be produced from wind at the optimal sail angle viewed over the average conditions of global shipping routes?
III. How much power can be produced at the optimal combination of solar and wind system?
IV. How much fuel saving can be achieved at the optimal combination of solar and wind application?
V. How much emission reduction can be achieved at the optimal condition?

1.5 Research scope
The study focused on the optimisation of the rigid sail angle on the global sailing routes using the probability wind matrix provided in the MEPC 62/INF.34 (MEPC, 2011) in order to maximise wind propulsive power. Flettner rotors, kites and free sails were not considered in this study. For an integration of solar and wind application, only the available deck area was optimised in this study. Some other variables which affect performance or decision to adopt wind sail systems and solar applications, such as; stability, cost analysis were considered to be beyond the boundary of this study, and were not considered quantitatively. However, introduction of wind sails and solar panels affect stability. The sail height considered (50m) is within the range of previously existing sailing ships of lower length, for instance Preussen, and standards of solar application is similar to already operating ships meaning that it should not be entirely unrealistic. The construction cost is also
expected to increase, though operating costs would probably decrease. A detailed cost analysis is beyond the study.

1.6 Research outline
This thesis is composed of five chapters organised in the following order; Chapter one (1) introduces the topic and starts by giving the background information of the topic, provides the problem statement, an outline of main and specific objectives and the scope of the study. Chapter two (2) gives a review of existing literature on wind and solar systems applications, and reviews optimisation methodologies. Chapter three (3) outlines the methodologies that have been used in this study, and describes the rigid sail angle optimisation model and the solar and wind power deck area optimisation model. The chapter further explains the working principle of the programs developed for the implementation of the models. Chapter four (4) outlines all the calculations, presents the results, and discusses them. Finally, Chapter five (5) gives the conclusion and recommendations for further study.
CHAPTER 2: LITERATURE REVIEW

2.1 Chapter overview
This literature review focuses on the application of wind propulsion systems and solar power and their integration as hybrid systems comprising both wind and solar power as alternative sources of energy. Finally, this literature review discusses optimisation algorithms and software tools to maximising the power output of hybrid systems.

2.2 Hybrid system components
Hybrid renewable energy systems are systems which combine one or more energy systems, for instance; solar, wind, batteries, fuel cells. The integration of such systems help to improve efficiency and reliability in a more economic, environmental friendly in all loads demand conditions as compared to the single use. According to (Djelailia, Kelaiaia, Labar, Necaibia, & Merad, 2019), no single measure is sufficient to achieve meaningful efficiency and reduction of GHG emissions. But, emissions can be reduced by more than 75% by integrating the technologies through good policies and regulations. At present the shipping industry is adopting various technologies to improve energy efficiency and meet the target of IMO initial strategy on reducing GHG emissions. Technologies, such as; wind and solar systems (Djelailia et al., 2019).

2.3 Wind power
Wind energy is an indirect form of solar energy which originates from the heating of the atmosphere along with the earth rotation creating planetary and local wind patterns (Kaygusuz, 2015). Wind power is the form of the renewable energy which has been used for thousands of years in a variety of applications, such as ; electricity production, water pumping, power supply in remote areas and ship propulsions. Later, due to the industrial revolution wind power was replaced by other forms of energy, for propulsion, particularly fossil fuels. The oil crisis of the 1970s renewed
the interest in wind energy technology (Lele & Rao, 2017). GHG emissions regulations, volatility of fuel prices which affects operating costs of ships, and energy security as result of declining reserves of non-renewable resources, have made renewable energy resources increasingly popular with wind energy being the most widely used. Wind Assisted Ship Propulsion (WASP) is currently becoming the popular solution because it is among the few ship technologies which are offering double-digit fuel and emissions savings, and it is believed to be an important renewable energy source for the future shipping industry (Lloyd's Register, 2015). According to (Nelissen, Traut, Köhler, Mao, Faber, & Ahdour, 2016), currently it is one of the debated technologies on the amount of fuel oil that can be saved when using wind power systems. For instance, in 1980 a rigid wing sail ship was constructed and generated an average annual saving of between 15% and 30% as compared to previously consumed fuel rate. But, in another study conducted in the year 2000, a product carrier with rigid wind sails was designed for the Danish ministry of environment and energy, she was estimated to make an annual saving of up to 15% of fuel, while in another study full scale test showed that kites combined with conventional engines could enable an annual saving of up to 35% (Kaygusuz, 2015). Despite this potential, none of the technologies have reached market maturity yet. At present large number of vessels which are operating using wind technologies are small vessels on small voyages with only two large commercial vessels in use (Lele & Rao, 2017). In order to improve this, many innovative wind propulsion technologies concepts have been proposed and are currently being developed for commercial shipping. The vessels which are ideal and are most likely going to benefit from the technology are ocean going low speed bulk carriers and oil tankers. This is because these vessels, can accommodate additional superstructure on deck and their low speed operation increases the spectrum of wind directions where sails and wing sails can generate useful thrust. Furthermore, the wind sail assisted propulsion decreases the voyage time mostly in restricted waters due to freedom of manoeuvrability in port. This is possible because sails can be regulated easily in order to make them harness more power during ships maneuver hence reducing turn
around time at port (Viola, Sacher, Xu, & Wang, 2015). Currently there are about 11000 bulk carriers and 8000 tankers of dead weight or greater which are operating world wide and these two ships together represent 75% of the global ocean going fleet in distance (Atkinson, Nguyen, & Binns, 2018). This means that if most of these vessels will adopt wind technologies can results into significantly reducing greenhouse gas emissions.

### 2.3.1 Wind technologies for onboard ship application

Wind technologies which are used in ship board application are categorised as, soft sails, rigid sails/wing sails, hull sails towing kites and flettner rotor and wind turbines. Flettner rotors and wing sails are the most popular technologyes. The relative saving of towing kites are by comparison higher for small vessels and lower for larger vessels, while relative saving for wind turbine are the lowest (Nelissen et al., 2016). In larger vessels fuel saving is high because they have large deck area allowing them to be equipped with taller turbines and operate on the open waters exposed to more wind area.

**(i) Concept of wing/rigid sails**

Rigid sails / wing sails combination with flaps works on the principal that when fluid (wind) is moving through the aerofoil it produces an aerodynamics force consisting of lift and drag. The drag and lift create resultant force figure 1 below. Therefore the total force created have the potential to provide an auxiliary or supplementary source of propulsion on powered ships. Many researches have already shown that ships fitted with these sails reportedly reduce their fuel consumption by between 10 to over 30% under favourable conditions (Atkinson et al., 2018).
(ii) Concept of kites

The concept of kites is not very complex but not commonly used in large ships because its fuel saving potential for large ships is very small. It is mostly installed at the bow, making use of high altitude winds. The Kites which are used for ship propulsion are dynamic kites that keep moving relative to the ship, figure 2.
(iii) Concept of Flettner rotor
A Flettner rotor (rotating cylinder) comprises the cylinder with an end plate affixed to the top mounted vertically to the deck of the ship. The movement of the rotor is initiated by the action of an electric motor. Therefore when the cylinder rotates in an air stream Magnus effect is created figure 4. This is a phenomenon which is created when fluid flow incident upon a spinning body. As a result a lift force is generated that creates a propulsive force to move the ship, figure 3. Flettner rotors contribute to large fuel reduction potential, for instance; two Norse-power rotor sails of 30 metres tall with a diameter of 5 metres combined are expected to reduce average fuel consumption on typical global shipping route by 7 to 10% (De Marco et al., 2016).

Figure 3: Flettner rotor onboard ship (Loyd's Register, 2015).

Figure 4: Magnus effects on the rotor (De Marco et al., 2016).
Despite wind technology becoming an attractive technology it has some challenges. These include; initial capital in investment of the technology, heavy winds might affect stability, obstructing the view bad for navigation, obstructing the movement of crew during emergency or maintenance. These impacts vary depending on the technology, for instance; sails during heavy winds are regulated to minimise their impact on stability while Flettner rotor affects much on the stability than obstruction of the view to navigation.

### 2.4 Solar energy system

Solar energy is the form of energy which is obtained directly from the sunlight. It can be harnessed using photovoltaic solar panels or solar thermal power plants (Yuan, Wang, Yan, Li, & Long, 2018). The use of photovoltaic solar panels to harness solar energy can be used for small applications and large applications. In small applications panels are used to provide power for appliances, namely; charging batteries for laptops, cell phones and calculators. While in large applications, one or more panels are combined in order to power large loads, for instance; street lights, a house in a micro-grid application, or a pump water using electric pumps.

Recently, most solar applications are land based as compared to marine application. Some notable marine uses include; supplying power to small light houses, buoys and charging batteries used for small yachts. On ship board applications solar system can be used for main propulsions or for auxiliary purposes. According to (Bukar & Tan, 2019), it is now noted that due to the volatility of fuel prices, increasing regulations on greenhouse gas emissions, new ecological policies, marine companies are now forced to systematically start adopting the use of photovoltaic technologies on vessels applications. As of the year 2017 it was found out that solar systems were contributing to about 4% of energy out of the total renewable energy supply and it was also predicted that the use of solar power will double by 2023 according to (IEA, 2018). In order to promote the technology further in the marine industry, at the moment, there are many projects which are taking place researching about solar
photo-voltaic application on board vessels. One of the typical example is the first solar system that was applied on Auriga Leader, a ship of 60000 gross tonnage which was built by NYK Line company in 2011. In this application a hybrid system composed of solar panels, diesel engine and hydrogen cells and batteries were installed on board (NYK, 2011). Currently, the cost of installing solar systems is about 3$ per kilowatt, this price is lower than the previous years. It is expected that the price will continue to go down because of expected initiatives including inclusions of subsidies on the price to compete with land based solar systems, (GloMEEP, 2019).

Solar thermal systems use solar collectors to absorb heat from sunlight. Figure 5 shows how a solar thermal system operate to produce power from sunlight to consumers. A large area with high amount of sunlight goes through lens mirrors to converge into small area of concentrated light. Then, the sun power passes through conjunction box. Finally, the power will reach to consumers through electric power storage and electric power generator. At present this system is not yet introduced on ships because it requires a large area for installation (Ibrahim S.Seddiek, 2017).

![Diagram of Solar Thermal System](image)
2.4.1 Manufacture and Production Processes of Solar Panels

Solar cells are basic components of solar PV system, figure 6. Cells are divided into thin layer and crystalline cells. Crystalline cells are made from raw material of silicon whose atoms are organised in crystalline grids. Mono crystalline cells are made from single crystalline silicon structure while polycrystalline consists of several crystals with different orientations. Thin film solar cells (TFSC) are made by putting together thin layers of semiconductors materials on a substrate glass, such as; amorphous silicon, cadmium tellurides copper, and carbon based organic photovoltaic cells (Fahrenbruch & Bube, 2012).

In order to produce a large voltage, the solar cells are connected together in series to create solar panels. Then the solar panels are linked together as a solar array to meet the power requirement of a solar system. A solar array will absorb sunlight to produce power. In order to make the absorbed process more effective, inverters and trackers are used. Inverters are used incase the load requires alternating current. When the system load requires alternating current inverters converts direct current (DC) to alternating current (AC). While trackers are used to optimise the orientation of solar panel in order to produce more power. The tracker can be single axis or dual axis. According to (Tang, Wu, & Li, 2018), observed that solar systems are simple interns of installations and maintenance, because the system only need enough area to absorb sunlight which is converted into power. This is the reason the rate of use of solar applications is growing at a fast rate, and this makes them to have clear advantage in some aspects as compared to solar thermal applications. But in other aspects, for instance; water heating, thermal application is better than direct solar applications (Ibrahim S.Seddiek, 2017).
2.4.2 Process of harnessing power from solar

Solar cells are composed of two different types of semi-conductors, namely; P-type and N-type which are joined together to create P-N junction. The cells are doped with another element in order to create freedom of movement of electrons. For instance, P-type silicon cells are doped with boron while in N-type, silicon cells are doped with phosphorus. So when photons from sunlight strikes the cells, the electrons are excited, allowing them to move from N-type cell to P-type cell. This is because phosphorus is a group five element while Boron is the group three element in the periodic table (Fahrenbruch & Bube, 2012). Therefore, free electrons on the outer cell of phosphorus move to fill up the vacant outer cell on Boron element. As a result of this movement, a positive charge is created on the N-type and Negative charge is created on the P-type. In this case, by joining two types of semiconductors an electric field is formed in the region. This electric field causes the negatively charged particles to move in one direction and positively charged in the other directions, as illustrated in the figure 7 below;
2.4.3 Application of Solar Energy on board ship

When designing a solar energy system for shipboard ship applications, important factors need to be considered include; solar radiation data, availability of sufficient deck area which is exposed to the sun, suitable number of solar PV panels recommended for the system, techno-economic considerations of solar panels selected for the system, solar panel grid connectedness with other devices and design of the system lay out.

(i) Solar irradiation

Solar irradiance is the amount of solar resource at a particular position and time. The term resource applies to anything coming from outside the system that is used by the system to generate electricity or thermal power. The solar resource depends strongly on latitude and climatic conditions. Therefore, the first thing when designing a solar system requires that data should be gathered for the location or routes of interest. Solar resource data indicate the amount of global solar radiation that strikes earth surface measured in kilowatts-hour per meter squared (kW/m²) which can be either hourly, monthly or yearly (Mars Bodell & Tapia Chiriboga, 2018). The measure of solar irradiance is determined by surface clearness index. Clearness index is the measure of the clearness of the atmosphere. It is measured as the ratio of the solar radiation striking earths surface to that of solar radiation striking the top of the
atmosphere. For ship applications, weather routing data plays a major role on determining the system installation on board ship as the ship travels from port to port for transportation. In addition, the ship always needs a stable power when working for a specific task, for example maneuvering at port during berthing and casting out. This will require the ship to have a large and reliable energy storage to maintain a safe power supply. Otherwise, working condition of solar panels are affected by these climatic harsh conditions because of the changing location of ships and the affects of sea-water on board (Lan, Wen, Hong, Yu, & Zhang, 2015).

The area through which the solar system is to be installed is crucial when designing the solar system on board ship. This is because of the available area depending on ship type, ship dimensions and machinery arrangement. The larger the area of solar panels, the more sunlight is absorbed and converted into electricity. Maximising the solar collection area is also important in other situations such as cloud cover or low angled and low intensity light, such as can occur during winter because large number of panels installed on them still have the capability of generating energy. The deployment of solar panels has to be done with consideration of the stability of a ship because large areas being used for solar panels could affect ship stability by weight of large volumes of solar panels, batteries, and inverters (Alexandru & Ion, 2017).

(ii) Types of Solar panels
The performance of the solar panel depends on many factors, such as; types of panels, inclination on the deck, dirt and dust, mismatch, life time degradation. The most commonly used panels are mono crystalline, polycrystalline and amorphous. Polycrystalline and mono-crystalline are efficient but are made from expensive raw materials while amorphous are less efficient but made from cheaper raw materials. The rated maximum capacity of solar panels is called the peak capacity, it is the amount of power it would produce under standard test conditions of 1kwh/m² irradiance under test conditions of a temperature of 25°C (Ibrahim S.Seddiek, 2017). These measurements are taken while also considering the orientation and inclination
angle of the PV array on the surface, for instance; deck area. It is the angle at which the PV array is inclined on the deck at the particular location of the earth surface, the time of the year and time of the day. This orientation angle of the array may be fixed or may vary according to the tracking system (Tang et al., 2018). Dirtiness and dust also affects the Performance of the solar panels. Its impact on the panel is determined by the derating factor. This is the scaling factor meant to account for the effects of dust on the panel, wire losses, elevated temperature, or anything else that would cause the output of the PV array to deviate from that expected power under ideal conditions. Another factor which affects the performance of the panel is mismatch, this is the lower maximum output power in relation to the estimated total power of the array expected to be produced. Furthermore, the efficiency of solar panels lowers down depending on usage time because of the slow deterioration of the laminate material over time. According to (Fahrenbruch & Bube, 2012), the rating of solar panels which are used now were found for stationary use. Therefore, more research is needed to determine the exact rating of the solar panel for practical ship applications. Therefore, more practical experience is required to understand the PV behaviour in sailing conditions, for instance; temperature, humidity, sun irradiation and ship course.

(iii) Techno-economic aspects

Poly crystalline and mono crystalline solar cells have high efficiency but materials which they were made from are expensive, while amorphous type of panels are made from less expensive material but thier efficiency it is lower (Mars Bodell & Tapia Chiriboga, 2018). Therefore when designing the solar system considerations should be made on the cost and produced energy. This is done by using the following criteria; the net present cost (NPV), levelised cost of energy (LCE) and life cycle cost. NPV is the total present value obtained by total cash flows which includes the initial cost of all the systems components, any cost of replacement that occurs within the project life time, cost of maintenance and investment costs plus the discounted present values of all estimated future costs during the life time of the system.
Levelised cost of energy is commonly used in the design and optimisation of energy systems. It is expressed as the ratio of the total annualised cost of the system to the annual energy delivered by the system. Life cycle cost include all the costs over the systems life time from initial investment and capital costs, to operation and maintenance, such as; fuel and financing cost.

(iii) Other components of solar system
Apart from solar panels there are other devices which complement the solar system, these devices include; power conditioning unit (PCU), maximum power point tracking system (MPPTS) and alternating current (AC) and direct current (DC) motors. A PCU typically consists of DC-DC converter and DC-AC inverter. It is used to enhance system efficiency by regulating PV system output voltage or by helping generate PV maximum output power when the MPPTS is applied. A DC-DC converter is used to step up the low magnitude DC voltage from the photovoltaic panels to a higher voltage by a single phase or three phase inverter in order to produce usable AC voltage depending on the load supplied. A DC-AC inverter converts DC power to AC power. The DC-DC converter is commonly used in PV system application because the single stage inverter is difficult to use in MPPTS (Kurniawan, 2016).

A Maximum Power Point Tracking System (MPPT), is the system aimed at increasing photovoltaic (PV) system efficiency by maximising PV output power at every weather condition. An MPPT changes the orientation of a solar panel to optimise its orientation with respect to the direction of the solar radiation. A PV module has different maximum power at each weather condition especially at different solar irradiation. The value of PV maximum power at each weather condition can be obtained if the PV output voltage is at certain value called maximum power point voltage. MPPT has a role to generate optimum voltage reference for DC-DC converter so that PV can produce its maximum power at every different conditions (Mars Bodell et al., 2018). On the other hand an MPPT system is
disadvantageous as compared to fixed installation, this is because of its energy consumption needed to operate the system. Therefore, it is advisable to use a fixed system installation than a movable system.

Solar power can either be used for the main propulsion of the ship or to supply auxiliary power to the ship. For the main propulsion, electric motors are used to drive the propeller shaft. These motors can either be of DC or AC type. In terms of operation, a DC motor is easier to control in terms of operating speed compared to an AC motor. But in terms of cost AC motors are preferred because they are cheaper, have a lower weight and smaller dimensional size at the same power compared to DC motors (Kurniawan, 2016).

(iv) Battery application
Battery cell is another essential component of the solar PV system which is used to store excess energy that can then be used during the hours when no direct solar energy is produced figure 8. A battery converts electrical energy into chemical energy and is able to reverse the cycle and able to supply electricity with desired voltage (Yan et al, 2018). Battery electrodes are located in a container filled with either liquid, solid or paste state electrolyte. A cell is composed of positive and negative electrodes separated by the electrolyte materials. It produces specific voltage depending on whether it is connected in series or parallel to make a battery bank. The performance parameters of a cell is measured in current-time (ampere-hours) at its nominal voltage, before the battery voltage reaches the end of the life cycle.
Batteries are classified according to the material which were used during construction, such as; lead lithium, nickel, sodium and zinc. The most common widely used battery cells in the industry, include; the lithium and lead acid. Lithium batteries are mostly used on electric vehicles and grid connected storage where high energy density is required. More than 90% of lithium ion anodes are composed of graphite which is produced at a low cost. Silicon and titanium based materials are occasionally used to get better life time for this type of cells (Tang et al., 2018). Lead acid batteries are made from a mixture of lead plates and sulphuric acid. Because of their materials which were used during the construction, lead acid batteries have shorter life span, lower cost, are less efficient and have a lower reliability than lithium ion batteries (Mars Bodell et al., 2018).

Designing of the battery system lay out depends on the available space on the ship. Together with other factors the amount of power which can be produced can be determined and will help to know the maximum load which the system can support, figure 9.
2.5 Optimisation

The problems related to the use of alternative renewable energy sources is its nature of unreliability arising from variations of solar irradiation and fluctuations of wind speed. In order to solve this, integration of the resources into a suitable hybrid combination is a solution to provide the potential to improve the system efficiency and energy supply reliability. In order to come up with suitable combination optimisation has currently become the useful tool by many researchers, (Bhandari, Lee, Lee, Cho & Ahn, 2015). Optimisation is a scientific tool for finding the best solution based on the given objective function (Ölçer, 2008). It is defined as a problem of finding a vector of decision variables, which satisfies constraints and optimises a vector function whose elements represents the objectives function (Osyczka, 1985). Optimisation problems are described in terms of mathematical formulae to which algorithms are applied in order to find the optimal solution.

Optimisations problems can be classified as single and multi objective functions. A single objective optimisation is where one decision variable is chosen and its merit is chosen whether to minimise or maximise the output. Multi objectives combinatorial optimisations (MOCO) two or more objective variables are chosen for optimisation.
in order to come up with the best solution. In most MOCO problems the concept of trade off applies where one best solution at the expense of the other is chosen. Sometimes the solutions that are not dominated by one solution within the entire search space are denoted as Pareto - optimal set or Pareto-optimal frontier (Ölçer, 2008).

There are many approaches to solving optimisation problems, one of them is using full factorial experimental design. In this methodology an experiment can be conducted testing various factors simultaneously but still the effect on the response can be isolated. In a full factorial experimental design all possible combination of all factor levels and results produced and the response is measured (Andersson, 2012). For instance, to maximise power in a renewable energy system comprising of wind and solar power, the response would be the produced renewable power. A full factorial experimental design model can be developed and the conditions at which maximum power is produced are identified.

Other approaches for solving optimisation problems, include; simulations, mathematical programming (linear or dynamic), decision and risk analysis, decision support system, multiple attributes and decision making, meta-heuristics and evolutionary programming, game theory, efficiency/data envelopment analysis (Sinha & Chande, 2015). Computer software tools are used together with methodologies to facilitate attainment of reliable outcomes. For instance, the National Renewable Energy Laboratory developed an optimisation algorithm using hybrid optimisation model of electric renewables (HOMER) (Lambert, Gilman & Lilienthal, 2006). This model uses a computer simulation in order to optimise hybrid renewable energy systems in micro-power plants, such as; solar-battery systems, wind-diesel systems, natural gas micro-turbines mostly connected to a grid. Hoga is another optimisation model developed in order to minimise Net present cost and the life cycle of CO2 emissions for a hybrid renewable energy systems (HRES) comprised of PV-diesel system with battery storage system for ship application. This
model used genetic algorithms (GA) as the methodology to solve the problem. GA give sufficient enough solutions when applied to highly complex problems. It is a global search heuristic, a search technique used in computing to find true or approximate solutions for the optimisation and search problems (Sinha & Chandel, 2015). (Sastry, Goldberg & Kendall, 2005) carried a GA optimisation to find the reliability of hybrid system designs. It was found out that the reliability of the system prominently increased when two systems were hybridised with the inclusion of storage device and the optimum sizing of the hybrid energy system components represent the important part of the power system. (Geleta & Manshahia, 2018), developed an optimisation model using an iterative method in order to determine the system size of each components of the hybrid system of wind and solar to meet the desired load with minimum cost. This methodology starts by initialising the basic decision variables of number of wind turbines and number of solar panels starting from the minimum numbers to maximum up until possible optimum results of the system are found. (Geertsma, Negenborn, Visser & Hopman, 2017), also developed an optimisation model in order to find the optimal operation of the HRES when a ship is at port. This problem intergrated renewable energy system and cold ironing. In order to solve the problem optimal control and model predictive control methodologies were developed. The results showed that optimal operation of maritime hybrid energy system (HES) can bring promising electricity, cost-savings and improved system robustness. (Dagdougui, Minciardi, Ouammi, Robba, & Sacile, 2012) found the optimal solution for the energy demand of a building using a predictive control model. The dynamic decision model was developed to integrate a different mix of renewable energy system (solar, wind and biomass) and one storage device to satisfy the different demands (electric, heating and water) feeding green building in the sustainable way (Sinha & Chandel, 2015). Artificial Intelligence (AI) is another optimisation techniques used to conduct studies and design of intelligent agents where an intelligent agent takes action that maximise the chance of success (Erdinc & Uzunoglu, 2012). The AI comprises Artificial Neural Networks (ANN), GA fuzzy logic and hybrid system combining two or more of the above branches.
There has been a recent trends towards using AI for the optimisation of hybrid renewable energy system, and results suggest that AI may provide good optimisation of systems even if without extensive long term weather data (Sinha et al., 2015).

2.6 Summary of literature review

The literature review has shown that renewable energy technologies are more advanced on land based industry as compared to marine industry. This is because on land the limitations to the technologies are lower as compared to ship applications, such as; restriction on installation area on ships, increased variations of weather factors as the ship moves from one place to another. Furthermore, the literature has shown that more optimisation research was focused on land systems than marine, for instance optimisation methodologies have widely been used for the design of land based systems, rather than the marine sector. Therefore, it is because of these gaps, that this research was initiated in order to improve solar and wind systems so that these technologies should be more attractive and increasingly adopted into the marine sector.
CHAPTER 3: RESEARCH METHODOLOGY

3.1 Chapter overview

In order to achieve the objectives of this study, two single objective optimisation models were developed. The objective of the developed models was maximisation of renewable energy power. These models were implemented by using python software programming language version 3.6 and microsoft excel computer packages. The first model, was used to optimise wind sail angle while the other model was used to determine the best combination on the available deck area for solar and wind power systems. In order to achieve this, mathematical formulae were developed and were used in the models to calculate solar and wind power. Data for calculating wind power were obtained from wind tunnel tests published by the National Advisory Committee for Aeronautics (NACA) (Sheldahl & Klimas, 1981), and for calculation of solar power, raw data were obtained from recent literature on photovoltaic applications. The optimum total power obtained from model 2 was applied in EEDI formula to determine carbon dioxide reduction. The steps of the methodology is summarised in the figure 10 below;

![Figure 10: Summary of steps of the methodology](image-url)
3.2 Sail angle optimisation model.

A sailing ship converts wind power into propulsive power by the wind blowing relative to its sails moving with the ship. This wind velocity blowing relative to the sails is called the apparent wind speed, and is the result of the superposition of wind velocity and ship velocity. It has magnitude and direction, which after striking the sail creates lift and drag forces at right angles to each other. The force created from these two forces is called the resultant force. The product of this force and the area of the sail and the angle between resultant force and ships velocity produces total propulsive force component in the direction of the ship’s heading, or thrust force ($F_t$).

In order to maximise $F_t$, a model optimising the best sailing angle was developed as part of this dissertation. The model calculates $F_t$ using the following steps.

Figure 11 shows the forces created on a rigid sail on a ship for propulsion system. The formulae for the model were built using these forces.

![Figure 11: Forces on the Aerofoil](image-url)
Step 1: Calculation of angle between wind velocity and ships heading

(i) \( \alpha = j.\text{Anglestep}. \frac{\pi}{180} \) (rad) \hspace{1cm} (1)

where \( \alpha \) is the angle between the wind velocity and ships heading, \( j.\text{Anglestep} \) is an increment of angle \( \alpha \) in radians, as explained in table 2.

(ii) \( \theta = \tan^{-1}\left( \frac{Q \sin \alpha}{P + Q \cos \alpha} \right) \) (rad) \hspace{1cm} (2)

where \( \theta \) represents the angle between apparent wind speed and ships velocity in radians, \( Q \) represent the magnitude of the ships velocity in meters per second (m/s) and \( P \) represent the magnitude of the wind velocity in m/s.

Step 2: Calculation of Magnitude of apparent wind speed

(iii) \( V_A = R = \sqrt{P^2 + 2P \cdot Q \cdot \cos \theta + Q^2} \) (m/s) \hspace{1cm} (3)

where \( P \) represents the magnitude of the velocity of the ship in m/s, \( Q \) represents the magnitude of the velocity of the wind in m/s.

Step 3: Calculation of Lift (L) and drag (D) forces

(iv) \( L = \frac{1}{2} \cdot \rho \cdot C_L \cdot A \cdot V_A^2 \) (N) \hspace{1cm} (4)

(v) \( D = \frac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot V_A^2 \) (N) \hspace{1cm} (5)

where \( \rho \) represents the density of air, \( C_L \) and \( C_D \) is the coefficient of lift and drag (Sheldahl & Klimas, 1981). \( A \) represents the area of the sail and \( V_A \) (R) is the magnitude of the apparent wind speed.

Step 4: Calculation of angle between the resultant force and lift force (Beta)

(vi) \( \beta = \tan^{-1}\left( \frac{D}{L} \right) \) (rad) \hspace{1cm} (6)

where \( D \) and \( L \) are the lift force and drag force respectively.

Step 5: Calculation of angle between the resultant force and ship velocity (Gamma)

(vii) \( \gamma = \frac{\pi}{2} - \theta + \beta \) (rad) \hspace{1cm} (7)

where \( \theta \) is the angle between wind speed and ships velocity, while beta (\( \beta \)) is the angle between resultant force and lift force.

Step 6: Calculation of the resultant force \( F_r \)

(viii) \( F_r = \sqrt{L^2 + D^2} \) (N) \hspace{1cm} (8)

where \( L \) and \( D \) is the lift force and drag forces respectively, as calculated above.
Step 7: Total Propulsive force component in the direction of the ship’s heading (thrust force).

\[ F_t = F_r \cdot A \cdot \cos \gamma \ (N) \]  \hspace{1cm} (9)

Fr. is the resultant force, A is the area of the sail, and gamma (\(\gamma\)) is the angle between the resultant force and the ship’s heading.

This procedure is repeated for all possible sail directions (in angle increments of 5 degrees), and the sail angle (\(\phi\)) producing the maximum thrust force is then identified and chosen as the optimum sail angle.
3.2.1 Wind sail angle program logic flow chart

The program has been summarised using the flow chart in figure 12 below. At the first stage, table 1 explains the meaning of each shape used in the flow chart.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminator</td>
<td>This shape means to start the program or end the program.</td>
</tr>
<tr>
<td>Data</td>
<td>It is for inputting or outputting the data into the program or out of the program.</td>
</tr>
<tr>
<td>Process</td>
<td>This one mainly means calculates formulas.</td>
</tr>
<tr>
<td>Decision</td>
<td>This shape is the decision-making function. If the decision is right, it goes to the ‘Yes’ direction. If it is not, it goes to the ‘No’ direction.</td>
</tr>
</tbody>
</table>

Table 1: Shapes and their meaning
3.2.2 Explanation of the flow chart structure

The flow chart in Figure 12 summarises the principle of the wind propulsion optimisation program. The flow chart starts with the input of data and the definition of constant variables. These are then are inserted into the calculation loops. In the first loop, the values of wind direction start changing from 0 to 355 degrees with an increment of 5 degrees forming seventy-two values of wind directions inside the loop. When the value of wind direction is chosen, the first calculation is implemented in the first loop. In the second loop, 25 values of wind speeds ranging from 1 to 25 meters per second (m/s) are used. A condition clause (‘if’ statement) was used to make the inverse tangent (‘atan’) function valid for all angles. Inside the second loop, the third loop (loop 3) is used to calculate the resultant thrust force, and repeated for all sail angles to optimize the best sail angle for this sailing condition. Next, when the third loop is completed, the program returns back to loop 2 to calculate the new value of the wind speed. Finally, when all the cases of the first loop are calculated, the final step is to plot the results with a diagram of angles and file texts. It is described in detail in the following sub-sections.

In the flow charts, all diamond-shaped boxes are ‘IF’ statements, in which the computer program checks whether the statement is fulfilled or not, and the computer program makes a decision in the flow-path accordingly.
Figure 12: Flow chart of the model 1
### 3.2.3 Definition of variables

In this step, initial values of variables are defined. Table 2 shows a summary of input variables and their meaning used in the program.

<table>
<thead>
<tr>
<th>Name (abbreviation)</th>
<th>Variable name in program</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Θ</td>
<td>theta</td>
<td>Angle between apparent wind speed and ship (rad).</td>
</tr>
<tr>
<td></td>
<td>Angle Step</td>
<td>An increment from one angle to another = 5(degrees)</td>
</tr>
<tr>
<td>α</td>
<td>alpha</td>
<td>The angle between the ship and the apparent wind speed (rad).</td>
</tr>
<tr>
<td>β</td>
<td>beta</td>
<td>The angle between resultant force and lift force (rad).</td>
</tr>
<tr>
<td>γ</td>
<td>gamma</td>
<td>Angle between resultant force and ship velocity (rad).</td>
</tr>
<tr>
<td>ρ</td>
<td>ρ</td>
<td>The density of air (kg/m³)</td>
</tr>
<tr>
<td>P = V_{ref}</td>
<td>Vref</td>
<td>Velocity of ship (m/s)</td>
</tr>
<tr>
<td>Q = u</td>
<td>Q = u</td>
<td>Velocity of wind (m/s)</td>
</tr>
<tr>
<td>C_L</td>
<td>C_L</td>
<td>Lift coefficient for the NACA Aerofoil</td>
</tr>
<tr>
<td>C_D</td>
<td>C_D</td>
<td>Drag coefficient for the NACA Aerofoil</td>
</tr>
<tr>
<td>F_r</td>
<td>F_r</td>
<td>Resultant force (N)</td>
</tr>
<tr>
<td>F_t</td>
<td>F_t</td>
<td>Force total produced to ship (N)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Meaning</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>( \rho )</td>
<td>rho</td>
<td>Density of air ((\text{kg/m}^3))</td>
</tr>
<tr>
<td>( L )</td>
<td>L</td>
<td>Lift force ((\text{N}))</td>
</tr>
<tr>
<td>( D )</td>
<td>D</td>
<td>Drag force ((\text{N}))</td>
</tr>
<tr>
<td>( A )</td>
<td>A</td>
<td>Area ((\text{m}^2)) (in the program a standard value of unity ((1 \text{ m}^2)) is used, and the sail area can later be scaled up to the appropriate size of the sail)</td>
</tr>
<tr>
<td>( \text{U}_{\text{start}} )</td>
<td>Minimum speed of wind (=1 \text{ (m/s)})</td>
<td></td>
</tr>
<tr>
<td>( \text{U}_{\text{max}} )</td>
<td>Maximum speed of wind (=25 \text{ (m/s)})</td>
<td></td>
</tr>
<tr>
<td>( \text{Angle}_{\text{max}} )</td>
<td>Maximum wind angle (=360 \text{ (degrees)})</td>
<td></td>
</tr>
<tr>
<td>( \text{Datapoints} )</td>
<td>Number of coefficient of drag and lift force (=116)</td>
<td></td>
</tr>
<tr>
<td>( \text{F}_{\text{thrust}} )</td>
<td>Force to ship from wind ((\text{N}))</td>
<td></td>
</tr>
<tr>
<td>( \text{F}_{\text{thrustOptimum}} )</td>
<td>The maximum force from wind ((\text{N}))</td>
<td></td>
</tr>
<tr>
<td>( \text{F}_{\text{angle}} )</td>
<td>The angle between the resultant force and ship velocity in real value ((\text{degree}))</td>
<td></td>
</tr>
<tr>
<td>( \text{Forceangle} )</td>
<td>The optimum angle of gamma to have maximum wind force ((\text{degree}))</td>
<td></td>
</tr>
<tr>
<td>( \text{LiftdragData} )</td>
<td>The input of lift and drag coefficient</td>
<td></td>
</tr>
<tr>
<td>( \text{Optimunangledata} )</td>
<td>Best angle of attack between wind and sail ((\text{degree}))</td>
<td></td>
</tr>
<tr>
<td>sailangle</td>
<td>The angle of attack between wind and sail (degree)</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Aparentwindangle</td>
<td>The angle between apparent wind speed and ship in radian</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Parameters of the developed model

3.2.4 Input data step
In this step, the constants used in the calculation of the program are read and loaded into the computer memory. These comprise the density of air, the sail area of the ship, the range of wind speeds considered, and the sailing speed of the ship.

3.2.5 Loop 1 - Changing wind direction loop
As illustrated in figure 13 below, the main variable of this loop is “j” that runs in range of (0, Anglemax/Anglestep). Anglemax is usually 355 degrees, and the angle increment Anglestep is 5 degrees, yielding 72 variations in sail position. The variable j is used to calculate alpha (α) as shown in section 3.2.1 equation (1). Alpha is the angle between the ship’s heading and the apparent wind velocity (rad). After that, alpha (α) is used for the loop 2. One value of “j” is used in the calculations of loop 2, and when loop 2 is completed, the programme will increase the value of j to j = j + 5 with 5 being the Angle step to run the next loop 1.
Figure 13: Loop 1
3.2.6 Loop 2 - Changing wind speed loop

As shown in figure 14, the loop 2 is inside loop 1. The variable is wind speed “i” that changes from \( U_{\text{start}} \) to \( U_{\text{max}} \) with increment = 1. There are 3 cases using the ‘if’ condition in this loop. These cases depend on the value of the velocity of wind as shown below:

- “If 1”: \[ V_{\text{ref}} = -u \times \cos(\alpha) \] then \( \theta = \pi/2 \)
- “If 2”: \( \alpha \leq (\pi/2) \) or \( \alpha \geq (3 \times \pi/2) \) then \( \theta = tan^{-1}\left(\frac{u \times \sin\alpha}{V_{\text{ref}} + u \times \cos\alpha}\right) \)
- “If 3”: \( \alpha > (\pi/2) \) or \( \alpha < (3 \times \pi/2) \) then \( \theta = tan^{-1}\left(\frac{u \times \sin\alpha}{V_{\text{ref}} + u \times \cos\alpha}\right) + \pi \)

This was necessary to correctly model the angle theta using the atan function in all four quadrants (see also https://en.wikipedia.org/wiki/Atan2).

Then the value of “\( \theta \)” is used to calculate the apparent wind speed. The next step is the loop 3. In loop 3 the forces produced by the sail and propulsive thrust force of the ship are calculated. When loop 3 is completed, the program comes back to the starting point of loop 2 to begin a new process.

![Figure 14: Loop 2](image)
3.2.7 Loop 3 Optimization of sail angle,

As shown in figure 15, loop 3 is inside the loop 2, for each value of ‘i’ loop 3 is calculated for sail angles throughout a whole 360° rotation of the sail, with the variable ‘k’ changing for every iteration. The variable ‘k’ is used to choose the input data consisting of angle of attack, coefficient of lift (C_L) and coefficient of drag (C_D) from “datapoints1.txt” file used in the “Input Data” process. The input file datapoints1.txt contains the angle of attack of the aerofoil, the lift coefficient C_L, and the drag coefficient C_D ordered in rows. These data were taken from wind tunnel tests performed in an experimental facility (Sheldahl & Klimas, 1981). In this case, the numbers of data points are 116 values. The program runs a “For” loop with the “k” values from 1 to 116. Inside the loop, the lift coefficient and the drag efficient are imported from the “datapoints1.txt” file. The lift force and the drag force are calculated based on equation (4) and (5) in section 3.2.1. In order to be continued, there are 3 ‘If’ conditions to identify angle between resultant force and lift force:

- ‘If 1’: \( L = 0 \) then \( \beta = \pi/2 \)
- ‘If 2’: \( L < 0 \) then \( \beta = \tan^{-1} \left( \frac{D}{L} \right) - \pi \)
- ‘If 3’: \( L > 0 \) then \( \beta = \tan^{-1} \left( \frac{D}{L} \right) \)

This ‘If’ statement was necessary correctly account for negative lift coefficient values. Then the angle between resultant force and ship velocity was used to calculate the component of the resultant force which is acting in the same direction as the ship is moving. This was used to calculate the forward thrust of the ship. The sideways force was ignored. This assumption was made in order to limit the complexity of the model and was done using the assumption that the ship had a very effective keel that could keep the ship moving in its direction of heading, despite sideways forces being applied.

Finally, the program identified and chose the maximum value of the force from wind (FthrustOptimum) and the corresponding best angle of attack between wind and the sail. Then the angle between the optimum resultant wind force (forceangle) and the
optimum angle of the sail (sailangle) were calculated. After that, the next loop 2 continued with the same process and all the values were saved into the matrix of the program to print in the next steps.

Figure 15: Loop 3
3.2.8 Plot results

The final step was to export the results into graph and data files in text format. In this program, the graph was used to illustrate the optimum sailing condition for a given wind speed and direction, by plotting the angles of the below values with different colours:

![Polar graph for NACA0015 Aerofoil at a ship speed of 13 knots and a wind speed of 25 m/s](image)

Figure 16: Polar graph for NACA0015 Aerofoil at a ship speed of 13 knots and a wind speed of 25 m/s

The text files that can be shown are listed below:
- 'FthrustOptimum.txt' - Maximum force from wind (N)
- 'optimumangledata.txt' - Best angle of attack between wind and sail
- 'sailangle.txt' – Angle between the sail and the ship velocity
- 'aparentwindangle.txt' – Angle between the apparent wind and the ship velocity.
'gamma.txt' - Angle between the resultant force and the ship velocity.

Figure 16 is showing the polar graphs of NACA 0015 aerofoil using experimental data at the ship speed of 13 knots corresponding to the design speed of the vessel, and investigated 3 Aerofoils (NACA 0012, 0015, and 0018), and chose the one that provide the highest power under conditions laid out in the Circular MEPC 62/INF.34 (IMO,2011).

### 3.3 Calculation of available effective propulsive power

Then, using the optimum propulsive force obtained above, the effective power was calculated using the formulae below; This formula was approved by MEPC (IMO, 2000).

\[
\begin{align*}
\text{f}_{\text{eff}} \cdot \text{P}_{\text{eff}} &= \left( \frac{0.5144 \cdot V_{\text{ref}}}{\eta_f} \sum_{i=1}^{m} \sum_{j=1}^{n} F(V_{\text{ref}})_{i,j} \cdot W_{i,j} \right) - \left( \sum_{i=1}^{m} \sum_{j=1}^{n} P(V_{\text{ref}})_{i,j} \cdot W_{i,j} \right) \\
&= \left( \frac{0.5144 \cdot V_{\text{ref}}}{\eta_f} \sum_{i=1}^{m} \sum_{j=1}^{n} F(V_{\text{ref}})_{i,j} \cdot W_{i,j} \right) - \left( \sum_{i=1}^{m} \sum_{j=1}^{n} P(V_{\text{ref}})_{i,j} \cdot W_{i,j} \right)
\end{align*}
\]

(i) Where \( F(V_{\text{ref}}) \) is the propulsive force of the wind propulsion system for a given ship speed calculated as above,

(ii) \( \text{F}_{\text{eff}} \) is the factor which determines the power available according to EEDI definitions,

(iii) \( \text{P}_{\text{eff}} \) is the power reduction factor according to EEDI definitions,

(iv) \( V_{\text{ref}} \) is the ship speed recommended for EEDI calculations (knots),

(v) \( \eta \) is the total efficiency of the main drives at 75% MCR,

(vi) \( W_{ij} \) is the global wind distribution matrix as proved by the MEPC,

(vii) \( P(V_{\text{ref}}) \) is the external power demand matrix of respective wind propulsion system for a given ship speed \( V_{\text{ref}} \).

In this calculation assumption was made on the mechanism to operate the sail is equal to zero (0).
3.4 Solar Power calculation

The Solar power was calculated basing on the considerations made on the geographical position, types of photovoltaic panel and efficiency. The geographical area determines the amount of solar irradiance a particular position is able to receive.

In this study, solar power has been calculated using average global irradiance of 200 W/m² (Bent, 2010). The types of solar panels produce power depending on the materials which the modules were manufactured from, for instance; poly crystalline, mono crystalline and amorphous silicon. On the market mono-crystalline are considered the most efficient panels (Ibrahim S. Seddiek, 2017). In the study an average panel size of 1.968 m² and efficiency of 17.1% was used for the calculation.

In order to find available deck area the same bulk carrier as previously used in the wind power calculation of this study was used. Bulk carriers are ideal vessels because they have open decks exposed to solar irradiance. Therefore, to calculate power the formula which was used is the following;

\[
\text{Amount of Solar energy} = I \times \mu \times A
\]

where \( I \) represents solar irradiance in watts per m², \( \mu \) represents the efficiency of the PV cells, \( A \) total surface area of the PV cells in m².

3.5 Optimisation model of solar and wind Power

The optimisation model of hybrid system for wind and solar was developed where the objective function was to maximise power. This optimisation model is a single objective because it is only optimising the available deck area on the ship in order to produce maximum power. In order to achieve this, wind power and solar power was calculated using the models outlined above. The constraints for the system is to have enough deck area to support all the systems. Therefore, the available deck area is optimised using the developed python program in order to find optimal combination of solar and wind systems that produce maximum power.
3.5.1 Process of development of a Solar and wind power optimisation model

A data table was formulated, shown in Table 3. In the table’s first column values of ships surface area are expressed as a percentage (%). In the second column values of wind power are expressed in watts (W) and the third column contains values of solar power in watts (W). These values were created by the researchers to give an example and demonstrate the working principle of the model. Real values are used in chapter 4.

<table>
<thead>
<tr>
<th>Ships surface Area (%)</th>
<th>Wind Power (kW)</th>
<th>Solar Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 %</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25 %</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>50 %</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>75 %</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>100 %</td>
<td>75</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3: Area and power produced from wind and solar

In this table, area represents the part (fraction) of the ship (expressed as a percentage) used for installation of renewable energy system which is either solar or wind power systems. In the wind and solar column is the power produced from wind and solar systems depending on the percentage area used on the ship.
3.5.2 Description of the working principal of the program

The flow chart in Figure 17 describes the working principle of the optimization program of solar and wind power. The program begins in the “Start block”. Then data is imported from table 3 and is inserted in the program in the “Input Data block”.

![Flow chart of the second model](image)

Figure 17: Flow chart of the second model
The program consists of Loop 1, Loop 2, an “If” block and Optimization block. Loop 2 is inside Loop 1 and the “If” block is inside loop 2. Also Loop 1 has a conditional clause and letter “i” which represents the values of wind power. The values of ‘i’ in range of (1, 5) increases by 1 for a new value of “i” in a successive loop. When the value of “i” reaches 5 Loop 1 is completed and move to an Optimization block. For Loop 2 has values of “j” that runs from 1 to 5 with an increment of 1 for the next loop. Inside Loop 2, there is the “calculation block” where there is a function to calculate the total combined power of wind and solar using the available total deck area. Next, the program continues with the “If” block. The conditional clause of “If” is to check the limit of total deck area. If the total area is above 100% and below 0%, the total power is equal to 0 and the program returns back to the beginning of Loop 2. Then, after finishing Loop 1, the values of total combined power are saved into the program. Then the optimization block has function to choose the maximum combined power. The final step of the process is outputting the data. The program prints a matrix value of total power and value of power for optimum combination. It also prints the optimum area used for wind and solar power. Figure 18 demonstrates the program works with data created by the researchers in table 3, real data was used in chapter chapter 4.

```
[[0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0.]
 [0. 0. 0. 0. 0.]]
[[ 0.  20.  60.  80. 100.]
 [ 40.  60. 100. 120.  0.]
 [ 60.  80. 120.  0.  0.]
 [ 70.  90.  0.  0.  0.]
 [ 75.  0.  0.  0.  0.]]
```

(1, 3)

*optimum area used for windpower is 25 %
optimum area used for solarpower is 75 %
total power for optimumcombination is 120.0 MW*

Figure 18: Demonstration results of solar and wind optimisation

In this demonstration, it shows that to produce maximum power, 25 percent of available deck area should be used for installation of wind power system and 75
percents for installation of solar power system. At this optimum combination power produced is 120 MW. In chapter 4, a deck area of bulk carrier selected for this study was investigated for this optimisation.

### 3.6 Determination of carbon dioxide (CO₂) reduction

In order to determine carbon dioxide CO₂ reduction from innovative technologies of solar and wind which were introduced on board a vessel, calculation was done using two formulae. The first formula was used to calculate required EEDI and the other for calculation of Attained EEDI (IMO, 2000). Therefore, the CO₂ reduction was obtained by the difference of Required Energy Efficiency design Index and Attained Energy Efficiency Design Index. In order to calculate, Required EEDI the following formulae was used;

\[(1 - \frac{X}{100}) \times \text{Reference line value},\]

where X is the reduction factor found depending on the year of built and type of the ship, while reference line value was calculated using another formulae; \(ab^c\) where a and c are given on guidelines for calculations of reference lines, resolution MEPC. 231(65) (IMO, 2013), and b represents the dead weight tonnage of the type of vessel selected for the study.

And Attained Energy Efficiency design Index was calculated using the formulae;

\[
\left( \prod_{i=1}^{n} \sum_{j=1}^{m} P_{\text{r}(i,j)} \cdot \text{SFC}_{\text{r}(i,j)} \right) + \left( \prod_{i=1}^{n} \sum_{j=1}^{m} P_{\text{a}(i,j)} \cdot \text{SFC}_{\text{a}(i,j)} \right) = \left( \prod_{i=1}^{n} \sum_{j=1}^{m} P_{\text{r}(i,j)} \cdot \text{SFC}_{\text{r}(i,j)}^* \right) - \left( \sum_{i=1}^{n} f_{\text{r}(i)} \cdot P_{\text{r}(i)} \cdot \text{SFC}_{\text{r}(i)} \right) - \left( \sum_{i=1}^{n} f_{\text{a}(i)} \cdot P_{\text{a}(i)} \cdot \text{SFC}_{\text{a}(i)} \right) \]

(Equation 12)

Where the parameters inside the formulae represents;

- \(P_{\text{ME}}\) is the power produced by the main engine,
- \(C_{\text{FEME}}\) is the carbon factor of the fuel of the main engine,
- \(S_{\text{FCME}}\) is the specific factor of the main engine,
- \(P_{\text{AE}}\) is the power of the auxiliary engine,
- \(P_{\text{AF}}\) is the carbon factor of the fuel used in the auxiliary engine,
$P_{AE}$ is the specific fuel consumption of the auxiliary engine,

$P_{pti}$ is the propulsive power of the shaft motor,

$P_{eff}$ is the availability factor of the innovative energy efficiency technology introduced in the system,

$P_{AEeff}$ is the Auxiliary effective power of the innovative technology,

$P_{eff}$ is the main engine effective propulsive power from the innovative technology,

Capacity is the deadweight of the vessel selected for the study,

$V_{ref}$ is the reference speed of the vessel selected for the study,

$f_w$ is the factor indicating the decrease in speed due to change of weather condition,

$f_i$, $f_c$, $f_j$ these are correction factors applied to distinguish ships designs.

Finally, data which were used for the calculations in the formulae were from the bulk carrier which has been selected as scenario vessel for the study while the other were obtained from the calculations above. Full calculation file is presented on the appendix 6 and results are presented on chapter four (4).
3.7 Summary of the research methodology

In summary the rigid sail angle optimisation model was used to find the maximum thrust by optimising the sail angle. Then the optimum thrust for the global wind probability matrix was used to find the average available effective propulsive power from wind. Solar power was calculated using the average solar irradiation between -30 and +30 degrees of latitude on earth, and assuming an efficiency of available photovoltaic technology available in the literature. Power from wind and solar was applied in the wind and solar power optimisation program in order to find optimum power on the available deck area. Finally, the optimum power from wind and solar was applied in the EEDI formulae in order to find CO₂ emission reduction.
4.1 Chapter overview
In this chapter, results of sail angle optimisation model were presented and analysed. After this, the calculations of wind and solar power were done using the equations outlined in chapter three (3) and their results were discussed. The calculations were done using the specifications of the bulk carrier selected for the study. The first calculations were done to find available effective power from wind technology. This was done using the results of optimum force obtained from wind sail angle optimisation program and was applied in the effective available propulsive power formulae equation ten (10). This calculation was followed by the calculation of solar power. Thereafter, power of wind and solar were used in the wind and solar optimisation program. Finally, using equation eleven (11) emission reductions were determined.

4.2 Sail optimisation model result
4.2.1 Validation of Reynolds number
The Reynolds number measures the ratio of initial forces to viscous forces and describes the degrees of laminar or turbulent flow. Systems that operate at the same Reynolds number will have the same flow characteristics even if the fluids, speed and characteristics length changes. From NACA data (Sheldahl & Klimas, 1981), three aerofoils of the chord width 0012, 0015, and 0018 were selected for this study. In the data in order to find the lift and drag coefficient Reynolds number (Re) was applied. The figures used in respective of chord width were the following; 0012 (10^4 < Re < 10^7), 0015 (10^4 < Re < 10^7) and 0018 (10^4 < Re < 10^6). Therefore, in order to validate the Reynolds number, the following equation was used;

\[ Re = \frac{\rho V l}{\mu} = \frac{\nu^{*} l}{v} \]

where \( \rho \) represents the density of the fluid, V velocity of the fluid, l represents the characteristics length of the chord width of an aerofoil, \( \mu \) the dynamic viscosity of the fluid, \( v \) the kinematic viscosity of the fluid.
The calculation was done using the following parameters;

$V = 12.5 \text{ (m/s)}$ Velocity of wind chosen from a range of 1 to 25 m/s used in the wind sail calculations

$L = 5 \text{ (m)}$ chord length of the aerofoil this number was chosen basing on the assumption

$\rho = 1.225 \text{ (kg/m}^2\text{)}$ Density of air

$\mu = 10^{-3} \text{ (kg/ (m/s))}$ Absolute viscosity

Substituting from the equation (Re) number was found as $76562.5$. The results from the calculations are within the (Re) number which are on the data. This signifies that results obtained are the true reflections of the aerofoils performances.

4.2.1. Results obtained from sail angle optimisation model

In this section the results of the program after it was run for three times using 3 cases of aerofoil; NACA – 0012 Aerofoil (Re = $10^4$), NACA – 0015 aerofoil (Re = $10^4$), NACA – 0018 aerofoil (Re = $10^4$) are presented. These results are presented in the following order; figure 19, polar graphs at different wind angle directions and optimum sail angle are shown, then each case with a figure and explanation is provided. Also, the results of angles (degrees) with respect to the ship heading are taken from the text files of the programs, and they are shown in table 4. The optimum force thrust of 3 types of aerofoils at wind speed of 25(m/s) are compared and a graph is shown in figure 28. The data of the Lift and Drag Coefficients of 3 aerofoils are also compared and presented in figure 29 and 30. Finally, the graph of optimum forward thrust of the NACA 0012 aerofoil at wind speed of 25 m/s is explained and illustrated in figure 31.
4.2.2 The Polar graph of optimum sail angles applying to Aerofoil NACA – 0012 at wind speed of 25 m/s

The full code of the program is provided in appendix 2. After running the program of “Sail optimisation model” that is applied to aerofoil NACA – 0012 (Re = 10^4) at wind speed of 25 m/s, the optimum sail angles was identified. In the following polar graphs (Figure 19), there are 4 coloured lines:
- Wind direction is represented by the black line.
- Sail angle is represented by the red line.
- Apparent wind is represented by the green line.
- Resultant force angle is represented by the blue line.

![Polar graph of optimum sail angles](image)

Figure 19: Optimum sail angle at different wind angle directions at ship speed 13 knots, wind speed 25 m/s.
Table 4: Results of angles in degrees with respect to the ship heading.

In ensuing part, the discussion results of figure 20 will be explained in more detail. The ship’s heading in following figures, as in the following figures will be defined as moving from the left side to the right side. “v” is the ship velocity, “u” is the wind velocity, and “V_\Lambda” is the apparent wind angle. The angle will be positive when it is above the middle line of the polar graph, and it will be negative when it is below the middle line of the polar graph.

1. The first polar graph shows that the wind angle is blowing at 0 degree to the ship. This is illustrated in figure 20;

Figure 20: Optimum sail angle at 0 degree. Ship speed 13 knots, wind speed 25 m/s.

Figure 20 shows that when the wind direction blows to the ship with the wind angle of 0 degrees. The wind and ship velocity is on the same line, but in opposite direction. It produces the apparent wind $V_\Lambda = u - v$, which causes a big drag force. So the sail need to turn to the angle of 180 degrees comparing to the wind direction. It is to reduce the drag force as much as possible.
2. The second polar graph above shows wind direction blowing at 45 degrees. This is illustrated in figure 21 below;

Figure 21: Optimum sail angle at 45 degrees. Ship speed 13 knots, wind speed 25 m/s.

The wind direction heads to the ship direction in an angle of 45 degrees, and it sums together to create the apparent wind, which has 35.6 degrees of angle heading to the ship direction. At this moment, the sail turns to the angle of -154.4 degrees in order to produce the maximum force thrust ($F_t$). This program also calculates that the angle between the resultant force and the ship direction is about -63.7 degrees.
3. The third polar graph above shows wind direction blowing at 90 degrees. The position of optimum sail angle is illustrated by figure 22;

![Diagram of sailboat and wind angles]

Figure 22: Optimum sail angle at 90 degrees. Ship speed 13 knots, wind speed 25 m/s.

The wind direction heads to the ship direction in an angle of 90 degrees, and it sums together to create the apparent wind, which has 74.4 degrees of angle heading to the ship direction. To achieve the maximum forward thrust, the sail turns to the angle of 34.4 degrees. The angle between the resultant force and the ship direction is about -56.2 degrees. In this case, the force thrust almost achieves the highest force comparing to other case of wind angle.
4. The fourth polar graph above is showing wind direction at 135 degrees. This is illustrated by figure 23;

![Diagram showing wind direction and sail angle](image)

**Figure 23: Optimum sail angle at 135 degrees. Ship speed 13 knots, wind speed 25 m/s.**

The wind direction heads to the ship direction in an angle of 135 degrees, and they sum together to create the apparent wind, which has 121.2 degrees of angle heading to the ship direction. In this case, the ship direction and the wind direction is in the same direction, which is heading to the right side. To achieve the maximum force thrust, the sail turns to the angle of 66.2 degrees. The angle between the resultant force and the ship direction is about -23.2 degrees.
5. The fifth polar graph above is showing Wind direction at 180 degrees. This is illustrated by figure 24 below;

![Diagram of sailboat with wind direction and resultant force](image)

Figure 24: Optimum sail angle at wind direction 180 degrees. Ship speed 13 knots, wind speed 25 m/s.

In this case, the wind direction is on the same direction to the ship, which is in an angle of 180 degrees. The apparent wind is produced and $V_A = u - v$ makes the ship moving forward. To achieve the highest values for force thrust, the sail angle is 90 degrees. Finally, the resultant force is created with the angle of 7 degrees, comparing to the ship’s direction.
6. The sixth polar graph above is showing Wind direction at 225 degrees. This is illustrated by figure 25;

Figure 25: Optimum sail angle at wind direction 225 degrees. Ship speed 13 knots, wind speed 25 m/s.

In this case, the wind direction also blows from the back of the ship. It makes an angle of 225 degrees comparing to the ship velocity. To achieve the highest values for forward thrust, the sail angle is at -66.2 degrees. The apparent wind $V_A$ is produced and $V_A$ hits the sail at the angle of $121.2 - 66.2 = 55$ degrees. Finally, the resultant force is created with the angle of 23.2 degrees, comparing to the ship’s direction.
7. The seventh polar graph above is showing Wind direction at 270 degrees. This is illustrated by figure 26;

Figure 26: Optimum sail angle at wind direction of 270 degrees. Ship speed 13 knots, wind speed 25 m/s.

In this case, the values of angles are opposite (mirrored by the plane of the ship’s heading) to the values of case 3 (wind angle = 90 degrees). The wind hit directly to the left side of the ship under an angle of 90 degrees, then it creates the apparent wind that have an angle of -74.4 degrees, comparing to the direction of the ship.
degrees is the angle of the resultant force to the ship’s direction. Finally, the sail angle moves to the angle of -34.4 degrees to produce the maximum force.

8. The eighth polar graph above is showing Wind direction at 315 degrees. This is illustrated in figure 27;

![Figure 27: Optimum sail angle at wind direction of 315 degrees. Ship speed 13 knots, wind speed 25 m/s.](image)

The direction of sail and forces in this case is opposite to case 2 (wind angle of 45 degrees). The wind heads to the ship under 315 degrees and created the apparent wind that has -35.6 degrees of angle, comparing to the ship direction. To produce the highest forward thrust, the sail turns to the angle of 154.4 degrees and it causes the resultant force, which has 63.7 degrees of angle comparing to the ship direction.

It also notices that the value of angles in these cases (wind angles of 225, 270 and 315 degrees) are opposite to the values of angles at the cases (wind angles of 135, 90, and 45 degrees). The reason is the lift coefficients (wind angles from 0 to 180 degrees) have opposite values with the lift coefficients (wind angles from 360 to 180 degrees).
4.2.3 Forward thrust optimum at wind speed of 25 m/s for 3 aerofoils.

Figure 28: Optimum force thrusts of 3 aerofoils at wind speed of 25 m/s.

Figure 28 is drawn by importing the data from 3 files of optimum force thrusts of 3 aerofoils at a wind speed of 25 m/s. Comparing 3 types of aerofoils, the optimum force thrusts of Aerofoil NACA 0012 has the highest values in the range of wind angle (0,50), (100,130), (200, 250), and (325, 360). According to equations (4), (5), (8), (9) in section (3.2.1), the force thrust is linear with the Lift and Drag coefficient. Following to this analysis, in the next section, the data of Lift and Drag coefficients of three aerofoils are also compared and analysed.
4.2.4 Comparing Lift and Drag coefficients of 3 aerofoils

Figure 29: Comparing lift coefficients of 3 aerofoils

Figure 30: Comparing drag coefficients of 3 aerofoils
The lift and drag coefficients of 3 aerofoils are imported into the data input of the model to calculate the best sail angle. Figure 29 compares the lift coefficients of 3 aerofoils in the range of wind angle changing from 0 to 360 degrees. The values of lift coefficients of aerofoils NACA 0012 are almost higher than the values of the other 2 Aerofoils. Also, the values of lift coefficients of aerofoils NACA 0015 have the second-highest values in the list of 3 aerofoils. On the other side, figure 30 shows the comparison of drag coefficients of 3 aerofoils. The values of drag coefficients of all 3 aerofoils are almost the same, and this makes the lines seem like only one line. Overall, the Lift coefficient is a decisive factor that affects the results of the maximum force thrusts of an aerofoil.

4.2.5 Force thrust optimum – NACA 0012 at wind speed of 25 m/s

Figure 31 describes the values of maximum force thrusts for the NACA 0012 aerofoil calculated corresponding to 25 values of wind speed, ranging from 1 to 25 m/s and changing the wind angle from 0 to 360 degrees with the increment of 5 degrees. The figure shows that the maximum force at wind speed of 25 m/s had the highest values of the optimum force thrust. Then the force produced is reducing progressively when the wind speed goes down from 25 to 1 m/s. It also means that the lowest force occurs at a wind speed of 1 m/s.
Furthermore, figure 31 shows that the force thrusts increased slightly in range of wind angle from 0 to 90 degrees. Then a sudden leap occurred at the wind angle of 90 degrees, and the values reached a peak at 95 degrees. The reason is because the drag force is maximum and the lift force is 0 at 95 and 265 degrees, which creates a big resultant force. After that, the values decline significantly in the range of wind angle from 90 to 120 degrees, then the values go slightly down when the wind angle increased from 120 to 180 degrees. In contrast, the changes of the force thrusts with the wind angle going with opposite trend from 180 to 360 degrees comparing to the increasing of changing wind angle from 0 to 180 degrees. In case of wind speed of 25 m/s, the highest Fthrust optimum was about 375 Newtons at 2 values of wind angles, 95 and 265 degrees. In conclusion, higher forward thrust was created when there was a stronger wind speed and when the sail was positioned at its optimum sail angle.
4.3 Case study: Application to a Bulk carrier type of vessel

A bulk carrier with IMO number 9798337 which was built in January 2017 was selected for the study, (Clarkson data, 2019). The specification of the vessel are outlined in the table 5 below:

<table>
<thead>
<tr>
<th>Vessel specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of ship</td>
</tr>
<tr>
<td>IMO number</td>
</tr>
<tr>
<td>Year of built</td>
</tr>
<tr>
<td>LOA</td>
</tr>
<tr>
<td>LBP</td>
</tr>
<tr>
<td>Drought (D)</td>
</tr>
<tr>
<td>Beam (B)</td>
</tr>
<tr>
<td>Gross tonnage</td>
</tr>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>Engine power</td>
</tr>
<tr>
<td>Deadweight</td>
</tr>
<tr>
<td>Hatch dimensions</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Table 5: Bulk carrier specifications

4.3.1 Calculations of available effective power

The optimum force averaged over time on the world’s shipping route according to the wind conditions provided in IMO Circular MEPC 62/INF.34 (IMO,2011), the time averaged forward thrust produced at the optimum force angle for the NACA-0012 rigid sail was found to be 20.59 Newtons per m² of sail area. Then using equation 10, this time averaged forward thrust multiplied by a constant speed of 13 knots yielded a time averaged propulsive power of 137.67 Watts per m² of sail area. For the calculation of wind power using equation 10, the efficiency is set to 100% because the power is not connected to the main engine and the force thrust of the sail
is used directly to propel the ship. Full calculations are shown on the appendix 3, 4 and 5. The extract of the results on the appendix are presented in the table 6 below;

<table>
<thead>
<tr>
<th></th>
<th>Total thrust</th>
<th>N/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>20.59</td>
<td></td>
</tr>
<tr>
<td>Available effective power</td>
<td>137.67</td>
<td>W/m²</td>
</tr>
<tr>
<td>Sail area per sail</td>
<td>250</td>
<td>m²</td>
</tr>
<tr>
<td>Total Available effective power per sail</td>
<td>34.42</td>
<td>kW</td>
</tr>
<tr>
<td>Number of sails</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Total wind power for all sails</td>
<td>1.2046</td>
<td>MW</td>
</tr>
</tbody>
</table>

Table 6: Sail forces, areas and propulsive power

In order, to calculate the total available wind propulsive power for the available deck space, the specifications of the selected bulk carrier shown in table 5 were used. Specifications of sails from (Nelissen et al., 2016) were used. One sail was assumed to have a height of 50m and a length of 5m, thus having a total sail area per sail of 250m². Therefore, multiplying power produced per square meter, one sail produces 34.42 kilowatts as shown in table 6 above. The length of the selected bulk carrier ship was 179m. Therefore, dividing by the length of the sail, the ship can support 35 sails if the entire deck of the ship could be used. This simplified value assumes that future sail ships would be optimised for sail propulsion and may have no superstructure obstructing the sails. The sails were assumed to be installed at the center line of the deck. Then multiplying power from one sail (34.42*35) = 1.2046 MW total potential sail power was obtained.

If it is assumed that the sails do not obstruct each other by blocking the wind from one another, then we can calculate what the total power would be produced, if the entire deck area was filled with sails. This calculation assumes that the sails do not
block the available wind for each other, and is thus strongly simplified. The power can be calculated by extrapolating the power of the sails that are installed in the center line of the ship. Then from that value, the total power is calculated.

\[ P_{\text{total wind power}} = \left( \frac{P_{\text{sails in center line}}}{2 \times B_{1 \text{ sail}}} \right) \times BOA \]  

(12)

where \( B_{1 \text{ sail}} \) is the chord length of 1 sail, \( BOA \) is the breadth of the ship. In this case, the power of the sails in the center line is scaled with the total wind power of the whole deck area by the breadth, and it is calculated according to equation 12.

\[ P_{\text{total wind power}} = \left( \frac{1.2046}{2 \times 5} \right) \times 32 = 3.8547 \text{ MW} \]

Therefore, it means 100% of available deck space a wind system installed can produce total power of 3.8547 MW, 75% of deck space can produce \((0.75 \times 3.8547) = 2.8910 \text{ MW}\), 50% of deck space \((0.5 \times 3.8547) = 1.9274 \text{ MW}\), and 25% of deck space can produce \((0.25 \times 3.8547) = 0.9637 \text{ MW}\). These results are summarised in table 7 below;

<table>
<thead>
<tr>
<th>Percentage of deck area (%)</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power in MW</td>
<td>0</td>
<td>0.9637</td>
<td>1.9274</td>
<td>2.8910</td>
<td>3.8547</td>
</tr>
</tbody>
</table>

Table 7: Wind power per available deck area

This is not a very realistic estimate, since we know that if we install several rows of sails next to each other the first row may already use most of the wind power, and the consecutive rows will be in the wake of the first row and not be able to produce much power. A detailed analysis of sail-to-sail interaction is beyond the scope of this work, and may require a Computational Fluid Dynamics (CFD) analysis, or wind tunnel tests. A simplified way of dealing with this problem will be proposed in section 4.4.
4.3.2 Calculation of solar power

The total solar power on the selected vessel was calculated using the available space on the deck area. In this research, it was assumed that the solar panel can be installed on the whole deck area to achieve the maximum power from solar. Therefore, calculations were done using the whole deck area = (179 * 32) = 5728 m². From equation 10, Solar power = 0.171*(5728m²)*(200/1000 kilowatts/m²) = 195.9 kilowatts. This is the power produced when 100% of the available area is used for solar installation. But if 25% of the area is used, power produced = (0.25*195.9) = 48.97 kilowatts while if 50% of the deck area is used = (0.5*195.9) = 97.95 kilowatts power is produced and if 75% of the area is used = (0.75*195.9) = 146.92 kilowatts of power is produced.

<table>
<thead>
<tr>
<th>Summary of solar power per available deck area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deck area/power</td>
</tr>
<tr>
<td>Power (kilowatts)</td>
</tr>
</tbody>
</table>

Table 8: Solar power per available deck area

4.4 Optimisation of Solar and wind power

The wind and solar power calculated above is summarised in table 9 below. As discussed in section 4.3.2., if several rows of sails are placed next to each other they will start affecting each other, and there will be a sort of saturation effect, where two or three rows of sails next to each other will produce not much more power than one full row of sails. This assumption was implemented by introducing an arbitrary saturation function that limits the sail power to that produced by one full row of sails. This could be achieved using a ‘Tanh’ function, as shown in Figure 32. In the table 9 “Tanh” function was introduced on wind power. If more than around 31% of the deck was used for sails the power remains almost constant even if more sails are added. In this study this effect was introduced in order to demonstrate qualitatively
how performance of several sail rows might be affected when they start blocking the wind for each other. To find its real quantitative effect was beyond this study, and may require a CFD analysis or wind-tunnel tests.

<table>
<thead>
<tr>
<th>Area (%)</th>
<th>Wind Power(MW)</th>
<th>Solar Power(MW)</th>
<th>Wind power with &quot;Tanh&quot; function(MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25%</td>
<td>0.9637</td>
<td>0.04897</td>
<td>0.9174</td>
</tr>
<tr>
<td>50%</td>
<td>1.9274</td>
<td>0.09795</td>
<td>1.1613</td>
</tr>
<tr>
<td>75%</td>
<td>2.891</td>
<td>0.14692</td>
<td>1.1986</td>
</tr>
<tr>
<td>100%</td>
<td>3.8547</td>
<td>0.19590</td>
<td>1.2038</td>
</tr>
</tbody>
</table>

Table 9: Solar and wind power on the available deck area

Figure 32: Solar and wind power

The blue graph shows how sail power would increase with deck area used for sails (linear increase) if the sails are assumed not to affect one another. This is because the increase of deck area would be assumed to provide bigger space for installing more sails which would increase the amount of power. But, this is not realistic in practice
because sails will block the wind for each other, resulting into a saturation effect presented by the graph of dotted line in red colour. This more realistic estimate of power is approximately equal to the maximum amount of power produced if the ship is equipped with one full row of sails, as represented by the constant line at 1.2 MW.

4.4.1 Results of Optimisation of solar and wind power
After the program was run the results obtained are the following;

![Optimisation results](image)

Figure 33: Results of Optimisation of solar and wind power

<table>
<thead>
<tr>
<th>Index</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>0%</td>
<td>0</td>
<td>0.04897</td>
<td>0.09795</td>
<td>0.14692</td>
</tr>
<tr>
<td>W2</td>
<td>25%</td>
<td>0.9174</td>
<td>0.96637</td>
<td>1.01535</td>
<td>1.06432</td>
</tr>
<tr>
<td>W3</td>
<td>50%</td>
<td>1.1613</td>
<td>1.21027</td>
<td>1.25925</td>
<td>0</td>
</tr>
<tr>
<td>W4</td>
<td>75%</td>
<td>1.1986</td>
<td>1.24757</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W5</td>
<td>100%</td>
<td>1.2038</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 10: Summary of results of Solar and Wind optimisation
The results from the code shown in figure 33 are summarised in table 10. The results are showing that optimising the available deck area for installation of solar and wind the maximum power is found at matrix index S2 and W4 as shown by red number in table 10. The power obtained at this optimum combination is 1.25925 MW. This power was found by summing up solar power produced at position (S3, W1) and wind power at position (S1, W3). At position (S3, W1) it means that 50% of deck area was used for installation of solar and produced 0.09795 MW power. At position (S1, W3) means that 50% of deck area was used for installation of wind system and produced 1.1613 MW power. This shows that in order to maximise power, 50% of the available deck area should be used for wind power installation and 50% of available deck area for solar power installation. The full code of the program is provided in appendix 1.

4.5 Reduction of carbon dioxide emissions

In order to determine amount of CO2 which can be reduced when innovative technologies are applied calculations were done using EEDI, full calculation are presented on the appendix 6. From the results, required EEDI was found as 6.20672gCO2/tnm, the attained EEDI without innovative technology was found as 5.87483gCO2/tnm. But, when the innovative technologies were introduced the attained EEDI lowered from 5.87483gCO2/tnm to 4.21071gCO2/tnm, a reduction of 1.66412 gCO2/tnm representing 28.33% GHG emissions per transport work were achieved. This showed that when innovative technologies are introduced on a ship a significant reduction gCO2/tnm can be achieved. Furthermore, as shown in table 11 the power specification of the main engine was 4.5 MW at 75% MCR and the power obtained from the renewable energy technologies was 1.26 MW. Therefore, wind and solar power provide 28% of the vessel’s main power. This is a substantial fraction of the ship’s main power, and it may thus be possible to consider operation of the ship on renewable power alone, if a lower speed can be accepted. A reduced speed of the ship will strongly lower its power requirements. Using the “power speed
cube law” as shown in table 12, it can be calculated that if this ship were to sail on 100% renewable energy, it can still be sailing at 65% of its original design speed.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MCRME</td>
<td>Main engine power</td>
<td>6100</td>
<td>kw</td>
</tr>
<tr>
<td>MCRAE</td>
<td>Auxilliary engine power</td>
<td>2400</td>
<td>kw</td>
</tr>
<tr>
<td>Capacity</td>
<td>Capesize a ship selected for the study</td>
<td>38971</td>
<td>dwt</td>
</tr>
<tr>
<td>V&lt;sub&gt;ref&lt;/sub&gt;</td>
<td>Reference speed</td>
<td>13</td>
<td>knot</td>
</tr>
<tr>
<td>SFC&lt;sub&gt;ME&lt;/sub&gt;</td>
<td>Engine specific fuel consumption</td>
<td>190</td>
<td>g/kwh</td>
</tr>
<tr>
<td>SFC&lt;sub&gt;AE&lt;/sub&gt;</td>
<td>Auxilliary engine specific fuel consumption</td>
<td>215</td>
<td>g/kwh</td>
</tr>
<tr>
<td>CF&lt;sub&gt;ME&lt;/sub&gt;</td>
<td>Main engine Carbon factor</td>
<td>3.114</td>
<td></td>
</tr>
<tr>
<td>CF&lt;sub&gt;AE&lt;/sub&gt;</td>
<td>Auxilliary engine carbon factor</td>
<td>3.114</td>
<td></td>
</tr>
<tr>
<td>f&lt;sub&gt;eff&lt;/sub&gt;</td>
<td>Availability factor of solar (energy efficiency technology)</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>f&lt;sub&gt;eff&lt;/sub&gt;</td>
<td>Availability factor of wind (energy efficiency technology)</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>f&lt;sub&gt;l&lt;/sub&gt; f&lt;sub&gt;j&lt;/sub&gt; f&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Correction factors</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>f&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Weather factor</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

| Required EEDI        | (1-X/100)*reference line value |     |    |
| X (reduction factor) | ab<sup>-c</sup>            | 0.1 |    |
| Reference line        | 961.79                     |    |    |
| B                     | 38971 DWT                  |    |    |
| C                     | -0.477                     |    |    |
| Reference line        | 6.212931108                |    |    |
| Required EEDI         | 6.206718176                |    |    |
| P<sub>ME</sub>        | 4575 kw                    |    |    |
| P<sub>AE</sub>        | 402.5 kw                   |    |    |
| P<sub>SOLAR</sub>     | 97.95 kw                   |    |    |
| P<sub>WIND</sub>      | 1161.3 kw                  |    |    |
| Required EEDI         | 6.206718176 gCO2/tnm      |    |    |
| Attained EEDI with innovative technology | 4.210708569 gCO2/tnm |    |    |
| Attained EEDI without innovative technology | 5.874826597 gCO2/tnm |    |    |

Table 11: EEDI calculation
4.6 Summary of discussion of results

The optimum sail angle model developed as part of this work determined the optimum sail angle at which the forward thrust of the ship (Fthrust) was maximised. At the optimum sail angle using results from NACA 0012 aerofoil, the optimum Fthrust per sail area was found to be 20.59 N/m². Then applying equation 10 the available effective power per sail area at optimum sail angle was found as 137.67 watts per m². Assuming that a single row of sails along the length of the ship, and assuming a sail height of 50 m, the total power produced from wind power propulsive system was found to be 1161.3kw. Solar power calculated from the available deck area on the chosen vessel was found as 97.95kw. Therefore, applying solar power and wind power in the optimisation model, the optimal power was found as 1259.25kw. Furthermore, the results showed that in order to produce optimum power 50 percent of the available deck area should be used for wind propulsive system and 50 percent of available deck area for installation of Solar system. When this optimal power was applied in the EEDI equation it was found out that there was 28.3 percent reduction of CO₂ compared to the same ship without any innovative technologies. The results further showed that if the ship were to sail only on wind and solar power, it can be sailing at 65 % of the original design speed.
CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions
The research focused on improving the performance of rigid wind propulsive system by optimising its sail angle and its integration with solar system in order to maximise power production on board ship application. This was achieved by two optimisation models which were developed. The first optimization model was used for calculating optimum thrust at the optimum sail angle based on the input data from global wind probability matrix on the global shipping routes. Optimum thrust found from the model was used to calculate the available effective propulsive power. The second model optimised the available deck area for application of solar and wind power systems. The optimum effective propulsive power from rigid wind sail and solar power were used to calculate the emission reduction using the EEDI formula. The input data for calculation of solar was obtained from the literature and the aerofoil data for wind power calculation was taken from NACA (National Advisory Committee for Aeronautics) wind tunnel tests. These two models were put into practice using programming a two computer programs written in the Python programming language and were post-processed using Microsoft Excel.

Therefore, the study has shown that adoption of innovative technologies on a bulk carrier a vessel selected for the study could reduce CO₂ emissions by 28.3% compared with the same vessel without innovative technologies. This showed that renewable energy technologies, such as; solar and wind when adopted and optimum measures employed on board a ship can help to improve efficiency resulting into reducing emissions as well as operating cost. It also showed that the ship could sail on 100% renewable power if sailing at 65% of its design speed. Finally, adoption of wind and solar as innovative technologies on-board vessel can be a milestone in meeting the requirements for IMO to implement phase three of EEDI regulation.
In summary the research has found the following;

(i) The developed methodology determined optimal sail angle which can be used in a wind propulsion system in order to produce maximum power. Furthermore, the model found out that operating at an optimum sail angle condition helped to maximise renewable energy power. The increased renewable power reduces use of fossil fuel hence also reducing emission and operating cost.

(ii) In the other developed methodology, the optimisation of the available deck area for application of solar and wind power system helped to determine the best use of the available space in order to produce maximum power. The optimised use of the available space with combination of technologies can further help to utilise all available weather conditions as compared to using one technology. For instance, places where there are good sunshine hours’ solar power produces more power while in high wind speed areas wind power also can produce more power in so doing producing maximum power in all weather conditions.

(iii) The research also found out that the more power produced from the use of combined use of renewable energy technologies also lowered fuel consumption from use of fossil fuels. Low fuel consumption also lowered the GHG emissions by 1.61686gCO₂/tnm representing 27.5 % reduction. When the ship uses only renewable it can be sailing at 64% of the speed as compared to initial speed, which is an advantage because there will be no emission and cost saving. This showed that adoption of renewable energy technologies can help to reduce operational cost as well as environmental impacts.
5.2 Recommendations

The research has shown that adoption of the renewable energy technologies can reduce the environmental impacts arising from use of fossil fuels, can help to comply to the growing pressure of the regulation, can help to sustain the depletion of fossil fuel energy resources and also reduce operations cost.

Therefore, the researchers recommend the following:

(i) The methodology developed for sail angle optimisation should be used as a planning tool during weather routing. Therefore, a route selected using probability wind matrix estimated power can be determined. As a result, duration of the voyage can easily be calculated, amount of fuel saving and the emission reduction can be determined beforehand.

(ii) The optimisation methodology for utilisation of available deck area should be used as design tool by engineers during the design phase. This tool will help engineers to make decision on the best way of utilising the available space for installation of renewable energy technologies; such as wind and solar systems.

(iii) Further research should be conducted to optimise other variables which affect performance of wind systems and adoption of the technology. These variables include; effect of technologies on the stability, cost analysis should be determined to test the viability of adoption of the technologies. Another research should also be conducted in order to find real effects of sails on one another when installed on the ship through computational fluid dynamic models (CFD).
REFERENCES


Leloup, R., Roncin, K., Behrel, M., Bles, G., Leroux, J. -, Jochum, C., & Parlier, Y. (2016a). A continuous and analytical modeling for kites as auxiliary propulsion devoted to merchant ships, including fuel saving estimations doi://doi.org/10.1016/j.renene.2015.08.036


MEPC. (2011). Global wind specification along the main global shipping routes to be applied in the EEDI calculation of wind propulsion systems. Retrieved from https://www.transportstyrelsen.se/contentassets/6c696ba2805c4302a019420184a056f0/62-inf34.pdf


Appendix

```python
import numpy as np
import cmath
import matplotlib.pyplot as plt

table = np.zeros((5, 3))
print(table)
table=np.array([[0,0,0],[25,0.9174,0.04897],[50,1.1615,0.09796],[75,1.1986,0.14692],[100,1.2038,0.1959]])
totalpower=np.zeros((5,5))
print(table)
print(totalpower)
for i in range(0,5):
    for j in range(0,5):
        wind = table[i,1]
        solar = table[i,2]
        totalpower[i,j]=wind+solar
        area = table[i,0]*table[j,0]
        if area<100:
            totalpower[i,j] = 0
optimumcombination=np.unravel_index(np.argmax(totalpower, axis=None),totalpower.shape)
print(totalpower)
print(optimumcombination)
print('Optimum area used for windpower is',table[optimumcombination[0],0],'
')
print('Optimum area used for solarpower is',table[optimumcombination[1],0],'
')
print('Total power for optimum combination is',totalpower[optimumcombination],'MW')
```

Appendix 1: Code of the optimisation of solar and wind power
Appendix 2: Code of Sail angle optimisation (applied to NACA 0012 aerofoil at ship speed of 13 knots)
Appendix 2: Code of Sail angle optimisation (applied to NACA 0012 aerofoil at ship speed of 13 knots) (continued)
Appendix 2: Code of Sail angle optimisation (applied to NACA 0012 aerofoil at ship speed of 13 knots) (continued)
Appendix 3: The Global wind probability matrix $W_{ij}$ (IMO, 2011)

<table>
<thead>
<tr>
<th>Wind angle</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
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Appendix 3: The Global wind probability matrix $W_{ij}$ (IMO, 2011) (continued)
Appendix 3: The Global wind probability matrix $W_{ij}$ (IMO, 2011) (continued)

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Appendix 3: The Global wind probability matrix $W_{ij}$ (IMO, 2011) (continued)
Appendix 4: Force thrust optimum of NACA 0012 at ship speed of 13 knots.
Appendix 4: Force thrust optimum of NACA 0012 at ship speed of 13 knots.

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Appendix 4: Force thrust optimum of NACA 0012 at ship speed of 13 knots.

(Continued)
Appendix 4: Force thrust optimum of NACA 0012 at ship speed of 13 knots.

(Continued)
Appendix 5: Multiplication of $W_{ij} \times F_{ij}$

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Appendix 5: Multiplication of $W_{ij} \times F_{ij}$ (continued)
Appendix 5: Multiplication of $W_{ij} \times F_{ij}$ (continued)
Appendix 5: Multiplication of $W_{ij} \times F_{ij}$ (continued)

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Appendix 6: EEDI calculation

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Required EEDI:

\[(1-X/100) \times \text{Reference line \_value} \times \text{X \_reduction factor} \times 0.1\]

Reference line:

\[a = 961.79\]
\[b = 38971\ \text{dwt}\]
\[c = -0.477\]

Reference line:

\[6.212931108\]

Required EEDI:

\[6.266718176\ \text{gCO2/mm}\]

Required EEDI:

\[4.210708569\ \text{gCO2/mm}\]

Attained EEDI:

\[5.874826597\ \text{gCO2/mm}\]