10-28-2023

Potential roles of vessel traffic services (VTS) in maritime decarbonization

Suleiman Mustapha Bunza

POTENTIAL ROLES OF VESSEL TRAFFIC SERVICES (VTS) IN MARITIME DECARBONIZATION

BUNZA SULEIMAN MUSTAPHA

A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the award of the degree of Master of Science in Maritime Affairs

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): 2**6th September 2023**

Supervised by: Dr. Alessandro Schönborn

Supervisor's affiliation: **....................**

Acknowledgements

First and foremost, I extend my profound gratitude to the Almighty Allah for His boundless mercies, guidance, and protection throughout the duration of this programme. I am immensely thankful to my office and sponsor, NIMASA, for providing me with the invaluable opportunity to study at this esteemed institution.

I owe a deep debt of gratitude to my dissertation supervisor and mentor, Professor Dr. Alessandro Schönborn. His professional insights, mentorship, and unwavering guidance were instrumental in the realization of this research work. I also extend my heartfelt thanks to the entire staff of the Maritime Energy Management Specialization and staff of WMU. Special mentions to Professor Dr. Aykut I. Ölçer and Professor Fabio Ballini, for the invaluable knowledge they have shared with me.

My parents, Dr. M.M. Bunza, Hajiya Hadiza, and Hajiya Madina Bunza, have been pillars of strength and wisdom in my life. Their endless prayers, support, love, and guidance have been my guiding light, and I am eternally grateful to them.

Words cannot express my gratitude to my beloved fiancée, Khadija Bello. Her unwavering support has been my anchor, and this achievement would not have been possible without her by my side. To my siblings, nieces, and nephews, Asma'u, Khalifa, Lamido, Zarah, Hafsa, Rayyan, Bilqees (Queen) and Amal Abdulmajid to mention but a few; your love and encouragement have been invaluable.

Lastly, to my cherished course mates and friends, your camaraderie and encouragement enriched this journey. I am deeply grateful for each one of you. May Allah bless and reward your kindness.

Abstract

Title of Dissertation: **Potential Roles of Vessel Traffic Services in Maritime Decarbonization**

Degree: Master of Science

The global shipping industry, responsible for a significant portion of the world's greenhouse gas emissions, is under pressure to adapt and align with international decarbonization targets. This dissertation investigates the potential roles of Vessel Traffic Services (VTS) in facilitating and accelerating this pivotal shift towards a more sustainable maritime industry. VTS, traditionally used for navigation, safety, and traffic coordination, possesses latent potential for enhancing energy efficiency and reducing emissions in shipping.

By optimizing vessel routing, minimizing idling and anchorage times, and facilitating real-time decision-making based on environmental conditions, VTS emerges as a crucial tool for emission reduction. This research explores potential options of howVTS can be instrumental in energy conservation and emission reductions.

However, the journey isn't without challenges. The dissertation highlights barriers such as technological availability and resistance to adoption that impede the full utilization of VTS for decarbonization purposes. Through a combination of case studies and data analysis, this study explores the transformative potential of VTS in reshaping the shipping industry's carbon footprint, emphasizing the urgent need for stakeholders to recognize and leverage its capabilities in the face of the global climate crisis.

KEYWORDS: VTS, GHG, Decarbonization, Carbon footprint

Table of Contents

List of Tables

List of Figures

List of Abbreviation

C4i	= Command, Control, Communications, Computers and Intelligence
DWT	= Deadweight Tonnage
EEZ	= Economic Exclusive Zone
ETA	= Estimated Time of Arrival
ETD	= Estimated Time of Delivery
GHG	= Greenhouse gasses
GoG	= Gulf of Guinea
GT	= Gross Tonnage
IMO	= International Maritime Organization
JiT	= Just in Time
MARPOL	= The International Convention for the Prevention of Pollution from Ships
NIMASA	= Nigeria Maritime Administration and Safety Agency
NOx	= Nitrous Oxides
PV	= Photovoltaic
SDG	= Sustainable Development Goals
SFC	= Specific Fuel Consumption
SFOC	= Specific Fuel Oil Consumption
SOLAS	= International Convention for the Safety of Life at Sea
SOx	= Sulfur oxides
UN	= United Nations
UNCTAD	= United Nations Conference on Trade and Developmen

VTS	= Vessel Traffic Services

Chapter One: Introduction

1.1 Background/Problem Statement

Climate change today is a result of primarily human activities like burning fossil fuels like coal, oil, and gas. The fossil fuels burned (coal, oil, and gas) generate greenhouse gases (GHG), which act as a shield around the earth’s atmosphere, thereby trapping more heat and increasing the temperature within (United Nations, 2022).

The shipping industry plays a crucial role in global trade and commerce. It provides a vital link in the supply chain, connecting producers with consumers and facilitating the flow of goods and services between countries, which account for more than 80% of global trade by volume.

However, the shipping industry contributes significantly to greenhouse gas emissions (Nast, 2013), accounting for approximately 3% of global GHG emissions (Zaman et al., 2017). Shipping emits large quantities of carbon dioxide (CO_2), which is the primary GHG emitted by the sector, as well as other pollutants such as nitrogen oxides (NO_x) and sulfur oxides (SO_x). These emissions have a significant impact on the environment and contribute to global climate change in the form of temperature imbalances and abrupt weather patterns.

If the current trend continues, it is expected that these emissions will increase, further exacerbating the problem. Therefore, there has been increased pressure in recent years to reduce the carbon footprint of the shipping industry, with efforts focused on improving energy efficiency and reducing emissions (Agarwala et al., 2021).

The International Maritime Organization (IMO) makes efforts aimed at promoting energy efficiency and sustainable practices in the shipping industry. IMO’s strategic direction (SD) 3, “Respond to Climate Change,” aligns with the United Nations Sustainable Development Goal (SDG) 13 of “Climate Action," which is a call for joint effort in every capacity towards a sustainable use of the planet and its resources. "MARPOL at 50: Our commitment goes on" is the theme of the 2023 World Maritime Day celebration (IMO, 2022) and also to commemorate the 50 years of advancement in shipping since the adoption of the International Convention for the Prevention of Pollution from Ships (MARPOL), according to the IMO Secretary-General (2022). This is being complemented by ongoing efforts in the maritime sector and previous World Maritime Days, particularly in 2020 and 2022, “Sustainable Shipping for a Sustainable Planet” and “New Technologies for Greener Shipping," respectively. All these are more focused on decarbonization with respect to digitization and technology.

By improving energy efficiency and reducing emissions, the shipping industry can play a key role in mitigating the negative impact on the environment, supporting the global effort to combat climate change, and promoting sustainable practices in the global economy.

Ships are increasingly equipped with sensors and algorithms that enable them to perceive their environment (Berman & Stern, 2012). Location-sensing data, which is derived from location-based signals like Wi-Fi positioning, is the foundation of the location services employed by the transportation sector (Shi et al., 2020). The transportation sector has adopted this for use in navigation and to identify nearby transportation services. With the help of global positioning systems and other location sensing technologies, location services are getting increasingly precise (Grejner-Brzezinska et al., 2016).

The potential roles VTS can play in reducing emissions and improving energy efficiency in shipping have received limited attention.

Vessel Traffic Services (VTS) is a shore-side maritime navigation safety system designed to improve the safety and efficiency of vessel traffic in specific maritime areas. The system is used to monitor, control, and regulate shipping traffic in busy waterways, ports, and harbors (IMO, n.d.). Vessel Traffic Services (VTS) are critical components of maritime operations, providing real-time monitoring and control of vessel movements to ensure safe and efficient navigation (Relling et al., 2021).

VTS consists of a combination of electronic and human elements, including radar and other surveillance systems, communication equipment, and trained VTS operators. The VTS operators use this equipment to monitor vessel movements, exchange information with ships, and provide vessel traffic information and guidance to ships navigating in the monitored area.

The main objectives of VTS are to enhance the safety of life and property at sea, prevent collisions and groundings, protect the marine environment, and improve the efficiency of vessel traffic. The system helps reduce the risk of maritime accidents by providing real-time information and guidance to ships, which enables them to make informed decisions and take appropriate action to avoid potential hazards.

The current research on the role of VTS in the decarbonization of shipping, however, has been limited and fragmented, with a lack of comprehensive studies that assess the full potential and impact of VTS on energy efficiency and emissions reduction. The purpose of this research is to address this knowledge gap and explore the potential of VTS to contribute to energy efficiency and decarbonization in the shipping industry.

1.2 Aim and Objectives

The aim of the research is to explore the potential of VTS to contribute to reducing the carbon footprint of shipping and improving energy efficiency in the shipping industry.

The objectives are proposed as follows:

1. To analyse the current practices and regulations in VTS with regards to energy efficiency and decarbonization.
2. To assess the impact of VTS on energy efficiency and emissions reduction in the shipping industry.
3. To explore the potential for new practices for VTS implementation that could contribute to energy efficiency and emissions reduction.
4. To make recommendations for how VTS can be further developed and implemented to support energy efficiency and decarbonization in the shipping industry.

1.3 Research Questions

The findings from this study will provide valuable insights into the potential of VTS to contribute to the decarbonization of shipping and will inform future initiatives aimed at improving energy efficiency and reducing emissions in the industry. In order to achieve the research's aim and objectives, the study will try to answer the following questions:

1. How can VTS improve energy efficiency and reduce emissions in the maritime industry?
2. What are the best practices and initiatives in place for the use of VTS to achieve energy efficiency and decarbonization?
3. What potential new practices for energy efficiency could be implemented using VTS?
4. What are the challenges and barriers to the effective implementation of VTS in the shipping industry for the purpose of energy efficiency and decarbonization?

1.4 Expected Result

Findings from this research are expected to provide insights into the implementation and impact of VTS on energy efficiency and emissions reduction in maritime operations. The research may also identify best practices and challenges associated with the implementation of VTS and inform decision-making by stakeholders. The results of the research could contribute to the advancement of knowledge and understanding of the role of VTS in decarbonization in the shipping industry, which could inform future research and practices in the field.

1.5 Scope and Limitations of The Research

The scope of the research will be focused on a specific aspect of VTS and its impact on energy efficiency and emissions reduction. It may not be able to draw broader conclusions or implications for the shipping industry as a whole.

Some of the limitations may include:

1. Data limitations: The availability and quality of data on VTS implementation, energy efficiency, and emissions reduction in the shipping industry may be limited, which could impact the accuracy and representation of the results.
2. Methodological limitations: The methodology used to conduct the research, such as the choice of data sources, research design, and analysis methods, may be subject to limitations that could impact the validity and reliability of the results.
3. Contextual limitations: The context in which the research is conducted, including the specific type of VTS, may impact the applicability and generalization of the results to other contexts.
4. Time limitations: The time frame for the research may be limited, which could impact the ability to observe long-term trends and outcomes related to VTS implementation, energy efficiency, and emissions reduction in the shipping industry.

Chapter Two: Literature Review

2.1 Introduction

The maritime industry is responsible for approximately 2.8% of all global GHG emissions. This is due to its rapid expansion, dependency on carbon-intensive fuels, and sheer size of the business (UNCTAD, 2022). As a result, the industry has been under growing pressure to reduce its carbon footprint. One of the potential players in the effort to decarbonize is the Vessel Traffic Service (VTS), which plays a critical role in coordinating and directing marine traffic. This chapter explores current research on the functions of VTS in energy efficiency and decarbonization, emphasizing its potential to boost efficiency, reduce emissions, and encourage sustainable behaviors.

2.2 Vessel Traffic Service: An Overview

VTS is defined according to IMO Resolution A.857 (20) as *"a service implemented by a competent authority, designed to improve the safety and efficiency of vessel traffic and protect the environment. The service should have the capability to interact with traffic and to respond to traffic situations developing in the VTS area."* The realities of modern shipping, such as bigger, difficult-to-maneuver ships in traffic with dangerous cargo and the potential for environmental damage, demanded the adoption of advanced risk mitigation and the establishment of VTS (IHMA, n.d.), which serves to provide reports on navigational and meteorological information for ships crossing waterways (Nofandi et al., 2022)

VTS, as maritime traffic monitoring systems developed for harbors, ports, and coastal authorities with the goals of enhancing navigational safety and effectiveness, environmental protection, and the safety of life at sea (IMO, 2019), and strategic elements for navigation in accordance with regulation V/12 of the International Convention on Safety of Life at Sea (SOLAS), 1974 (IMO, 1997), provides information services, navigational assistance, and traffic organization services, which can be leveraged to reduce carbon emissions.

2.3 Development of VTS

VTS is not a new concept, as different strategies have been utilized in the past to oversee sea activity in specific harbour approaches. Strategies such as flares and smoke signals were lit from the shore to the approaching ships; an advanced system of flags and semaphore was invented to help in ship-shore communications. In bad weather or with restricted visibility, this mode of communication between the ship and shore proved ineffective, and further developments were required to improve the management and monitoring of marine traffic, which necessitated the use of radios and radar systems (Alqurashi et al., 2022) for ship-shore communications. According to Nuutinen et al. (2007), the earliest vessel traffic surveillance systems were already in place by the middle of the 20th century; however, it wasn't until the 1980s and 1990s, when the available technology was advanced enough, that VTS operations completely transformed into what they are today.

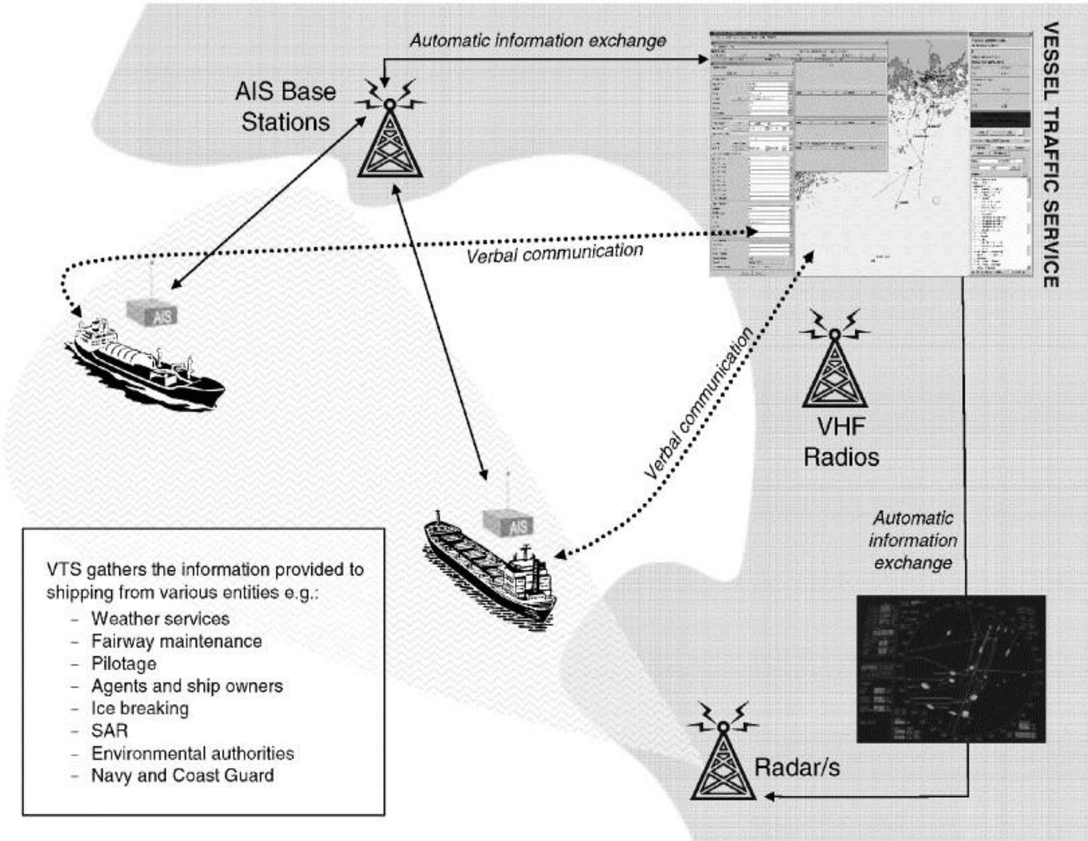

Figure 1: Means of general information exchange in VTS operations (Nuutinen et al., 2007)

2.3.1 Primary Functions of VTS:

The VTS, which was initiated for the safety of navigation, was later expanded to be used for commercial and other purposes. According to the IMO, the VTS will enhance the following:

1. Traffic Organization: VTS systems help manage vessel traffic by providing information on vessel movements, traffic density, and potential conflicts. This enables vessels to navigate safely and efficiently in congested waterways (Sheltermar, n.d.).
2. Navigational Assistance: VTS operators provide navigational advice to vessels, including information on weather conditions, water levels, and other factors that may affect navigation. This assistance helps vessels make informed decisions and avoid potential hazards (U.S. Coast Guard Navigation Center, n.d.).
3. Incident Management: In cases of emergencies or accidents, VTS systems play a crucial role in coordinating response efforts and providing timely information to relevant authorities (Marine Insight, n.d.).

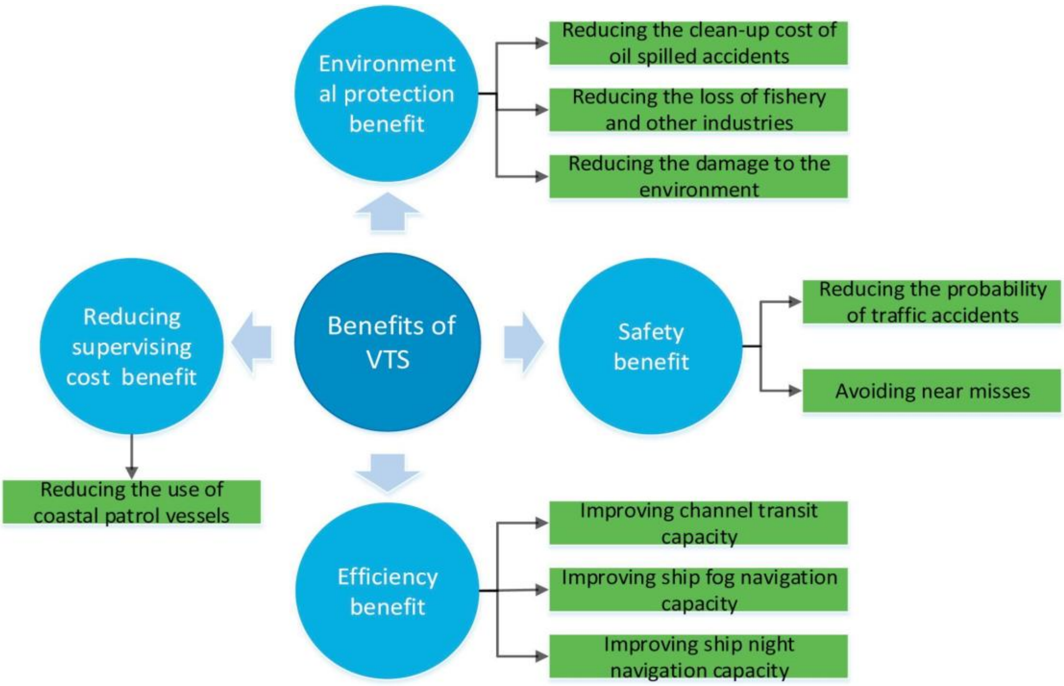

Figure 2: The Framework of Benefits of VTS (Mou et al., 2015)

2.4 VTS and Decarbonization: Theoretical Perspectives and Empirical Evidence

While the primary focus of VTS has traditionally been on enhancing maritime safety, VTS has often been studied with either a focus on safety, information needs, or communication. There is only a limited amount of research focusing on the VTS's energy-saving potential.

Optimizing fuel consumption to decrease costs associated with bunkering, energy use, and the consequences of CO_2, VTS could implore energy efficiency management strategies that consider both safety and economic factors to have more practical significance for enhancing the ship's energy efficiency (Lashgari et al., 2021).

The use of VTS for energy efficiency is a newer area of interest, as the maritime sector has begun looking into measures to increase energy efficiency and lessen its environmental impact as global concerns about climate change and greenhouse gas emissions have grown. As a result, the research on VTS pertaining to energy efficiency is less extensive.

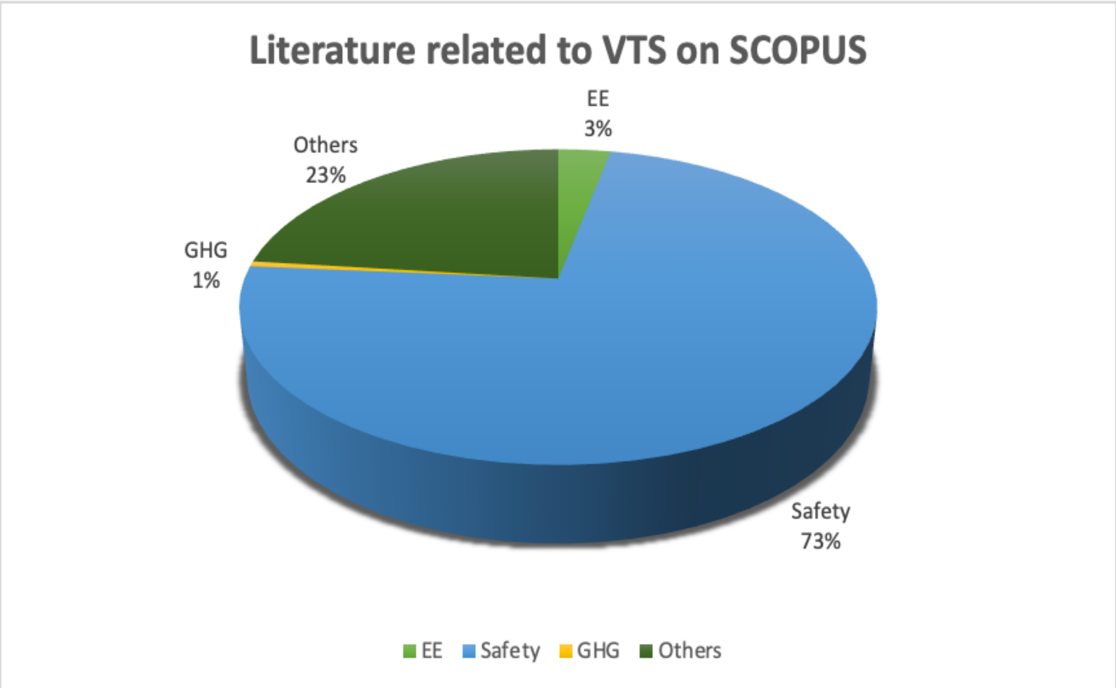

Figure 3: VTS literature on Scopus (Source: Researcher)

The desire to explore how VTS might improve energy efficiency, however, is growing. Studies have started to look into the potential of VTS in optimizing vessel routes, speeds, and traffic control to cut down on fuel consumption and emissions. For instance, Psaraftis and Kontovas (2010) argued that VTS can contribute to decarbonization by optimizing vessel speed and routing, thereby reducing fuel consumption and emissions. Similarly, Meng et al. (2016) suggest that VTS can facilitate just-in-time operations, which can minimize idling time and reduce emissions.

Empirical studies provide further evidence of the role of VTS in decarbonization. A study by the Port of Rotterdam (2022) suggests that while optimizing speed and routes, containerships could save their fuel consumption by up to 14.16% per voyage, and another study in the Journal of Navigation (2009) shows that tankers' fuel consumption can be reduced by up to 20% using VTS speed advisory services, which offer suggested speed restrictions and modifications based on factors like traffic, weather, and port conditions. Additionally, by providing real-time data on fuel supply, bunkering facilities, and other pertinent elements, VTS can promote the use of alternative fuels and energy-efficient technology.

Another study by Mou et al. (2015) evaluated the benefits of VTS and their expansion in China and their corresponding financial implications between the years 2010 and 2012. The study revealed that up to 19 million yuan was saved per year in terms of environmental benefits and 6.5 million by reducing the use of patrol vessels (which included fuel and overall cost of supervision).

Category of benefits	**Safety**	**Efficiency**	**Environmental**	**Supervision cost**
Sub benefit	Reducing accidents	Improving navigational capacity	Reducing oil spill accident	Reducing the use of patrol vessels
Benefits (10,000 yuan/year)	1761.160	1597.694	1895.091	649.965

Total	**59,039,030 yuan/year**

Table 1: Average benefit of the expansion of VTS per year from 2010 to 2012 (Mou et al., 2015)

2.5 VTS and Energy Efficiency

While being essential for monitoring traffic, VTS may play a role in minimizing fuel consumption and enhancing energy efficiency in the maritime sector through effective communication and information sharing between VTS centers, vessel operators, port authorities, and other relevant actors in potential decarbonization strategies. Speed optimization, route optimization, and weather routing are some of the promising ways VTS can play a significant role in decarbonizing the maritime sector.

2.5.1 Speed Optimization

VTS may provide guidance to vessels on the best speed for their route, taking into account factors like fuel consumption, arrival times, and environmental conditions. Optimizing fuel consumption has caught the maritime industry's attention, which has decreased costs associated with bunkering, energy use, and the impact of CO2 (Lashgari et al., 2021).

According to a study by the European Maritime Safety Agency (n.d.), VTS-guided speed reduction measures can increase ship fuel economy by up to 15% on average. These procedures include advising optimal speeds based on the present situation. When VTS centres have access to real-time data and the capacity for predictive analysis, these techniques are most successful. A study by Du et al. (2019) aimed to minimize fuel consumption by optimizing ship sailing speed. Wang et al. (2015) determined the linear regression link between speed and fuel consumption by linear regression and established the fuel consumption function, which is directly connected to shipping speed.

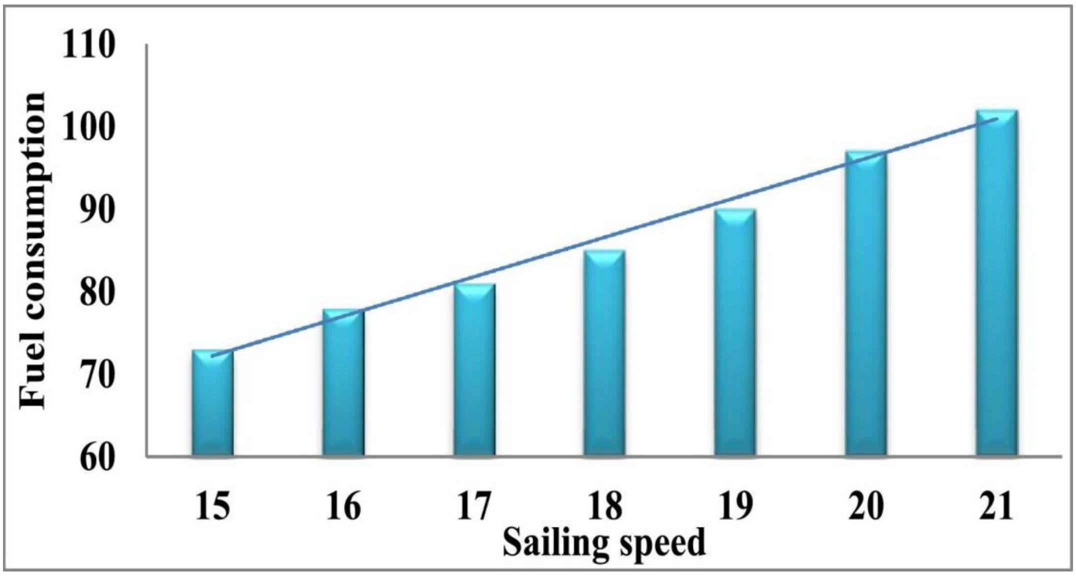

Figure 4: Fuel consumption at different speeds (Nautical miles) (Zhen L. et al., 2018; Lashgari et al., 2021).

Fuel consumption, which is a cubic function of ship speed (Lindstada & Eskeland, 2015; Ronen, 2011), according to Wartsila (2009), is significantly reduced by reducing ship speed

As shown in Table 2-1, speed reduction can result in energy savings of up to 23%, and decreasing the ship's speed by only 1 kn could save more than 5% of the energy consumption. Synchronizing vessel arrival times with port services saves ships from having to wait at anchor or slow down by sailing at optimum speed to meet the target time.

Speed reduction (kn)	**Energy savings (%)**
-0.5	7
-1	11
-2	17
-3	23

Table 2: Reduction of consumption according to the decrease in speed (Wartsila, 2009)

2.5.2 Weather Routing and Route Optimization

VTS can provide vessels with information on the most fuel-efficient routes, taking into account some external forces such as tidal currents, waves, and wind. These forces strongly influence the energy efficiency of ships and, if effectively managed, can reduce emissions and save energy (Kim & Lee, 2018).

Weather routing According to Kaster (1965), is determining and following routes that avoid unfavorable weather conditions while taking advantage of favorable conditions in the safest and most economical manner for the specific ship and crossing as provided by a shore office (VTS)

The old art of weather routing was practiced as far back as Benjamin Franklin, when, as Postmaster General, he advised ships carrying the U.S. mail to sail to Europe on a northern route but to return on a far southern route in what would later be known as the northeast trade wind zone (Bache, 1936).

A study by Tadros et al. (2022) estimated ship fuel consumption for different weather conditions along the ship route using different speed reduction strategies at 70% and 50% of the rated engine power and achieved 2.6% and 1.7% reductions in fuel consumption when compared to 90% rated engine power, respectively.

According to Armstrong and Banks (2015), weather-based route planning can save up to 3% fuel consumption by taking advantage of weather conditions to decrease total ship resistance, taking routes with minimum fuel consumption and the safety of the ship into account, and keeping to a competitive time of arrival (Lin et al., 2013).

By availing itself of data such as ocean currents and weather, VTS may provide information on the most fuel-efficient routes for ships and the impact of different routing strategies on fuel consumption and emissions.

VTS may offer useful data on vessel movements, weather patterns, and other parameters that affect energy consumption and emissions. Ships could achieve more energy-efficient navigation by integrating sea state and wind state (Roh, 2013) into their voyage planning.

2.6 VTS and Sustainable Practices: Challenges and Opportunities

By providing real-time information on vessel movements, VTS can enable more efficient use of resources and reduce environmental impact, which can promote sustainable practices in the maritime industry. It can also be used to support other green shipping practices, such as cold ironing (Notteboom & Vernimmen, 2009) and maritime single window, which can further reduce GHG emissions.

Technological constraints, regulatory compliance, and resistance from industry stakeholders are some of the barriers facing the decarbonization of the maritime industry (Psaraftis and Kontovas, 2010) and are also obstacles to the role of VTS in decarbonization, despite its promise. However, these difficulties also provide chances for innovation and development. For instance, technological advancements can improve the capabilities of VTS, while improvements in regulations may increase the incentives for decarbonization.

The available literature indicates that VTS is crucial to maritime decarbonization. VTS may aid the industry's efforts to lower its carbon footprint by increasing efficiency, lowering emissions, and encouraging sustainable practices. More study is necessary to fully comprehend and overcome the challenges faced.

Chapter Three: Research Methodology

3.1 Introduction

This research investigates the role of Vessel Traffic Services (VTS) in the maritime industry's decarbonization initiatives. VTS, akin to air traffic control in the aviation sector, provides critical services in navigational safety, efficient vessel movement, and marine environment protection. (Balduzzi et al., 2014). This technology is critical to improving the safety and efficiency of navigation, particularly in crowded marine environments.

The main purpose of this study is to learn ways VTS may help reduce greenhouse gas emissions and promote sustainable shipping practices in the context of the marine industry's decarbonization initiatives. This chapter describes the study methodology, which includes the research design, data collection, and analysis techniques, and addresses ethical concerns.

The research methodology will utilize a mixed-methods design. This will consist of both qualitative and quantitative research methods. Distinct methodologies, such as integrative literature reviews, were used to examine data obtained from diverse literatures in order to answer the research questions and meet the study objectives.

3.2 Research Outline

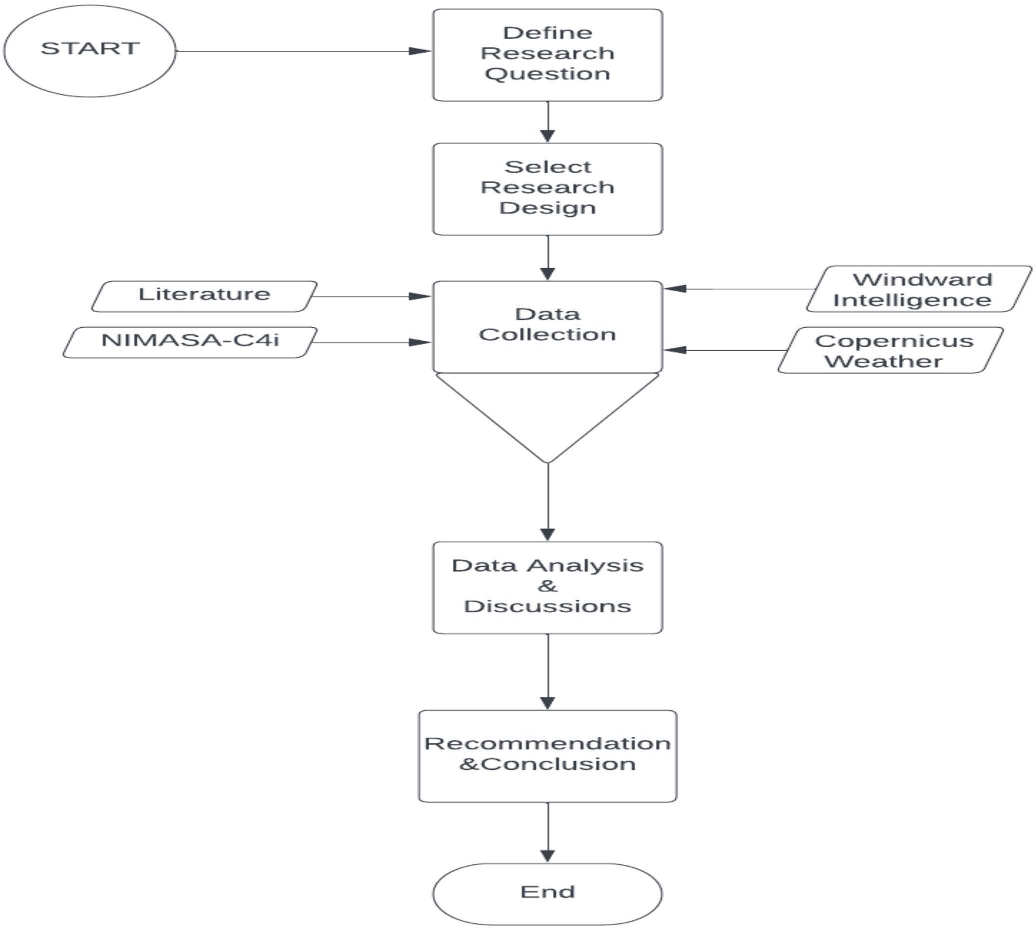

Figure 5: Research outline (Source: Researcher)

3.3 Research strategy

The research strategy outlines a systematic plan for the study, detailing the approaches to gathering, organizing, and analyzing data. Given the multi-faceted nature of this dissertation, a blend of strategies is employed to ensure a holistic and detailed examination of the topic. This strategy ensured the research was not only academically rigorous but also practical and applicable for industry stakeholders.

3.3.1 Problem Identification and Formulation

1. The initial phase involved clearly defining the research problem. With a focus on VTS, the study aimed to explore the mechanisms by which VTS could aid in reducing greenhouse gas emissions in the maritime sector.

2. Hypotheses were generated based on a preliminary literature review.

3.3.2 Mixed-Method Approach

1. Given the research design, the study embraced a mixed-methods approach. This strategy allowed for a more comprehensive understanding of the problem by integrating both quantitative and qualitative insights.
2. The quantitative aspect focused on empirical data collection, statistical analysis, and the potential for predicting fuel savings based on weather patterns.
3. The qualitative aspect prioritized understanding the broader implications of VTS in decarbonization, as garnered from literature reviews, case studies, and expert opinions.

3.3.3 Integrative Literature Review

1. To provide a foundational understanding of VTS role in the maritime industry and the industry's decarbonization initiatives, an integrative literature review was conducted.
2. The review aimed to highlight gaps in existing literature and outline areas where this study could contribute.

3.3.4 Data Analytics and Modelling

1. With the collection of data from various sources, such as NIMASA-C4i and Windward Intelligence, robust data analytics techniques were employed. This included regression analyses, pattern recognition, and predictive modelling using Python to understand the relationships between variables, especially concerning weather data and potential fuel savings.
2. Microsoft Excel played a supplementary role in presenting visual trends and ensuring the quantitative aspects were clearly represented.

3.4 Ethical Considerations

Ethical considerations permeated every facet of this research. The commitment to these principles ensures that the research not only contributes valuable insights to the field but does so in a manner that upholds the highest standards of academic integrity and social responsibility. careful consideration was given to a range of ethical issues

1. Data Privacy: The data sources utilized in this study, especially those related to ship movements, could potentially have privacy implications. It was paramount to ensure that no sensitive or private information, which could identify individual ships or crew members, was disclosed. Data obtained from systems like NIMASA-C4i and Windward Intelligence were treated with the highest confidentiality, ensuring that they were stored securely and only used for the purpose of this research.
2. Data Integrity: It was crucial to ensure that data was not manipulated or misrepresented to fit any preconceived narratives or biases. The research aimed to provide an unbiased view of the role of VTS in marine decarbonization, and as such, data was presented and analysed as objectively as possible.
3. Transparency: The research process, from data collection to analysis, was documented meticulously to ensure that the study could be replicated or reviewed by other researchers in the future. This transparency serves to bolster the credibility of the findings and demonstrates a commitment to genuine scholarly inquiry.
4. Stakeholder Respect: Recognizing that the maritime industry is diverse with various stakeholders, efforts were made to ensure that no group was unduly criticized or misrepresented. Respectful and objective language was used throughout the study.
5. Environmental and Social Implications: Given the focus on decarbonization, the broader environmental and social implications of the research findings were also considered. This study is rooted in the larger goal of promoting

sustainability, and care was taken to ensure recommendations and findings aligned with responsible and sustainable shipping practices.

3.5 Data Collection

Given the vast number of ships that traverse the oceans daily, it is impractical to examine the data of every ship for the purpose of this research. Thus, ships were selected at random and within Nigeria EEZ during the period of the study. Sample ship's data collected consist of:

Ship's Static Information: This is the data about a ship that remains constant over time and does not change frequently during its operations. This category includes essential details that uniquely identify the vessel and are used for administrative and regulatory purposes. The static information obtained include

1. Ship identity: Name and IMO number
2. Ship type
3. Gross tonnage
4. Engine details: Engine manufacturer, Engine power, maximum speed
5. Fuel Consumption: Data on the ship's fuel consumption rates for different engine operating conditions and speeds

Ship's Dynamic Information: This is real-time data about the ship's current status and activities. It includes information that can change frequently as the vessel moves and operates. This includes

1. Position: The latitude and longitude coordinates of the ship's current location.
2. Speed: The ship's sailing speed
3. Course: The direction in which the ship is heading.
4. Heading: The compass direction in which the ship's bow is pointing.
5. Navigational Status: Information about the ship's current status, such as "underway," "at anchor," or "moored."

Voyage Information: This is the data related to a ship's planned journey, passage, and activities during a specific voyage. It is dynamic in nature but specific to the voyage being undertaken, such as:

- Estimated Time of Arrival (ETA): The expected time when the vessel will arrive at its next destination or port.
- Estimated Time of Departure (ETD): The planned time when the vessel will depart from its current location or port.
- Waypoints: The planned route of the voyage, including specific locations or points the ship will pass through.

Weather Data: Historical weather data for the area of interest (where the vessel operates), including wind speed and direction, wave height and period, current speed and direction, and any other relevant meteorological and oceanographic parameters, is collected and analyzed to identify recurring patterns or trends.

3.6 Data Sources and Validity

This study will use weather data to estimate the potential speed reduction and calculate the amount of fuel that could be saved by optimizing vessel performance based on weather and sea conditions. By considering factors such as wind speed and direction, wave height and period, current speed and direction, and other relevant meteorological and oceanographic data, we attempt to understand ways to improve energy efficiency.

To calculate the potential fuel savings, we use historical weather data for the specific route or area of interest.

3.6.1 Data Sources

The research primarily relied on data from three major sources:

1. **NIMASA-C4i**: An integrated system employed by the Nigerian Maritime Administration and Safety Agency (NIMASA) for maritime domain awareness within Nigerian waters and Gulf of Guinea (GoG)
2. **Copernicus Weather:** A component of the European Union's Copernicus program that offers extensive information on climate and weather patterns
3. **Windward Intelligence**: A maritime intelligence system that leverages advanced technologies for data-driven insights in the maritime sector.

3.6.2 Validity and reliability of Data Sources

Ensuring data validity and reliability is fundamental to the research's credibility. The chosen data sources have proven track records and are recognized by relevant stakeholders in the maritime and climate sectors. The systematic and methodological data gathering and validation processes they employ guarantee the research's foundational strength and reliability.

1. **NIMASA-C4i**: The system's credibility stems from its official utilization by NIMASA, Nigeria's maritime regulator. It is constructed to adhere to international regulations and standards, ensuring the accuracy and relevance of its data. Moreover, NIMASA-C4i's functionality, which integrates various elements like Command, Control, Communication, Computers, and Intelligence, affirms its comprehensive data gathering and analysis capability.
2. **Copernicus Weather (C3S):** As a part of the European Union's Copernicus program, C3S boasts rigorous data collection and validation processes. The service collects its data from multiple trustworthy sources, such as satellite measurements and reputable terrestrial weather stations. The transparent approach it adopts, underscored by its open data policy, reaffirms its dedication to delivering current and precise climate-related insights.
3. **Windward Intelligence**: This platform's data integrity is vouched for by its use of advanced technologies, AI-driven insights, and wide-ranging services across risk assessment, compliance monitoring, and more. The sheer volume of maritime data it processes, such as vessel movements and cargo information, underscores its comprehensive approach to data reliability.

3.7 Data Analysis Tool

3.7.1 Microsoft Excel

Microsoft Excel, due to its versatility, is used for fuel consumption data analysis. The collected voyage and technical data were entered, including date, time, distance, fuel consumed, engine power, and vessel speed. Fuel efficiency is calculated by dividing the fuel consumed by distance or engine power. Visualizations through charts and graphs help to understand consumption trends. Excel's flexibility and various functions make it a useful tool for conducting the fuel consumption analysis for the voyage because of its small volume.

For weather data, which is relatively large, a specialized programming language was used in order to maintain data integrity.

3.7.2 Python

Python, a general-purpose data analysis programming language, is used to analyze weather data, calculate corresponding fuel savings, and perform statistical analysis. The choice for Python is because of its flexibility to be customized to analyze and visualize the data as required.

It helps to understand the relationship between weather conditions and fuel consumption and the opportunities for fuel savings. Python's flexibility and various libraries make it a powerful tool for handling large datasets and conducting sophisticated analyses. The Python libraries used are:

1. **netCDF4:** It is used to load the wind data and to convert time values from numeric form to datetime format.
2. **Numpy (np):** Used to perform mathematical operations like calculating the index of the ship's location, wind speed, fuel consumption, and savings.
3. **matplotlib.pyplot (plt):** Used to create a visual representation of the wind speed and sail power against time

3.8 Limitations

Every research endeavour inevitably faces certain limitations, and this study is no exception. Recognizing and addressing these limitations is essential to presenting a balanced perspective and ensuring that the results are interpreted in the correct context.

1. **Data Sources**: While the study relies heavily on secondary sources such as literature reviews, reports, seminars, and workshops, the authenticity and contemporaneity of these sources might pose challenges. Secondary sources are subject to interpretation bias and may not always capture the most recent advancements or shifts in the maritime sector or VTS technology.

2. **Weather Data Accuracy**: The weather data, which plays a pivotal role in analysing potential fuel savings, might not always be 100% accurate. Predictive meteorological models have inherent inaccuracies, and historical data might not necessarily be indicative of future patterns.
3. **Tool Limitations:** While Microsoft Excel and Python are powerful data analysis tools, they come with their own set of limitations. Excel's analysis is heavily reliant on the correct formulation and data input. Python, on the other hand, is as efficient as the libraries and algorithms chosen. Any oversights or errors in coding can lead to misinterpretations.
4. **Generalization:** The sample ship's data collected might not be representative of all vessels, particularly as ships can vary widely in terms of size, design, function, and age. This could affect the generalizability of the study's findings to the broader maritime industry.
5. **Temporal Constraints:** Given the time-bound nature of this research, it might not have been possible to capture a comprehensive picture of the maritime sector's decarbonization efforts and the evolving role of VTS in this transition.
6. **Subjectivity in Qualitative Analysis:** Qualitative research methods, like case studies and literature reviews, introduce an element of subjectivity. Interpretations may vary, and there's a risk of researcher bias influencing the results.

3.8.1 Addressing the Limitations:

- **Triangulation**: To address potential biases and discrepancies in secondary data, the study has attempted to triangulate information by referencing multiple sources.
- **Regular Tool Updates:** Ensuring that the Python libraries used are up-to-date and cross-verifying results between Excel and Python to minimize analytical errors.

- **Transparency:** By maintaining transparency in the research process and openly discussing these limitations, the study aims to foster a sense of trustworthiness and credibility.

Chapter Four: Analysis and Discussions

4.1 Introduction

This analysis focuses on the potential of VTS to promote fuel-efficient maritime operations, leading to decarbonization. Using a detailed scenario, this chapter demonstrates how VTS can contribute to reducing the carbon footprint of vessels through optimized speed suggestions and route advisories. Through mathematical models and empirical evidence, the study will explore how VTS, coupled with advanced maritime technologies, can significantly alter the energy consumption patterns of two (2) vessels, using two specific voyage scenarios to provide context.

4.2 Scenario 1: A Study in Speed and Fuel Consumption Optimization

A detailed scenario for the fuel consumption of a vessel during its voyage between Lagos and Calabar ports from July 2 to 5, 2023 Fuel consumption for varying speeds and powers, and a graph to visualize the relationship.

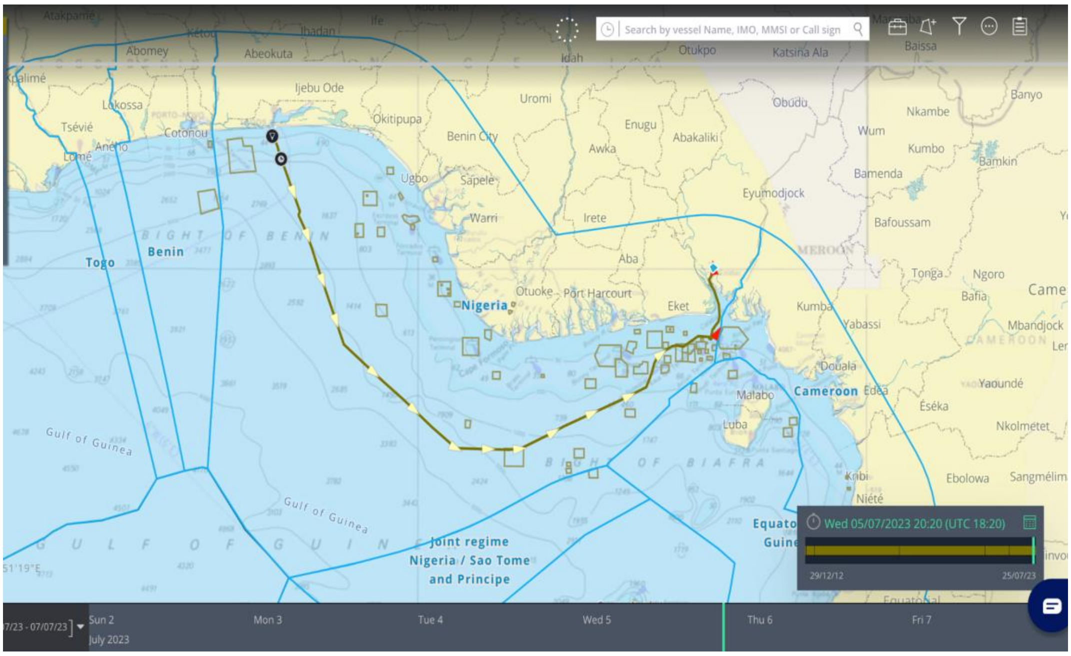

Figure 6: Vessel's voyage from Lagos to Calabar (Source: Nimasa C4i/Windward)

Vessel and Engine Details

Vessel Details

Vessel type	Oil product tanker
Length	180 meters
Height	44.12 meters
Maximum draft	12.8 meters
Deadweight tonnage (DWT)	42,622 tons
Gross tonnage (GT)	28,231 tons

Engine Details	
Engine manufacturer	HITACHI
Number of Cylinders	6
Engine Power	kW
Maximum speed	16.4 knots
Service speed	16 knots
Specific fuel consumption (SFC)	0.190 kg/kWh

Voyage Specifics

Voyage Details	
Port of Origin	Lagos, Nigeria
Destination	Calabar, Nigeria
Time of departure	July 2, 2023. 19:00

Time of arrival	July 5, 2023. 20:00
Voyage duration	74 hours
Voyage distance	495.32 NM (917.01 km)

4.2.1 Power-Speed Relationship

The engine power (P) is directly proportional to the cube of the ship's speed (V), with a constant factor C. This means that the power used by the engine has a cubic relationship with speed. As the speed increases, the power required or generated increases significantly faster than the speed itself. This relationship is essential for understanding and optimizing energy consumption, and predicting the power demands of different speeds.

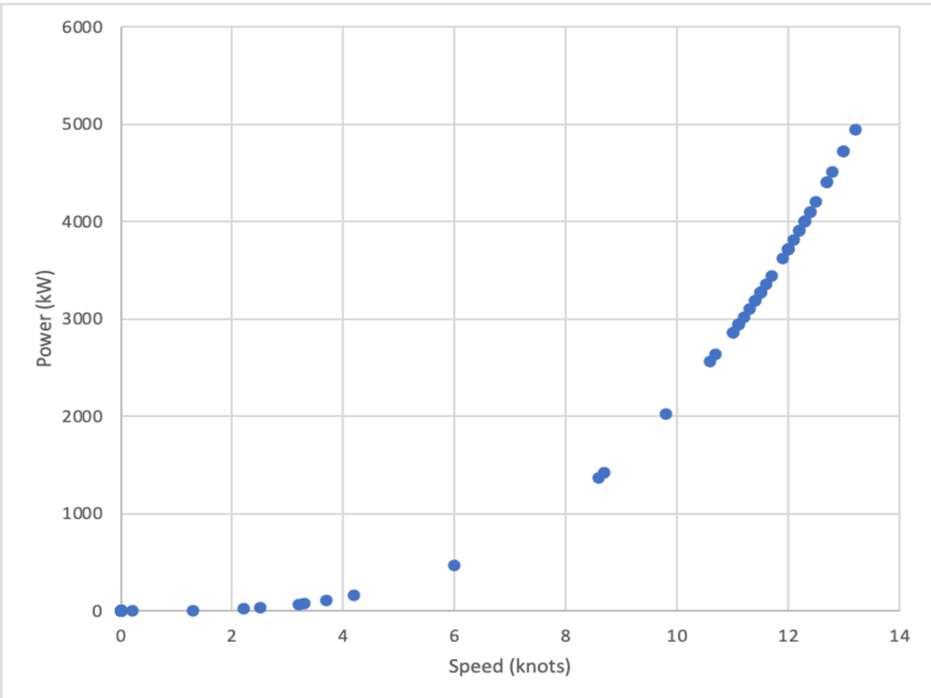

Figure 7: Power-speed relationship: Cubic relationship between power and speed (Source: Researcher)

4.2.2 Mathematical analysis for fuel consumption

Fuel consumption depends on engine power, specific fuel consumption, and time. For a given speed, fuel consumption (kg) is calculated as:

$$Fuel\ Consumption = Engine\ Power \times SFC \times Time$$

Derived from the vessel and voyage data:

- Maximum engine power (P): 9480 kW
- Maximum speed (V): 16.4 knots
- Specific fuel consumption (SFC): 0.19 kg/kWh
- Distance: 495.32 NM from Lagos to Calabar Ports in Nigeria.
- Total time of voyage: 74 hours

We can calculate the fuel consumption for the journey at different speeds.

$$Power = V^3 \times C$$

Given the engine power of 9,480 kW at maximum vessel speed of 16.4 knots,

$$Constant\ C = Power / V^3$$

$$C = 9480/16.4^3$$

$$C = 2.15$$

Engine Power = 9,480 kW

Maximum speed = 16.4 kts

Specific Fuel Consumption (SFC) = 190 g/kWh (0.19 kg/kWh)

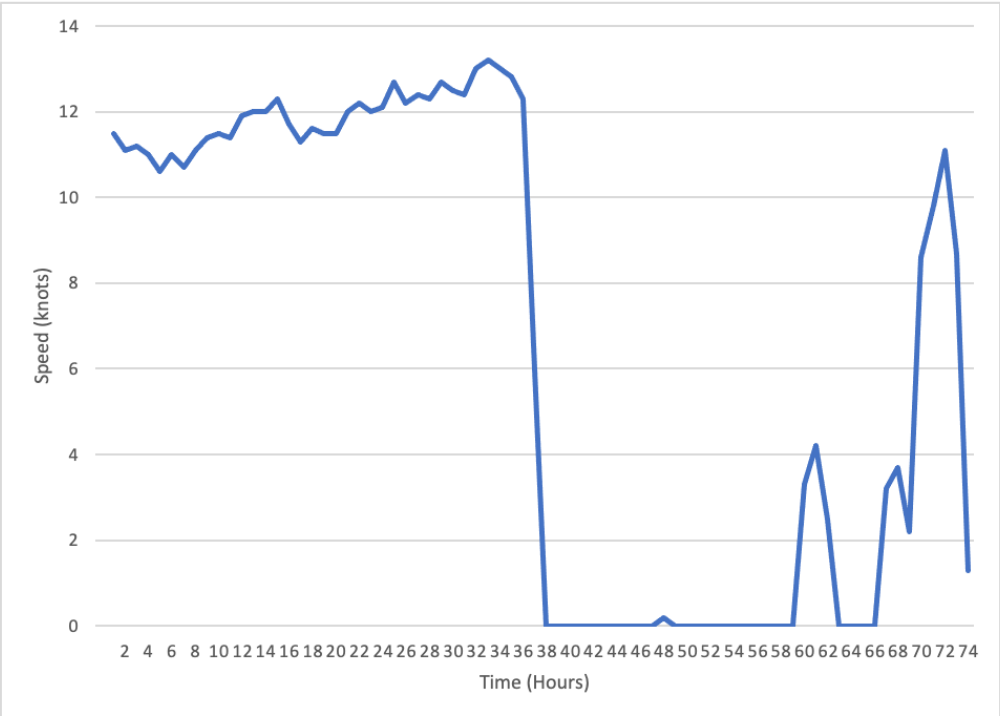

Figure 8: Vessel's speed during the voyage (Source: Researcher)

The chart above shows the speed of the vessel at each hour of the voyage.

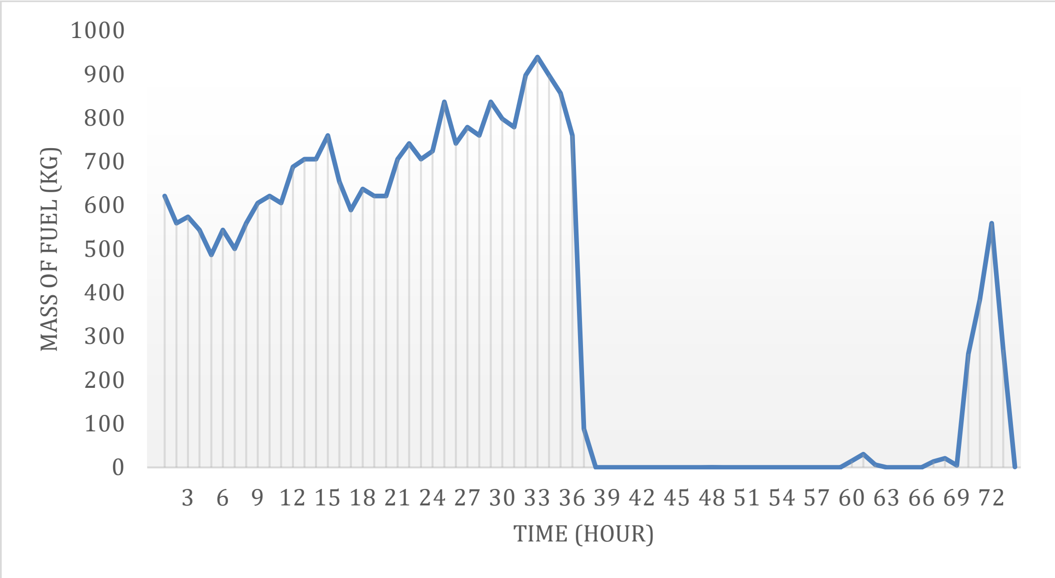

Figure 9:Hourly fuel consumption (Source: Researcher)

Based on available data, the study estimated the mass of fuel consumed hourly at the sailing speeds per hour and the total mass of fuel consumed for the entire voyage.

The amount of fuel consumed by the vessel is a product of engine power, specific fuel consumption, and the given time.

The fuel consumption at any given speed was calculated using the formula:

Fuel Consumption (kg) = Engine Power (kW) × Specific Fuel Consumption (kg/kWh) × Time (h)

From the data, the total fuel consumption for the 3-day journey from Lagos to Calabar is estimated at *26,603.39 kg* based on the calculations from hourly consumptions at different speeds throughout the voyage.

The analysis shows how the fuel consumption changes with different speeds, following a cubic relationship due to the power-speed relationship, which is a trade-off between speed and fuel efficiency, and it can be used for optimizing the vessel's operation to minimize fuel consumption.

4.2.2 Speed Optimization

To determine the minimum speed required to meet the ETA of July 5, with the distance of *495.32 NM or 917.01* km and the time frame of *72 hours*, the vessel can sail at *6.9 knots*, or approximately *7 knots.*

*Mass of fuel consumed = SFOC * Power * Time*

*Mass of fuel consumed for the 3-day journey = 0.19 kg/kwh * 737.175534 kW * 72 hours*

Mass of fuel consumed for 3 days at 7 kts = 10,084.5613 kg

The study optimized speed for the vessel to arrive at the 74th hour, just when the destination port is ready to receive it. The vessel is expected to cover a total distance of up to 495.32 NM in the given time. The study considers the cubic relationship between speed and power, fuel constraints, and other factors that may affect speed, such as currents, wind, etc. However, assuming a simple model without those external factors, we perform a basic optimization based on speed alone, with two basic constraints: Time and Distance

- Time: 74 hours.
- Distance: 495.32 NM.

To determine the speed profile that satisfies the constraints and possibly minimizes fuel consumption, we calculate the constant speed that would get the vessel to the destination exactly in time. Assuming the vessel sails at a uniform speed.

Constant Speed=Total Distance/Total Time

Speed =495.32/74 = 6.7 knots

Given that the power is proportional to the cube of the speed;

The power demand at a speed of 6.7 knots is *646.6 kW* and the mass of fuel that will be burned is ***9,088.4 kg***

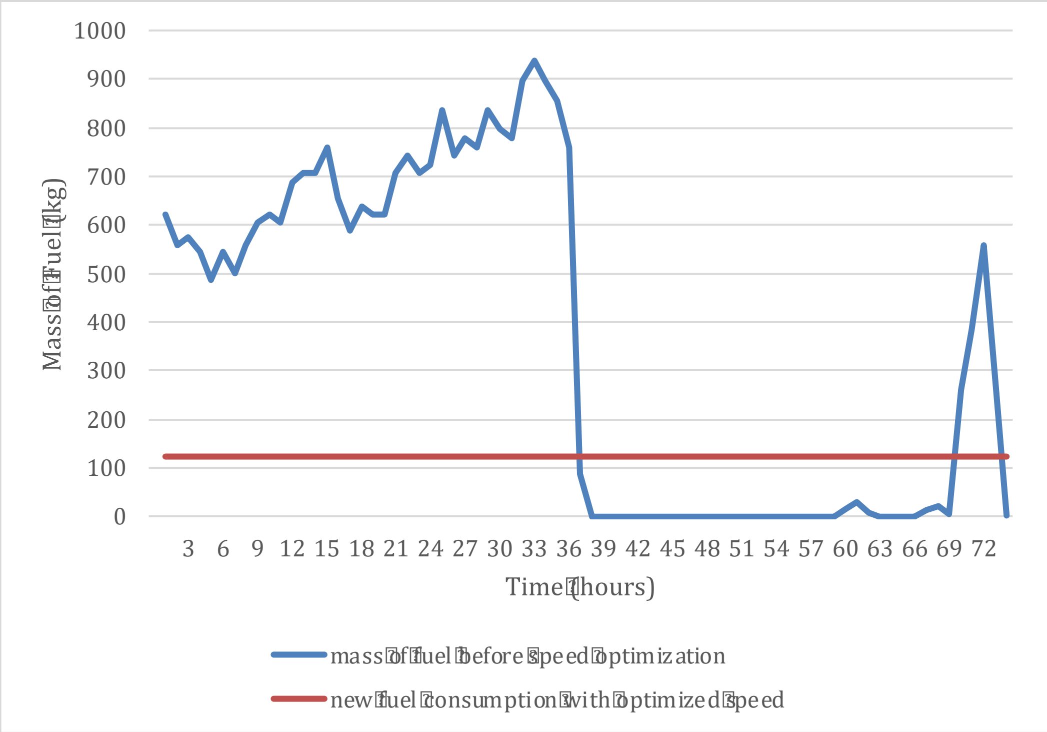

Figure 10: Fuel consumption before and after speed optimization (Source: Researcher)

Estimated fuel consumed without speed optimization: *26,603.39 kg*

By reducing speed in an attempt to minimize fuel consumption, this vessel can sail at a constant speed of 6.7 knots to arrive precisely at the 74th hour. Doing so reduces the power demand to 646.6 kW, leading to a fuel consumption of 9,088.4 kg. This optimized speed provides a potential fuel savings of up to ***17,514.99 kg,*** a 65% reduction.

4.2.3 Considerations and constraints

The realism of a sailing speed of 6.7 knots for the given voyage from Lagos to Calabar depends on various factors, including the vessel's type, design, load, weather conditions, sea state, and navigational constraints.

Considering the vessel's details:

- Vessel Type: Tanker
- DWT: 46,622 tons
- Power: 9,480 kW

- Maximum Speed: 16.4 knots
- Service speed: 16 knots

A speed of 6.7 knots is significantly below the service speed, which is the optimum designed operational speed. For a tanker of this size and power, such a speed is certainly attainable, but it's worth considering the following:

1. **Efficiency**: Sailing at a much lower speed than the design speed might be less fuel-efficient per nautical mile covered, as large vessels are often optimized for a specific cruising speed.
2. **Sea Conditions**: If the vessel encounters adverse weather or sea conditions, maintaining a low speed could be challenging, potentially requiring adjustments to the plan.
3. **Schedule and Operational Constraints**: Sailing at this lower speed might not align with typical operational practices or scheduling needs.
4. **Just-In-Time Arrival**: The 6.7 knot speed was derived to meet the 74-hour journey time exactly, so any deviation from this speed or unexpected delays could result in a late arrival.
5. **Navigation and Traffic**: The choice of speed must also consider navigational safety, maritime traffic, and any other local constraints as required by the shipping company, local authorities, regulations etc.

While a sailing speed of 6.7 knots is physically possible for this vessel, it might not be optimal or standard practice for the specific vessel.

4.2.4 Route Optimization

Route optimization, at its core, seeks to improve efficiency, reduce costs, and enhance maritime safety by identifying the most advantageous routes for vessels to take (Zeng et al., 2015). It entails a holistic view, considering not just the distance but the entirety of the potential challenges and implications of the chosen routes. While the shortest maritime route often seems ideal, complexities, like the presence of oil fields, can render such paths less favourable. Oil fields introduce navigation hazards such as physical obstructions, increased maritime traffic, the potential for oil spills, and security concerns. Balancing efficiency with safety is paramount in maritime operations.

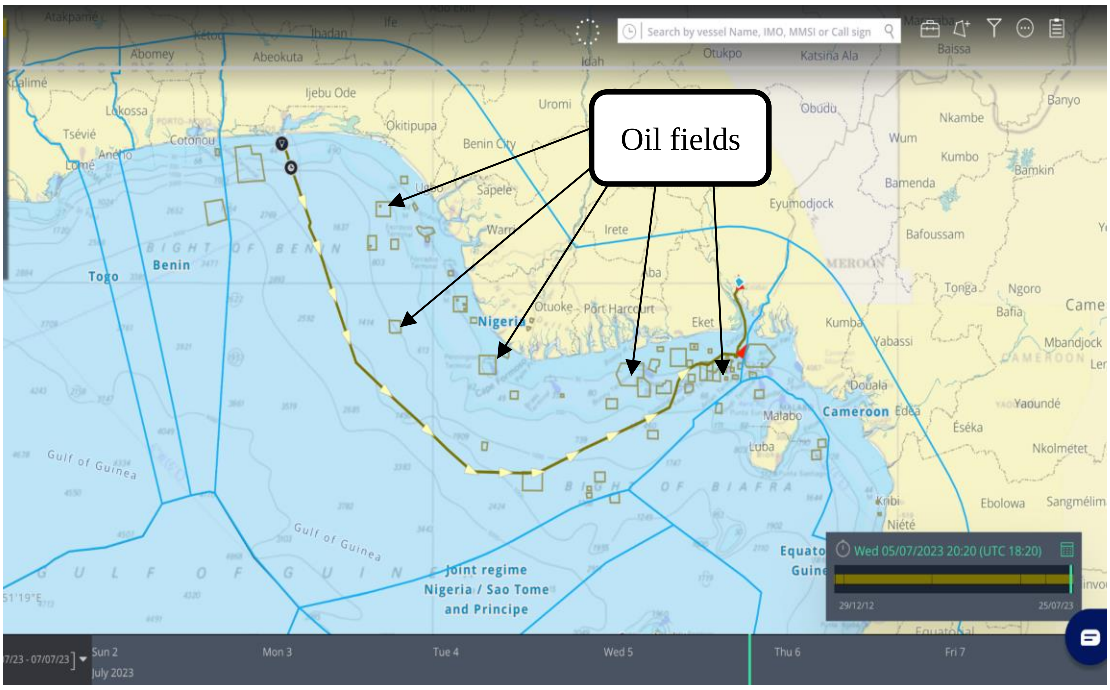

Figure 11: Path of Vessel and oil fields (Source: NIMASA C4i/ Windward)

In the specific case of this vessel, the possible shorter route passes through areas dense with oil fields. The presence of oil fields on this maritime route presents significant navigational hazards for several reasons:

1. **Physical Obstruction**: Oil fields, particularly those with surface infrastructure like rigs, platforms, and supply vessels, can physically obstruct the vessel. Navigating close to or through these structures increases the risk of collisions, which would result in catastrophic environmental and economic damages.
2. **Operational Activities:** Areas with active oil fields are often buzzing with auxiliary maritime activities such as supply runs, maintenance operations, and surveillance patrols. These can lead to increased marine traffic, further complicating navigation and heightening the collision risk.

3. **Environmental Concerns**: Accidental collisions or groundings in or near oil fields could result in oil spills, leading not only to ecological disasters but also to substantial financial liabilities. The surrounding marine ecosystem, already vulnerable due to the oil extraction activities, could face irreversible damage.
4. **Security Concerns**: Oil fields can sometimes be high-security zones. Unplanned incursions can lead to misunderstandings and might attract penalties, detentions, or other legal implications for the vessel.
5. **Route Predictability**: Vessels navigating through or near oil fields may need to frequently alter their course to avoid unexpected obstructions, which can reduce the predictability and consistency of the voyage.

Given these concerns, while the shorter route may seem more efficient at a cursory glance, the inherent risks and potential consequences make it a less favourable choice. In this situation, the principle of "Safety First" takes precedence over the pure optimization of distance. Opting for a longer but safer route ensures the vessel's integrity, the safety of its crew, and the protection of the environment.

4.2.5 The Potential of Wind-aided Propulsion

Wind-assisted propulsion has garnered attention in recent years as a sustainable solution to reduce the carbon footprint of maritime activities (Petković et al., 2021). The concept leverages wind power to supplement conventional fuel-based propulsion, thereby conserving fuel. Using historical wind data, the study explored how wind-assisted propulsion might benefit vessels like the one in this study. By calculating potential power derived from wind and estimating potential fuel savings, the exploration suggested that incorporating wind assistance can significantly reduce fuel consumption, underscoring the need for sustainable approaches in maritime operations.

The Wind data is from a netCDF file with a multi-dimensional scientific data format providing values for time, latitude, longitude, and wind components (u10 representing eastward and v10 indicating northward wind speeds).

Computation of Wind Speed: Wind speed at each time instance is deduced using the Pythagorean theorem, combining the eastward (u10) and northward (v10) wind speeds.

$$Wind\ Speed = \sqrt{U^2 + V^2}$$

Where u and v are the eastward and northward components of wind speed, respectively.

Under regular conditions (without wind assistance), the ship's fuel consumption (*fuel_normal*) is established by multiplying the ship's power, fuel rate, and duration. To estimate the impact of wind assistance, it's posited that the power derived from wind is

Potential wind Power = ½ * density * Area *Cp * speed^3

Hence, for each time step, the potential power attributable to the wind is computed. The reduction in fuel consumption, when this wind-derived sail power is leveraged, is then quantified. Any scenario where the wind offers more power than the ship's engine capacity (leading to negative fuel consumption) is logically adjusted to zero consumption.

The baseline fuel consumption without wind assistance (*fuel_normal*) was estimated as:

$$fuel\_normal = ship\_power \times ship\_fuel\_rate \times len(time)$$

Where:

- ship_power is the power of the engine in kW.
- ship_fuel_rate is the fuel consumption rate in kg/kWh.
- len (time) represents the duration for which the calculations are being made.

Subsequently, the fuel consumption with wind assistance (fuel_sailing) was calculated:

$$fuel\_sailing = (ship\_power - Potential\ wind\ Power) \times ship\_fuel\_rate \times len(time)$$

The fuel savings are then the difference between standard consumption and consumption with wind assistance.

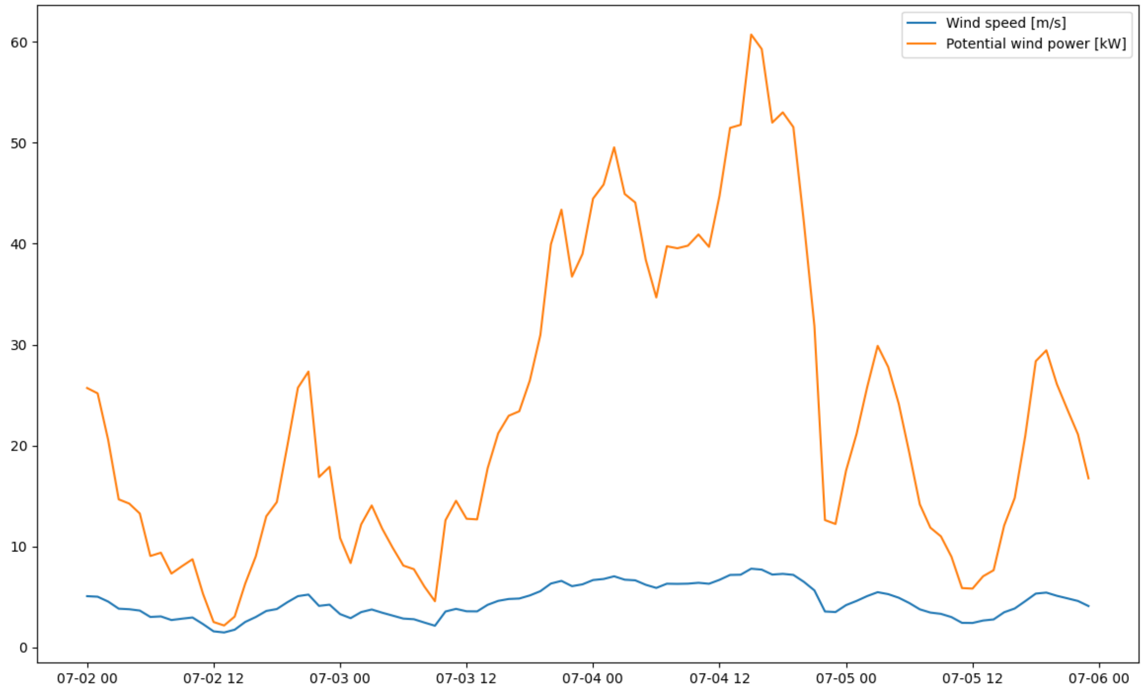

Figure 12: Chart of wind speed and Potential wind power (Source: Researcher)

The visualization of the data showed fluctuations in wind speed over time and the corresponding sail power that could be harnessed. This is simple estimate for vessels with wind turbines or sails that could take advantage of wind-assisted propulsion.

4.3 Scenario 2: A Study in Speed and Fuel Consumption Optimization

In this scenario, the research takes a vessel sailing from Port Harcourt to Lomé within a specific route from July 31 to August 5. By determining the fuel consumption for the entire voyage, the possible route that could be taken according to the VTS advisory to save fuel, and the amount of fuel that is saved by taking the route.

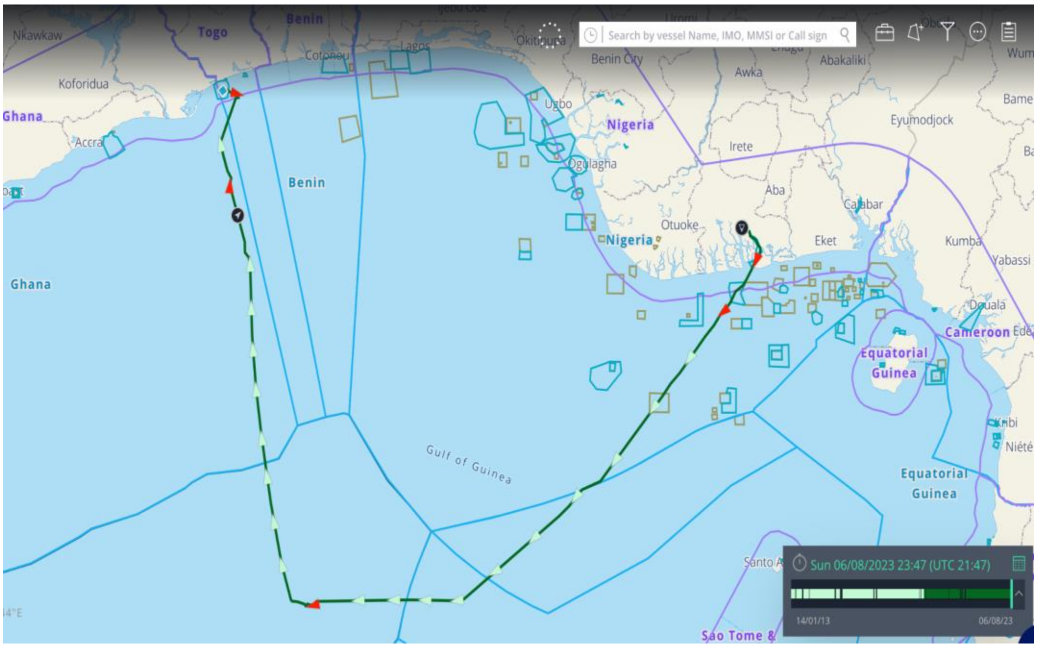

Figure 13: Map showing vessel's voyage (Source: NIMASA C4i/ Windward)

The image above visualizes the voyage from Nigeria to Togo. The vessel sailed from Nigeria's EEZ to the Joint Regime of Nigeria and Sao Tome and Principe, to Sao Tome and Principe's EEZ, then out to the high seas before changing course to Togo through Ghana's EEZ, covering a distance of 715.2 nautical miles.

Vessel Details

Vessel Details	
Vessel type	Bulk Carrier
Length	180 meters
Maximum draft	10.65 meters
Deadweight tonnage (DWT)	33,500 tons

Gross tonnage (GT)	22,137 tons

Engine Details	
Engine manufacturer	Hyundai
Number of Cylinders	6
Power	6480 kW
Maximum speed	N/A
Service speed	14 knots
Fuel type	Marine diesel
Specific fuel consumption (SFC)	kg/kWh

Voyage Details	
Port of Origin	Port Harcourt, Nigeria
Destination	Lome, Togo
Time of departure	July 31, 2023, 15:00
Time of arrival	August 5, 2023, 13:00
Voyage duration	119 hours
Voyage distance	715.20 NM (1324.6 km)

4.3.1 Analysis

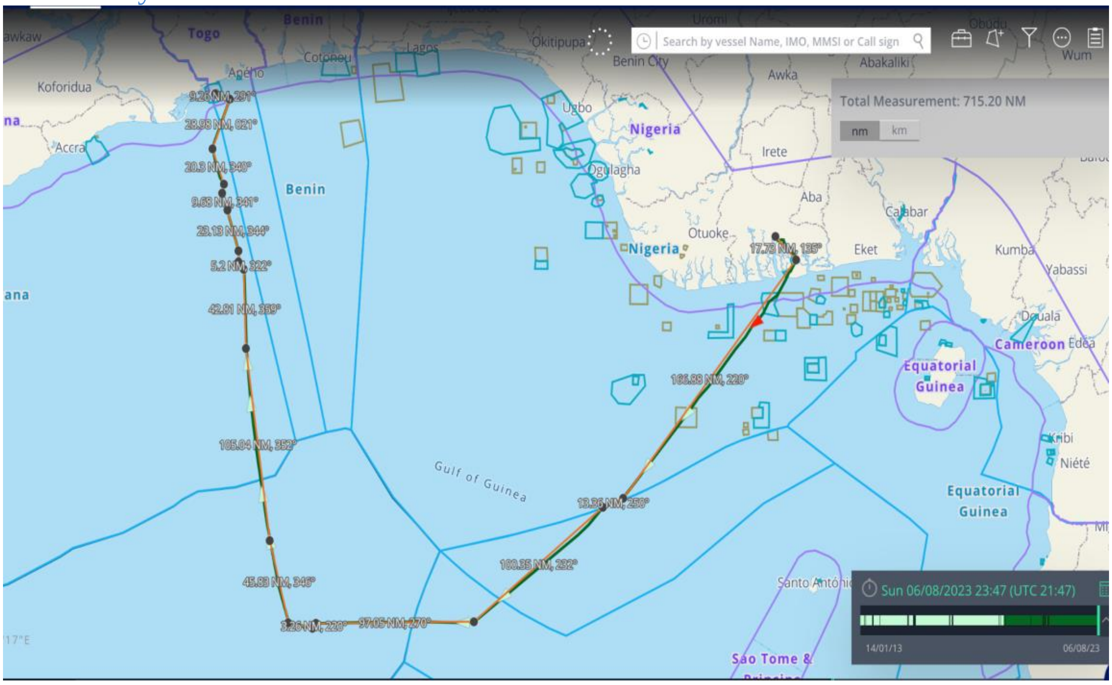

Figure 14: Voyage distance (Source: NIMASA C4i/ Windward)

Given the engine power of 6,480 kW, the Cubic relationship between power and speed with constant C; Power = V^3 * C

c= 6480/14^3

C= 2.4

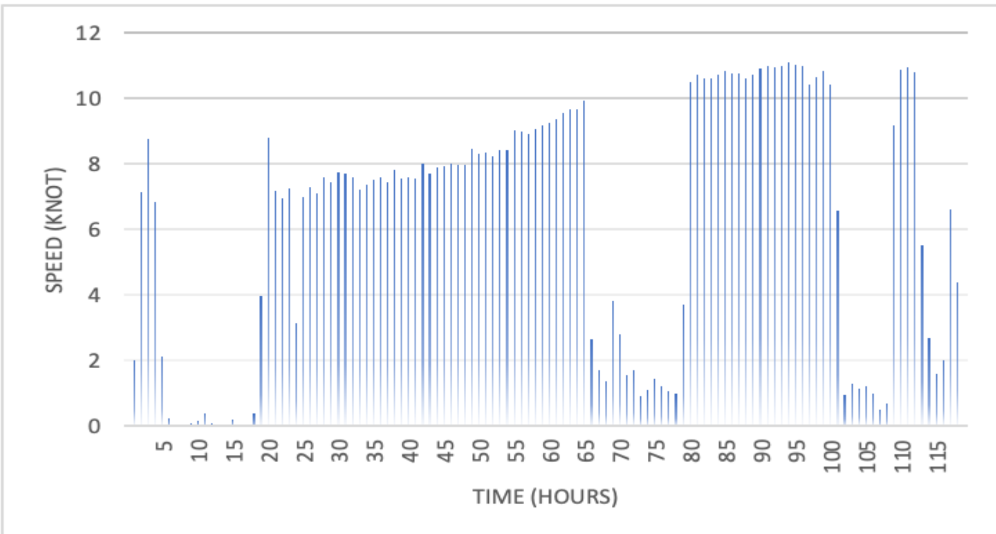

Figure 15: Vessel's speed (Source: Researcher)

The chart above shows the speed of the vessel at each hour of the voyage.

Distance: 715.2 nautical miles (NM) from Port Harcourt, Nigeria, to Lomé, Togo

Engine Power: 6,480 kW

Fuel consumption is 25 t/day at 14.00 knots

To find the SFOC, first convert the daily fuel consumption to an hourly rate and then determine the amount of fuel consumed per kilowatt-hour:

1. Convert daily fuel consumption to hourly:

25t/day x 1000 kg / 1 t x 1 day/ 24 hours = 1041.67kg/hr

2. Calculate SFOC:

SFOC = Fuel consumption (kg/hr) / Power (kW)

SFOC = 1041.67kg/hr / 6480 kW = 0.1607kg/kWh

SFOC = 0.1607kg/kWh × 1000 = 160.7 g/kWh

This represents the amount of fuel consumed per kilowatt-hour (kWh) of energy produced by the vessel's engine.

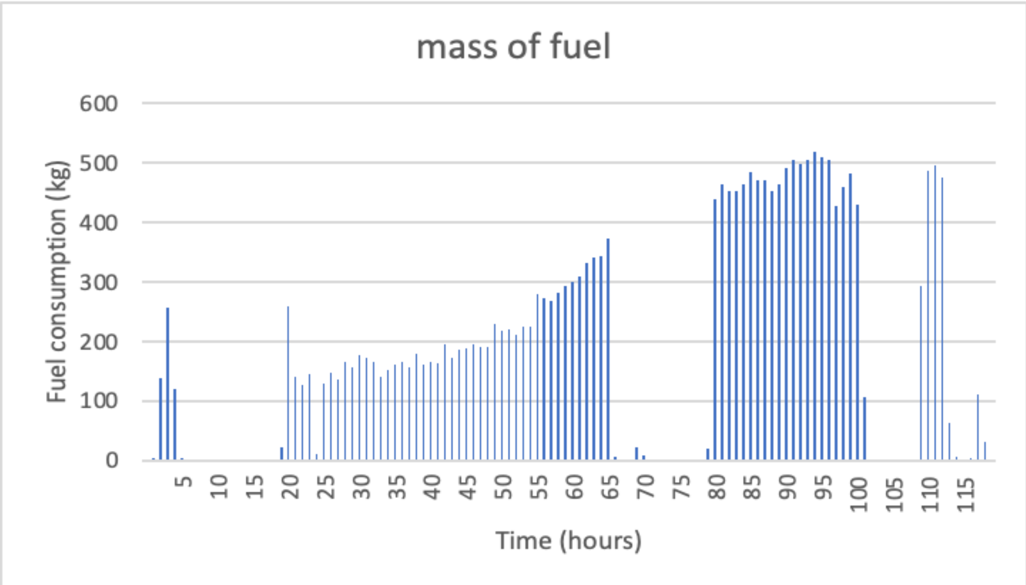

Figure 16: Fuel consumption (Source: Researcher)

The total mass of fuel consumed for the entire voyage is

Mass of fuel = SFOC x Power x time

Hourly mass of fuel was calculated by multiplying the SFOC of 160.7 g/kWh by corresponding engine power used at that hour. The summation of the hourly fuel consumed gave the approximate total fuel consumption for the entire voyage of 119 hours; which is 22,063.1 kg of fuel consumed.

Engine Power (at any given hour)

This is variable and corresponds to the power output of the engine in kilowatts at a particular hour 'h'. It was calculated for every speed of the journey

Total Voyage Duration = 119 hours

From Microsoft Excel analysis, we calculate the hourly mass of fuel consumed for a given engine power at every hour

Mass of Fuel = SFOC x Power

Therefore, the total fuel consumed over the entire voyage duration is the sum of the hourly fuel consumptions:

Mass of fuel = sum total SFOC x Power

From the analysis, we have:

Mass of fuel = 22,063.1 kg

Utilizing the SFOC of 160.7 g/kWh and the respective engine power outputs at each hour of the voyage, the total fuel consumption for the journey spanning 119 hours is computed to be approximately 22,063.1 kg. This result has been derived by summing the products of the SFOC and engine power for each hour throughout the duration of the voyage.

4.3.2 Route Optimization

Route optimization for a vessel involves identifying the most efficient and cost-effective route to reach its destination (Corbett et al., 2009). This optimization aims to minimize fuel consumption, reduce emissions, enhance safety, and ensure timely arrivals

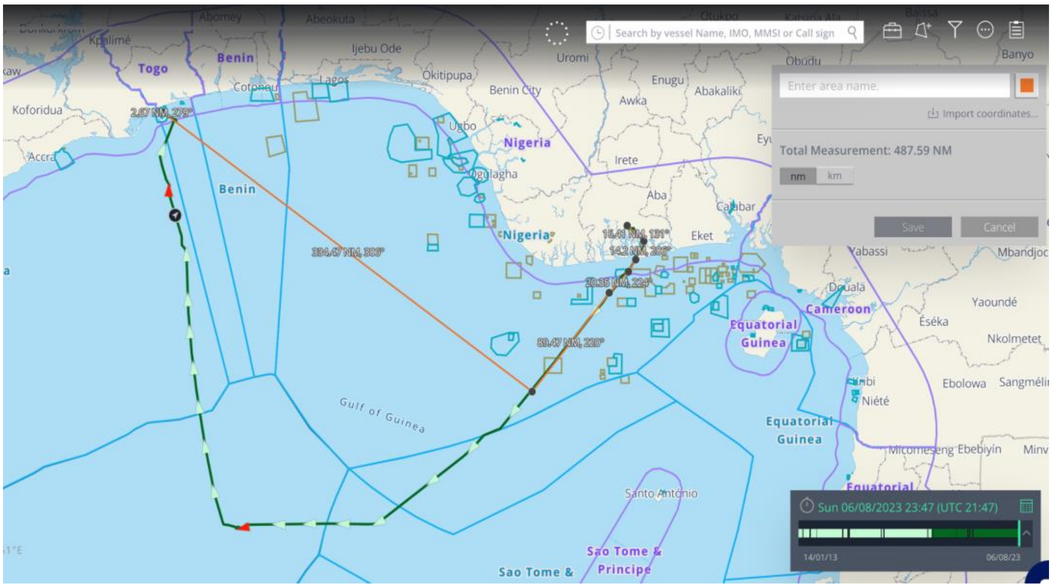

Figure 17: New route suggestion (Source: NIMASA C4i/ WIndward)

Here, potential fuel savings and route optimization strategies were evaluated in the context of VTS advisories; the vessel could have covered 31.8% less distance. having identified a shorter route for the journey, ensured there are no navigational hazards, restrictions, or other potential impediments, and determined that taking this route will offer benefits in terms of time and fuel consumption. The results emphasized the value of advanced route planning and the potential for fuel savings.

4.3.2.1 Time Factor

1. New Route and Speed

Considering the new route has a distance of 487.59 NM, and the average speed from the original voyage is 6.1 knots. That is;

- The vessel is considering a proposed route that is 487.59 Nautical Miles (NM) long
- The average speed at which the vessel plans to travel on this route is 6.1 knots.

2. Calculating Time

- To find out how long it would take for the vessel to travel this proposed route at the mentioned average speed, we use the formula:

Time = Distance / Speed

Using the figures:

Time = 487.59 NM / 6.1 kts

Time = 79 hours

Hence, the vessel would complete the journey on the proposed route in approximately 79 hours if it maintained an average speed of 6.1 knots.

3. Time Savings

- The original journey was expected to take 119 hours.
- Given that the new route at the proposed speed would only take 79 hours, the time saved is:

  Time saved = 119 hours - 79 hours

  Time saved = 40 hours

This means the vessel would reach its destination 40 hours earlier if it opts for the proposed route and maintains an average speed of 6.1 knots.

4. Fuel Consumption

- On this new route, taking 79 hours, the vessel is expected to consume **6,838.8 kg** of fuel based on the vessel's specific fuel consumption rate, its engine's power, and the duration of the voyage.

Therefore, opting for the proposed route and traveling at an average speed of 6.1 knots allows the vessel to reach its destination in 79 hours, saving 40 hours compared to the initial 119-hour voyage. This faster journey would cost the vessel a total fuel consumption of **6,838.8 kg.** This shows the importance of efficient route planning through VTS advisories, not just in terms of time saved but also in terms of potential fuel consumption and associated costs.

4.3.2.2 Speed Factor

Consideration is also given to the speed required to meet the initial ETA of 119 hours while sailing through the new proposed route of 487.59 NM.

1. New Route and ETA

- The vessel may be given the option of a new proposed route that spans 487.59 Nautical Miles (NM).

- The original ETA was 119 hours, and there's an interest in seeing what speed the vessel would need to maintain on this new route to meet the original ETA.

2. Calculating Speed

- To determine the speed required to meet the 119-hour ETA over the new route's distance, we use the formula:

  Speed = Distance / Time

  Speed = 487.59 NM / 119 hours

  Speed = 4.1 knots

Thus, if the vessel travels at a speed of approximately 4.1 knots on the new route, it will reach its destination within the original 119-hour ETA.

3. Implications on Fuel Consumption

- At this slower speed of 4.1 knots over the new route, taking 119 hours, the vessel is projected to consume about ***3,112.5 kg*** of fuel.
- This would likely be less fuel than what would be used if the vessel travelled at a faster speed for a shorter duration, as fuel consumption often doesn't scale linearly with speed (i.e., traveling faster usually consumes disproportionately more fuel).

By adopting the proposed route and reducing the sailing speed to 4.1 knots, the vessel can still meet the original ETA of 119 hours. In addition to this, it would lead to an estimated fuel consumption of ***3,112.5 kg***. This analysis presents a strategy to potentially reduce carbon emissions and operational costs by burning less fuel while still meeting the original ETA. It showcases the significance of adjusting speeds and how doing so can result in operational savings when combined with efficient route planning.

Senario 3: A Study in Fuel optimization through ocean data

In this study, the researcher examined a vessel's journey from Lagos, Nigeria, to Libreville, Gabon, with a primary focus on optimizing fuel consumption. By quantitatively assessing the vessel's fuel consumption throughout the voyage, the study investigates the potential for enhancing fuel efficiency by strategically harnessing the prevailing ocean data to enhance fuel efficiency by providing natural propulsion, reducing resistance, and enabling optimized routing. This leads to both economic benefits from reduced fuel costs and environmental advantages through decreased GHG emissions.

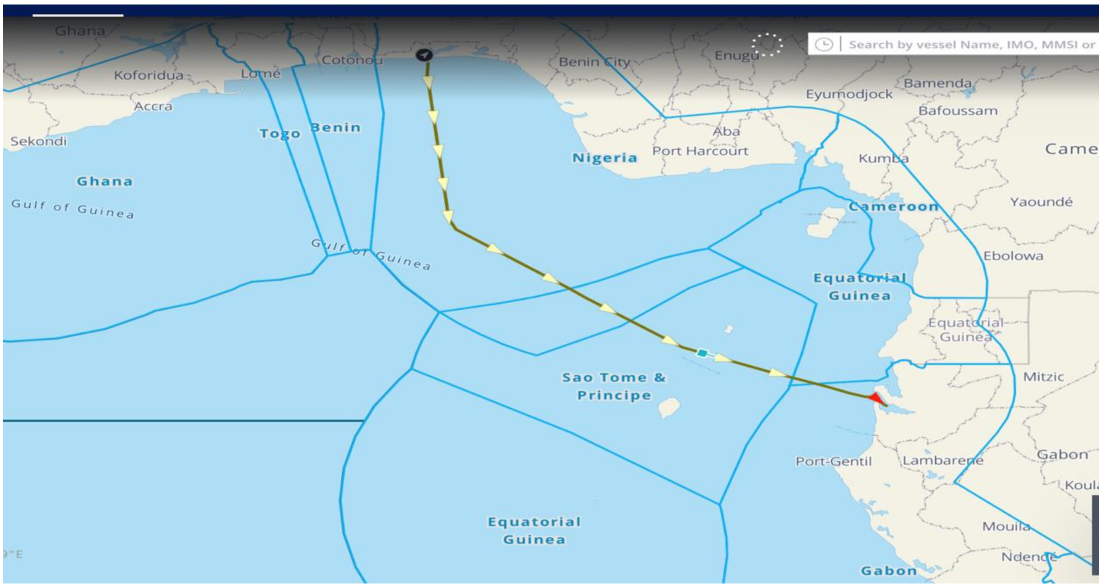

Figure 18: Vessel's route from Nigeria to Gabon (Source: NIMASA-C4i/ Windward)

Vessel and Engine Details

Vessel Details	
Vessel type	Bulk carrier
Length	190 meters
Height	N/A
Maximum draft	13 meters
Deadweight tonnage (DWT)	57,334 tons

Gross tonnage (GT)	33,348 tons

Engine Details	
Engine manufacturer	STX Engine
Number of Cylinders	6
Engine Power	9,480 kW
Service speed	14.3 knots
Specific fuel consumption (SFC)	190 g/kWh

Voyage Specifics

Voyage Details	
Port of Origin	Lagos, Nigeria
Destination	Libreville, Gabon
Time of departure	August 15, 2023, 18:00
Time of arrival	August 17, 2023, 18:00
Voyage duration	50 hours
Voyage distance	580.34 NM

Based on available data, the study estimated the mass of fuel consumed hourly at the sailing speeds per hour and the total mass of fuel consumed for the entire voyage of 50 hours.

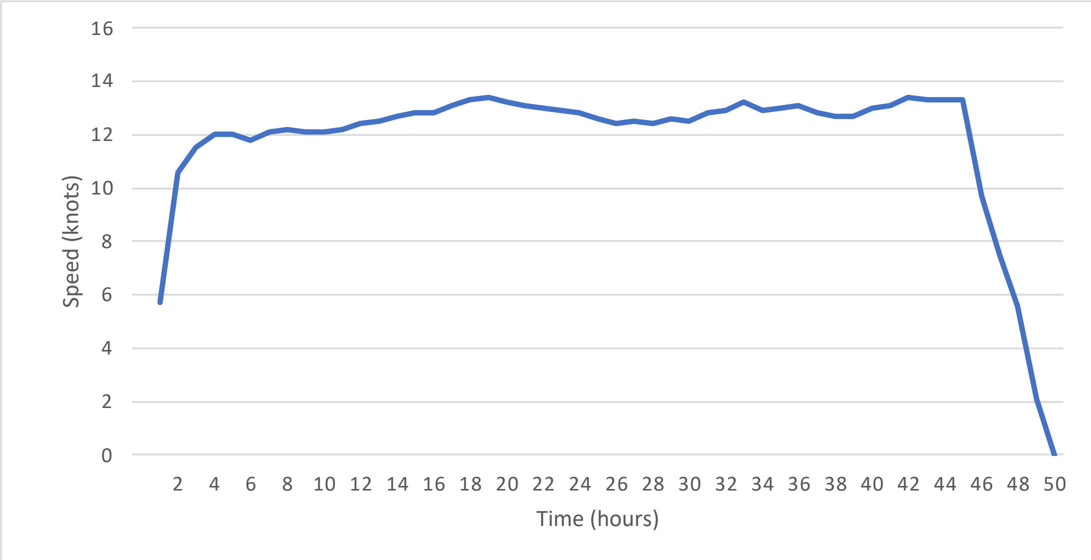

Figure 19: Ship's speed (Source: Researcher)

The total fuel consumption for the vessel's journey from Nigeria to Gabon was estimated at ***56,372 kg*** based on the speed and engine power.

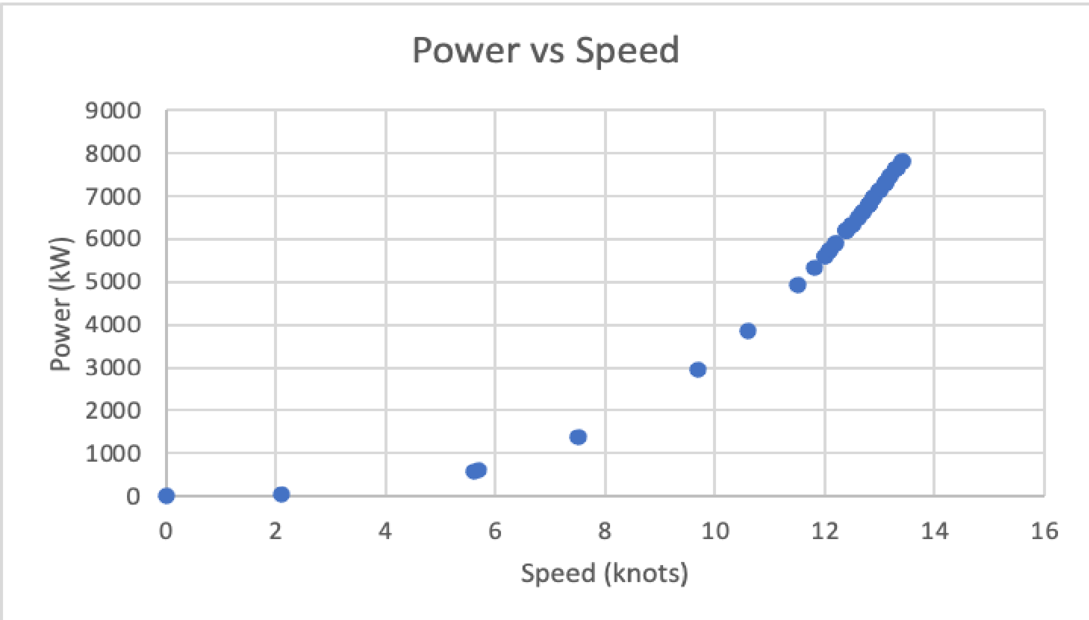

Figure 20: Power-speed (Source: Researcher)

The analysis also shows how the fuel consumption changes with different speeds, following a cubic relationship due to the power-speed relationship.

Ocean Data

Ocean data provides vital insights into various meteorological and oceanographic parameters (Qian et al., 2021). Such parameters are ocean currents and solar irradiation, which play crucial roles in understanding energy resources in the maritime sector.

Effect of Ocean currents on fuel consumption

In an effort to understand the interplay between ocean currents and fuel consumption, a computational analysis was conducted using ocean current data and the corresponding vessel's voyage details.

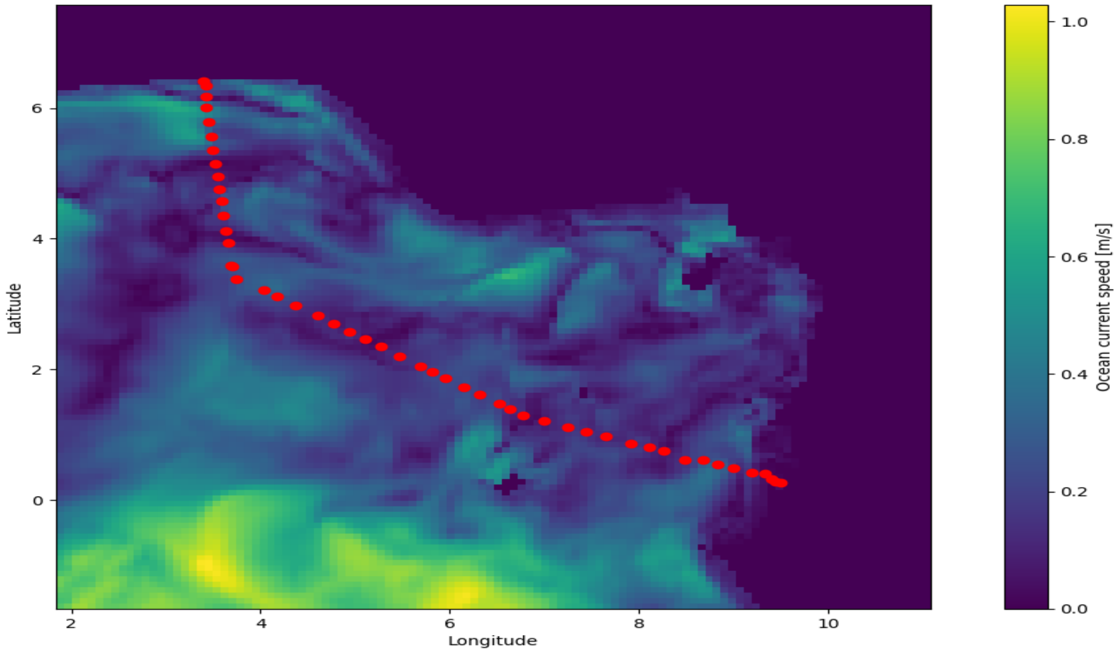

Figure 21: Vessel's movement along ocean current (Source: Researcher)

The study aimed to evaluate how a ship's trajectory and speed might be impacted by varying ocean currents on a voyage. A timely trajectory of the ship was mapped, and for each time point, the following parameters were computed:

1. Ship's heading based on its movement.
2. Ships's position

3. Magnitude and direction of the ocean current at the ship's location.
4. Angle between the ship's heading and the ocean current's direction.
5. Derived speed changes of the ship due to the influence of the ocean current

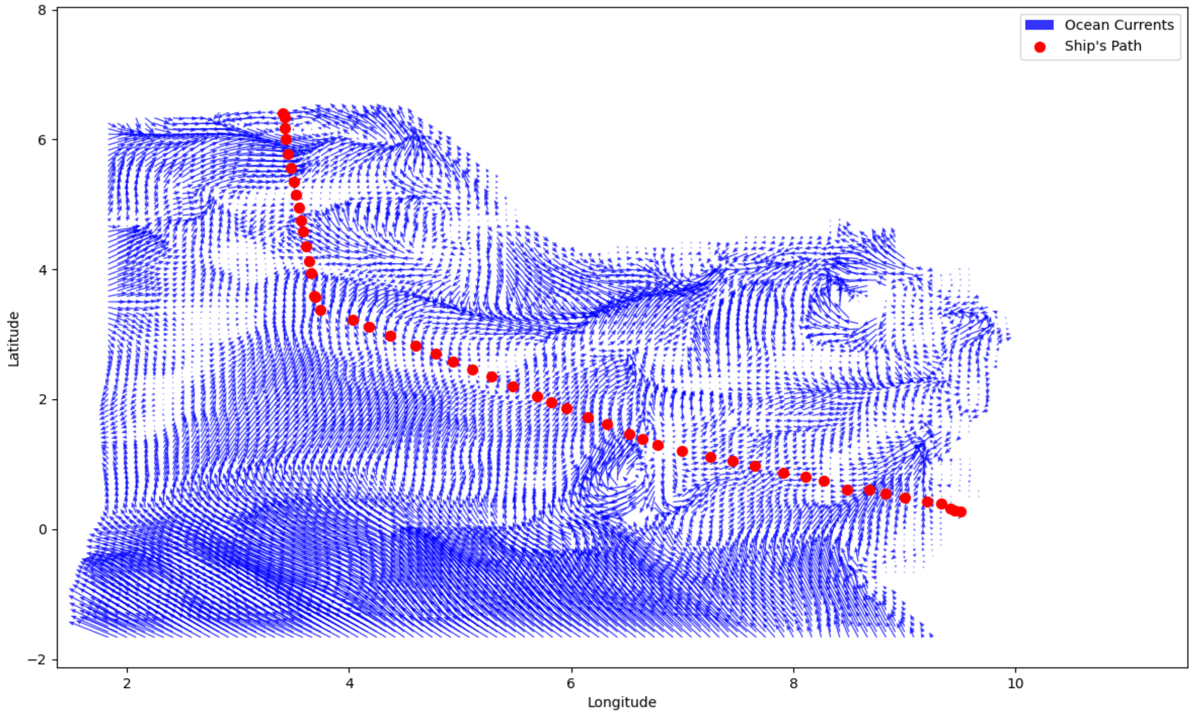

Figure 22: Direction of ocean current (Source: Researcher)

The initial visualization above showcases a heatmap of ocean current directions across the region of interest. Overlaying the ship's trajectory with red markers shows its path relative to the prevailing currents.

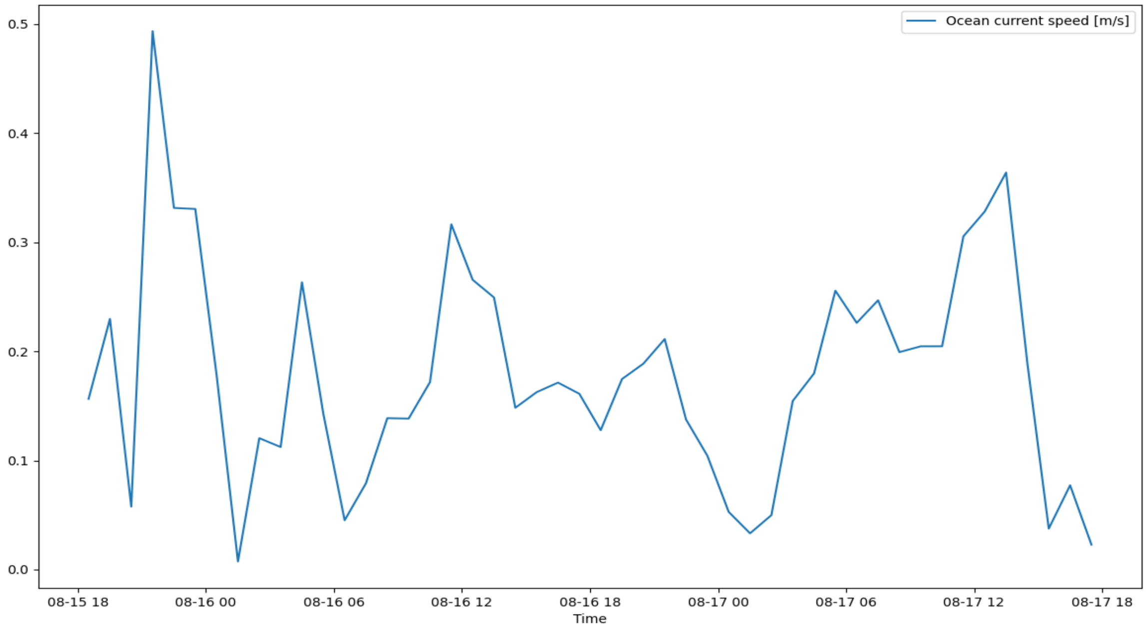

Figure 23: Speed of ocean current (Source: Researcher)

Ship's Interaction with Ocean currents

As the ship navigated its path, substantial variations were observed in its interactions with the ocean currents.

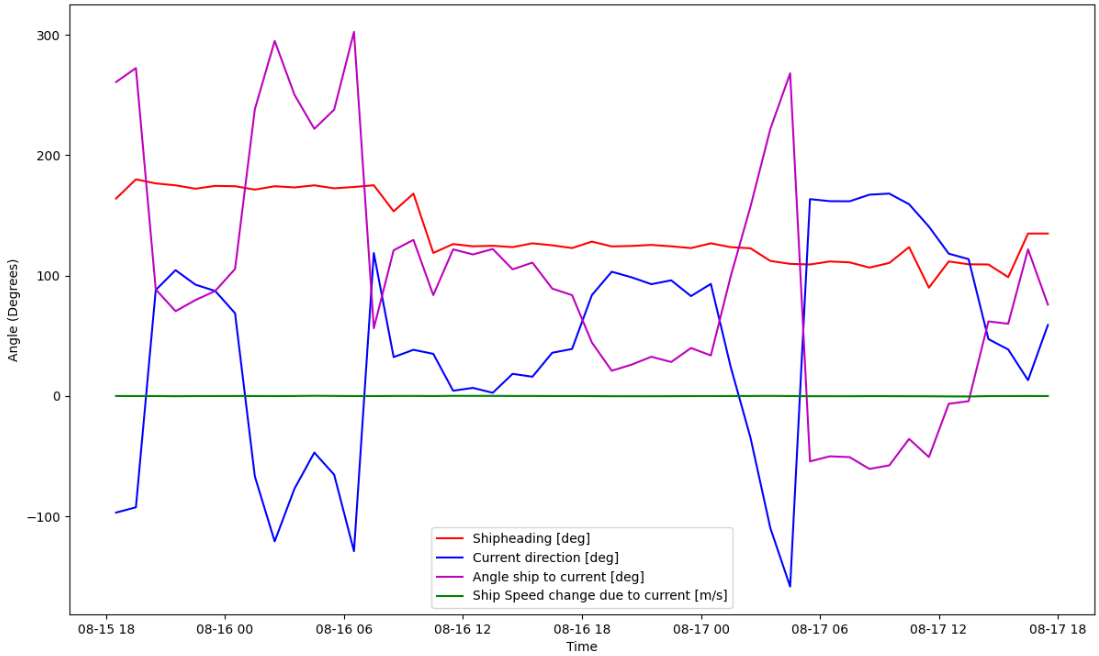

Figure 24: Angles of interactions between the ship and ocean (Source: Researcher)

Angle of Interaction and Speed Impacts

By comparing the ship's heading with the direction of the ocean currents, we derived the angles of interaction. These angles, combined with the magnitude of the currents, provided insights into the speed changes the ship might experience. Notably, during the early hours of the journey, the ship experienced significant speed reductions due to counteracting currents

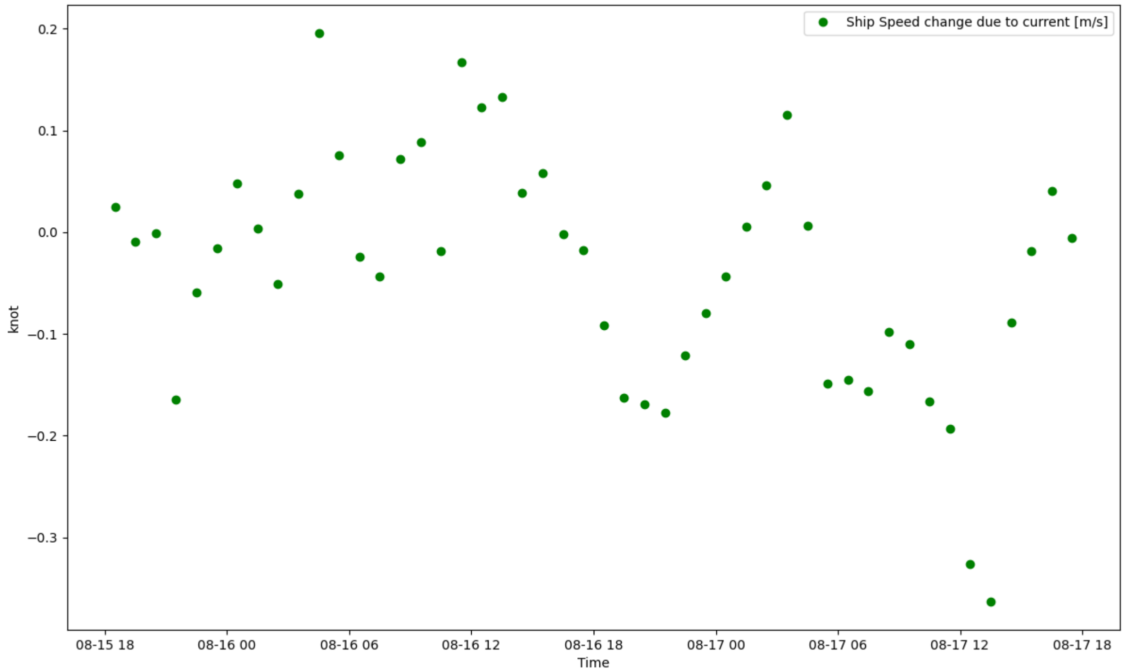

Figure 25: Effect of current on ship speed (Source: Researcher)

These angles, combined with the magnitude of the currents, provided insights into the speed changes the ship might experience. Notably, during the early hours of the journey, the ship experienced significant speed reductions due to counteracting currents.

The analysis of the ship’s speed and ocean data showed significant speed changes caused by ocean data. The speed change was higher in the early voyage hours when the currents were acting against the ship and lower towards the end of the journey when the ship's heading appeared to flow with the currents. There was a resultant speed change, which was used to estimate the new speed, showing the change in speed as a result of the ocean current.

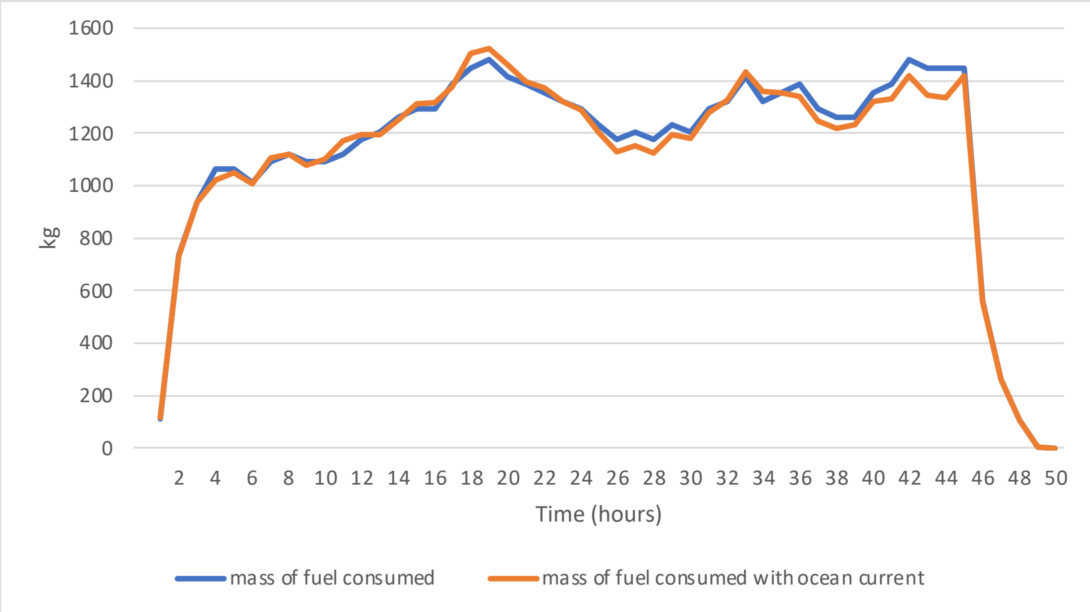

Figure 26: Effect of current on ship speed (Source: Researcher)

The projected fuel consumption was estimated to be a reduction to 55,832.84 kg from 56,372.2 kg, which is a marginal reduction in the fuel consumption of around 1%. As ships use more fuel when navigating against adverse currents, VTS's guidance to utilize favorable currents or avoid particularly strong counter-currents can contribute to lower fuel consumption by taking advantage of the ocean currents for navigation.

VTS and Solar Energy Utilization

In order to understand the role of VTS in supporting maritime decarbonization, it is important to assess the potential of natural energy resources, notably solar energy, as a tool for decarbonization. By using ocean data, this analysis offers insights into solar irradiation patterns along the ship's route.

To offer a clear understanding of the solar irradiation's distribution along the ship's route:

1. A heatmap was generated to represent solar irradiation values across the area of interest.
2. The ship's location was marked on this heatmap, visualizing the voyage in context.
3. A time series graph detailing the variation in solar irradiation at the ship's location throughout its journey.

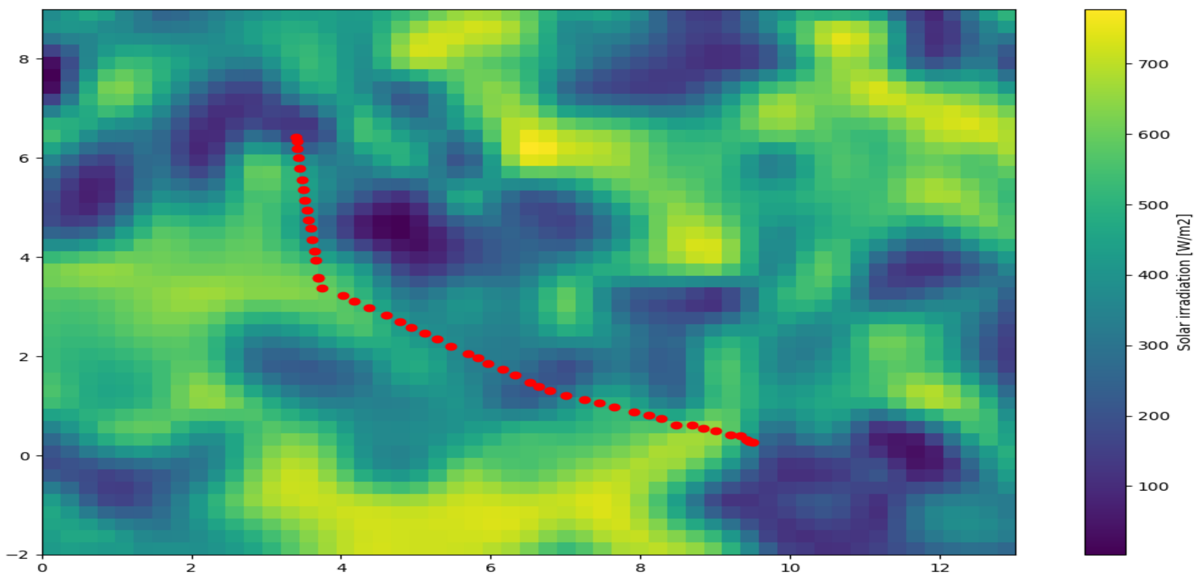

Figure 27: Effect of current on ship speed (Source: Researcher)

The study analyzed how VTS can employ data for vessels to optimize energy efficiency along their routes based on solar irradiation patterns. This is particularly beneficial for ships equipped with solar panels that could potentially harness maximum solar energy.

Solar Power

Power from solar PV could be used to compliment the main source of auxiliary power, which is the auxiliary engine. The graph below shows the amount of solar irradiation that could be harnessed over the course of the voyage.

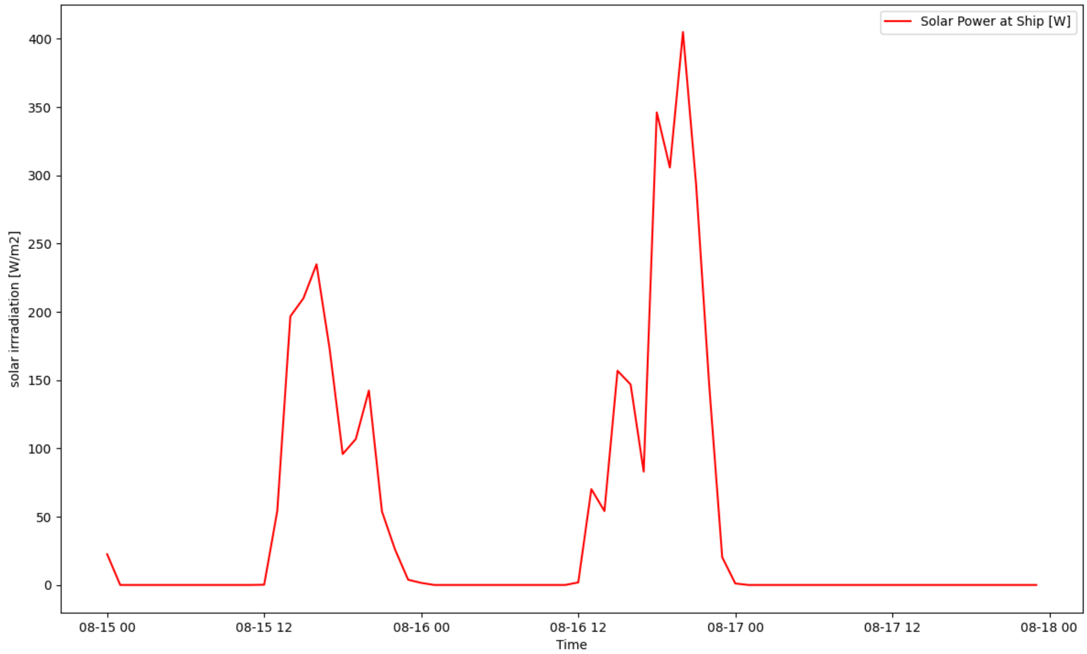

Figure 28: Effect of current on ship speed (Source: Researcher)

The power generated from the PV systems can be determined by the equation:

$$Power\ \ P = n * A * G$$

Where P is the power (w) produced by the system at the average global irradiance of G w/m2 per day, n is the efficiency (we assume 20% efficiency) of the solar module (PV), and A is the installation area in m2 (Saidyleigh, 2017). For this study, the hatch area for Handymax bulk carrier PV is adopted from the Saidyleigh (2017) database at 1720.40 m2.

Based on this analysis, there is potential to capture up to 1,154 kW of electricity from solar energy for the duration of the voyage, which could be used for auxiliary services.

This study serves as an example of how Vessel Traffic Services may go beyond their traditional responsibilities and actively contribute to maritime decarbonization through renewable energy sources. The combination of VTS and environmental data has the potential to significantly influence how marine activities are directed towards sustainability and lowering carbon emissions.

Chapter Five: Conclusion and Future Research

5.1 Conclusion

The maritime industry is witnessing a shift towards sustainable operations. As fuel prices rise and environmental regulations become more stringent, shipping companies need to embrace advanced technologies, data-driven insights, and sustainable practices. Fuel savings translate directly to reduced carbon emissions, which means a positive environmental impact This study's focal point is to shed light on how the VTS can support the maritime industry in its decarbonization efforts. In order to fulfill the objectives of the study, the research focused mainly on:

1. The ways VTS can relay information to vessels for energy-efficient operations such as optimized routing, reduced waiting time, speed recommendations, and predictive analytics
2. The best practices and initiatives in place for the use of VTS to achieve energy efficiency in the maritime industry, such as JIT arrivals, green/energy-efficient routes, promotion of alternative fuels and data sharing

There is a dearth of literature in this field of research; the researcher could find little or no literature on VTS relating it to energy efficiency or decarbonization This could be attributed to the fact that this is a new field of research and the concept of VTS has only been developed for the safety of navigation in the shipping industry. Scenarios were analyzed to estimate the fuel consumption of vessels and probable fuel savings through the VTS advisory. The analysis reveals that while technological interventions can significantly reduce the carbon footprint of maritime operations, integration with VTS systems can amplify these benefits. By optimizing routes and leveraging natural energy sources such as wind, vessels can reduce their reliance on fossil fuels, ensuring a sustainable maritime future. VTS has the potential to provide real-time insights on navigation hazards, maritime traffic, and more. The role of digital transformation in the shipping industry can never be overemphasized. Leveraging data-driven insights can lead to more informed decision-making by incorporating this data into route planning.

5.2 Future Research

5.2.1 Comprehensive Statistical Analysis

- **Sample Size and Diversity**: The current study, while providing valuable insights, was conducted with a limited number of vessel samples. To generalize the findings and better understand the vast potential of VTS in promoting decarbonization, future studies should incorporate a more diverse and larger sample of vessels, representing different types, sizes, and operational profiles.
- **Geographical Coverage:** This analysis was concentrated around specific geographical locations, potentially missing out on unique challenges and opportunities presented by other sea routes and climatic conditions. Expanding the scope of research to cover a broader range of global maritime routes will yield a more comprehensive understanding of VTS's role in decarbonization across varied marine environments.

5.2.2 Automation and Artificial Intelligence Integration

- **AI-Powered Voyage Planning**: Leveraging machine learning and artificial intelligence, future VTS systems can predict and suggest optimal voyage plans that account for various dynamic factors, including weather conditions, sea currents, and vessel traffic. Such systems could recommend routes that not only ensure safety and timely arrivals but also minimize fuel consumption and emissions.

5.2.3 Integration with Other Decarbonization Strategies

- VTS's role shouldn't be studied in isolation. It's essential to understand how VTS can complement other green shipping initiatives, such as the use of alternative fuels, retrofitting of vessels for better efficiency, and implementation of green port policies.

By addressing these areas, the maritime industry can further unlock the potential of VTS in its efforts for decarbonization, making strides towards more sustainable and eco-friendly shipping operations.

References

Agarwala, P., Chhabra, S., & Agarwala, N. (2021). Using digitalisation to achieve decarbonisation in the shipping industry. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, *5*(4), 161–174. https://doi.org/10.1080/25725084.2021.2009420

Alqurashi, F. S., Trichili, A., Saeed, N., Ooi, B. S., & Alouini, M.-S. (2022). Maritime Communications: A Survey on Enabling Technologies, Opportunities, and Challenges. *IEEE Internet of Things Journal*, 1–1. https://doi.org/10.1109/jiot.2022.3219674

Armstrong, V. N., & Banks, C. (2015). Integrated approach to vessel energy efficiency. *Ocean Engineering*, *110*, 39–48. https://doi.org/10.1016/j.oceaneng.2015.10.024

Bache, F. (1936). Where Is Franklin's First Chart of the Gulf Stream? *Proceedings of the American Philosophical Society*, *76*(6), 731–741. https://www.jstor.org/stable/984562

Balduzzi, M., Pasta, A., & Wilhoit, K. (2014). A security evaluation of AIS automated identification system. *Proceedings of the 30th Annual Computer Security Applications Conference*. https://doi.org/10.1145/2664243.2664257

Berman, S., & Stern, H. (2012). Sensors for Gesture Recognition Systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part c (Applications and Reviews)*, *42*(3), 277–290. https://doi.org/10.1109/TSMCC.2011.2161077

Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, *14*(8), 593–598. https://doi.org/10.1016/j.trd.2009.08.005

Du, Y., Meng, Q., Wang, S., & Kuang, H. (2019). Two-phase optimal solutions for ship speed and trim optimization over a voyage using voyage report data. *Transportation Research Part B: Methodological*, *122*, 88–114. https://doi.org/10.1016/j.trb.2019.02.004

European Maritime Safety Agency . (n.d.). *FINAL REPORT Study on Ships producing reduced quantities of ships generated waste -present situation and future opportunities to encourage the development of cleaner ships*. Retrieved July 11, 2023, from https://www.emsa.europa.eu/sustainable-ports/port-reception-facilities/download/1160/4511/23.html

Grejner-Brzezinska, D. A., Toth, C. K., Moore, T., Raquet, J. F., Miller, M. M., & Kealy, A. (2016). Multisensor Navigation Systems: A Remedy for GNSS Vulnerabilities? *Proceedings of the IEEE*, *104*(6), 1339–1353. https://doi.org/10.1109/jproc.2016.2528538

Hughes, C. T. (2009). When is a VTS not a VTS? *Journal of Navigation*, *62*(3), 439–442. https://doi.org/10.1017/s0373463309005396

IMO. (1997, December 3). *Guidelines for Vessel Traffic Services. International Maritime Organization, Resolution A.857(20)*. International Maritime Organization.

IMO. (2019). *Vessel Traffic Services*. Www.imo.org. https://www.imo.org/en/OurWork/Safety/Pages/VesselTrafficServices.aspx

IMO. (2022, July 18). *New World Maritime Theme highlights environmental legacy*. Imo.org. https://www.imo.org/en/MediaCentre/PressBriefings/pages/WorldMaritimeTheme2023.aspx

IMO. (n.d.). *Vessel Traffic Services*. Www.imo.org. https://www.imo.org/en/OurWork/Safety/Pages/VesselTrafficServices.aspx

International Harbour Masters Association. (n.d.). *Vessel Traffic Services (VTS) | IHMA*. Harbourmaster.org. Retrieved May 28, 2023, from https://harbourmaster.org/harbour-master/vts

KASTER, H. B. (1965). Ship Weather Routing in the Pacific. *Navigation*, *12*(2), 108–110. https://doi.org/10.1002/j.2161-4296.1965.tb02119.x

Kim, K.-I., & Lee, K. (2018). Dynamic Programming-Based Vessel Speed Adjustment for Energy Saving and Emission Reduction. *Energies*, *11*(5), 1273. https://doi.org/10.3390/en11051273

Lashgari, M., Akbari, A. A., & Nasersarraf, S. (2021). A new model for simultaneously optimizing ship route, sailing speed, and fuel consumption in a shipping problem under different price scenarios. *Applied Ocean Research*, *113*, 102725. https://doi.org/10.1016/j.apor.2021.102725

Lin, Y.-H., Fang, M.-C., & Yeung, R. W. (2013). The optimization of ship weather-routing algorithm based on the composite influence of multi-dynamic elements. *Applied Ocean Research*, *43*, 184–194. https://doi.org/10.1016/j.apor.2013.07.010

Lindstad, H., & Eskeland, G. S. (2015). Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution. *Transportation Research Part D: Transport and Environment*, *41*, 244–256. https://doi.org/10.1016/j.trd.2015.10.006

Louis De Vorsey. (1976). *Pioneer charting of the gulf stream: The contributions of Benjamin Franklin and William Gerard de Brahm*. *28*(1), 105–120. https://doi.org/10.1080/03085697608592433

Mead, H. P. (1935). The STORY of the SEMAPHORE. *The Mariner's Mirror*, *21*(1), 33–55. https://doi.org/10.1080/00253359.1935.10658699

Meng, Q., Du, Y., & Wang, Y. (2016). Shipping log data based container ship fuel efficiency modeling. *Transportation Research Part B: Methodological*, *83*, 207–229. https://doi.org/10.1016/j.trb.2015.11.007

Mou, J.-M., Zhou, C., Du, Y., & Tang, W.-M. (2015). Evaluate VTS benefits: A case study of Zhoushan Port. *International Journal of E-Navigation and Maritime Economy*, *3*, 22–31. https://doi.org/10.1016/j.enavi.2015.12.003

Nast, T. (2013). The Response of the International Shipping Industry to Global Climate Change. *Heinonline.org*, *44*(01), 29. https://heinonline.org/HOL/PrintRequest?collection=journals&handle=hein.journals/jmlc44&id=31&print=section&div=5&ext=.pdf&format=PDFsearchable&submit=Print%2FDownload

Nofandi, F., Widyaningsih, U., Rakhman, R. A., Mirianto, A., Zuhri, Z., & Harini, N. V. (2022). Case Study of Ship Traffic Crowds in The Malacca Strait-Singapore by Using Vessel Traffic System. *IOP Conference Series: Earth and Environmental Science*, *1081*(1), 012009. https://doi.org/10.1088/1755-1315/1081/1/012009

Notteboom, T. E., & Vernimmen, B. (2009). The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography*, *17*(5), 325–337. https://econpapers.repec.org/article/eeejotrge/v_3a17_3ay_3a2009_3ai_3a5_3ap_3a325-337.htm

Nuutinen, M., Savioja, P., & Sonninen, S. (2007). Challenges of developing the complex socio-technical system: Realising the present, acknowledging the past, and envisaging the future of vessel traffic services. *Applied Ergonomics*, *38*(5), 513–524. https://doi.org/10.1016/j.apergo.2006.10.004

Petković, M., Zubčić, M.-L., Krčum, M., & Pavić, I. (2021). Wind Assisted Ship PropulsionTechnologies – Can they Help in Emissions Reduction? In *Naše more*. https://www.nasemore.com/wind-assisted-ship-propulsiontechnologies-can-they-help-in-emissions-reduction/

Port of Rotterdam . (2022, June 13). *Up to 14% less containership CO2 emissions through Just In Time arrivals | Port of Rotterdam*. Www.portofrotterdam.com. https://www.portofrotterdam.com/en/news-and-press-releases/up-to-14-less-containership-co2-emissions-through-just-in-time-arrivals

Psaraftis, H. N., & Kontovas, C. A. (2010). Balancing the economic and environmental performance of maritime transportation. *Transportation Research Part D: Transport and Environment*, *15*(8), 458–462. https://doi.org/10.1016/j.trd.2010.05.001

Qian, C., Huang, B., Yang, X., & Chen, G. (2021). Data science for oceanography: from small data to big data. *Big Earth Data*, 1–15. https://doi.org/10.1080/20964471.2021.1902080

Ransom, J. E. (1941). Aleut Semaphore Signals. *American Anthropologist*, *43*(3), 422–427. https://www.jstor.org/stable/663141

Relling, T., Lützhöft, M., Ostnes, R., & Hildre, H. P. (2021). The contribution of Vessel Traffic Services to safe coexistence between automated and conventional vessels. *Maritime Policy & Management*, *49*(7), 1–20. https://doi.org/10.1080/03088839.2021.1937739

Roh, M.-I. (2013). Determination of an economical shipping route considering the effects of sea state for lower fuel consumption. *International Journal of Naval Architecture and Ocean Engineering*, *5*(2), 246–262. https://doi.org/10.2478/ijnaoe-2013-0130

Ronen, D. (2011). The effect of oil price on containership speed and fleet size. *Journal of the Operational Research Society*, *62*(1), 211–216. https://doi.org/10.1057/jors.2009.169

Saidyleigh, W. (2017). *Investigation of auxiliary power potentials of solar photovoltaic Investigation of auxiliary power potentials of solar photovoltaic applications on dry bulk carrier ships applications on dry bulk carrier ships*. https://commons.wmu.se/cgi/viewcontent.cgi?article=1589&context=all_dissertations

Shi, L., Shi, D., Zhang, X., Meunier, B., Zhang, H., Wang, Z., Vladimirescu, A., Li, W., Zhang, Y., Cosmas, J., Ali, K., Jawad, N., Zetik, R., Legale, E., Satta, M., Wang, J., & Song, J. (2020). 5G Internet of Radio Light Positioning System for Indoor Broadcasting Service. *IEEE Transactions on Broadcasting*, *66*(2), 534–544. https://doi.org/10.1109/tbc.2020.2981755

Tadros, M., Vettor, R., M. Rita Ventura, & C. Guedes Soares. (2022). *Effect of different speed reduction strategies on ship fuel consumption in realistic weather conditions*. 553–561. https://doi.org/10.1201/9781003320272-62

UNCTAD. (2022, December 19). *Roadmap to decarbonize the shipping sector: Technology development, consistent policies and investment in research, development and innovation | UNCTAD*. Unctad.org. https://unctad.org/news/transport-newsletter-article-no-99-fourth-quarter-2022#:~:text=The%20maritime%20sector%20presently%20accounts

United Nations. (2022). *What is Climate Change?* United Nations; United Nations. https://www.un.org/en/climatechange/what-is-climate-change

Wang, Y., Meng, Q., & Du, Y. (2015). Liner container seasonal shipping revenue management. *Transportation Research Part B: Methodological*, *82*, 141–161. https://doi.org/10.1016/j.trb.2015.10.003

Wartsila. (2009). *BOOSTING ENERGY EFFICIENCY*. https://www.shippingtech.it/PDF/convegni%202010/2tecnologie1/Baan.pdf

YOUNG, W. (1994). What Are Vessel Traffic Services, and What Can They Really Do? *Navigation*, *41*(1), 31–56. https://doi.org/10.1002/j.2161-4296.1994.tb02321.x

Zaman, I., Pazouki, K., Norman, R., Younessi, S., & Coleman, S. (2017). Challenges and Opportunities of Big Data Analytics for Upcoming Regulations and Future Transformation of the Shipping Industry. *Procedia Engineering*, *194*, 537–544. https://doi.org/10.1016/j.proeng.2017.08.182

Zeng, Z., Lian, L., Sammut, K., He, F., Tang, Y., & Lammas, A. (2015). A survey on path planning for persistent autonomy of autonomous underwater vehicles. *Ocean Engineering*, *110*, 303–313. https://doi.org/10.1016/j.oceaneng.2015.10.007

Appendices

Appendix A: Python script for Wind Assisted Propulsion

4.2.5.1 Python program

```
# Wind Program
from netCDF4 import Dataset
import numpy as np
import matplotlib.pyplot as plt
import netCDF4

# Load wind data
f = Dataset('new.nc')
time = f.variables['time']
t_unit = f.variables['time'].units
latitude = f.variables['latitude']
longitude = f.variables['longitude']
u = f.variables['u10']
v = f.variables['v10']

# Calculate windspeed
windspeed = np.zeros([len(time), len(latitude), len(longitude)])
for i in range(len(time)):
    windspeed[i] = np.sqrt(u[i, :, :]**2 + v[i, :, :]**2)

dates = netCDF4.num2date(time[:].squeeze(), t_unit,
only_use_cftime_datetimes=False, only_use_python_datetimes=True)

# Ship parameters
ship_speed = 12 # knots
ship_power = 9480 # kW
ship_fuel_rate = 0.19 # kg/kWh

# Ship location
latShip = 6
lonShip = 3
indexLat = np.abs((latShip - latitude[:])).argmin()
indexLon = np.abs((lonShip - longitude[:])).argmin()

# Estimate fuel consumption under normal conditions
fuel_normal = ship_power * ship_fuel_rate * len(time) # kg
```

```
# Estimate potential fuel savings
wind_power = np.zeros(len(time)) # Power from sailing (kW)
for k in range(len(time)):
# Assume that power from wind is proportional to square of wind speed
# This is a crude approximation
    wind_power[k] = windspeed[k, indexLat, indexLon]**2

# Estimate fuel consumption with wind assistance
fuel_sailing = (ship_power - wind_power) * ship_fuel_rate * len(time)
fuel_sailing[fuel_sailing < 0] = 0 # Cannot consume negative fuel

# Estimate fuel savings
fuel_saved = fuel_normal - np.sum(fuel_sailing)

# Visualise
plt.plot(dates, windspeed[:, indexLat, indexLon], label='Wind speed [m/s]')
plt.plot(dates, wind_power, label='Potential wind power [kW]')
plt.legend()
plt.show()
print('Estimated fuel savings: {:.2f} kg'.format(fuel_saved))
```

Appendix B: Ocean Data Python Script

```
# Ocean data program

from netCDF4 import Dataset
import numpy as np
import matplotlib.pyplot as plt
import netCDF4
import cartopy.crs as ccrs

f = Dataset('newocean.nc')

time = f.variables['time']
t_unit =f.variables['time'].units
latitude = f.variables['latitude']
longitude = f.variables['longitude']
u = f.variables['uo']
v = f.variables['vo']

#Specifiy hourly location of ship
latShip=[6.41, 6.34, 6.18, 6.01, 5.78, 5.56, 5.35, 5.15, 4.95, 4.75, 4.58, 4.35, 4.12,
3.94, 3.59, 3.57, 3.38, 3.22, 3.11, 2.98, 2.82, 2.7, 2.58, 2.46, 2.35, 2.2, 2.05, 1.96,
1.86, 1.73, 1.62, 1.47, 1.39, 1.3, 1.21, 1.12, 1.05, 0.97, 0.87, 0.81, 0.75, 0.61, 0.61,
0.55, 0.49, 0.42, 0.4, 0.32, 0.28, 0.27]
```

```
lonShip=[3.4, 3.42, 3.42, 3.43, 3.45, 3.48, 3.5, 3.52, 3.55, 3.57, 3.59, 3.61, 3.64,
3.66, 3.69, 3.7, 3.74, 4.03, 4.18, 4.37, 4.6, 4.78, 4.94, 5.11, 5.28, 5.47, 5.69, 5.82,
5.96, 6.15, 6.32, 6.52, 6.64, 6.78, 7, 7.25, 7.45, 7.65, 7.91, 8.11, 8.27, 8.48, 8.68,
8.83, 9, 9.2, 9.33, 9.41, 9.45, 9.5]

# Create matrix of zeros for ocean current
Oceancurrent=np.zeros([len(time),len(latitude),len(longitude)])
Current=np.zeros([len(time)])
u_current=np.zeros([len(time)])
v_current=np.zeros([len(time)])
shipheading=np.zeros([len(time)])
currentdirection=np.zeros([len(time)])
AngleShiptoCurrent=np.zeros([len(time)])
ShipSpeedChange=np.zeros([len(time)])
dates=netCDF4.num2date(time[:].squeeze(), t_unit,
only_use_cftime_datetimes=False, only_use_python_datetimes=True)

Latitude = np.zeros(len(latitude))
Longitude = np.zeros(len(longitude))

for j in range (1, len(Latitude)):
    Latitude[j] = latitude[j]
for j in range (1, len(Longitude)):
    Longitude[j] = longitude[j]

# Calculate resultant ship speed
for i in range (0, len(latShip)-2):

    indexLat=np.abs((latShip[i]-Latitude)).argmin()
    indexLon=np.abs((lonShip[i]-Longitude)).argmin()

    shipheading[i] = np.arctan2(lonShip[i+1]-lonShip[i], latShip[i+1]-latShip[i])
    print(shipheading[i]*180/np.pi)

    Oceancurrent[i] = np.sqrt(u[i,:,:]**2 + v[i,:,:]**2)

    u_current = u[i,0,indexLat,indexLon]
    v_current = v[i,0,indexLat,indexLon]

    Current[i] = Oceancurrent[i,indexLat,indexLon]

    currentdirection[i] = np.arctan2(u_current, v_current)

    AngleShiptoCurrent[i] = shipheading[i]-currentdirection[i]
```

```
    ShipSpeedChange[i] = Current[i] * (-np.cos(AngleShiptoCurrent[i]))

# Visualise the ocean data
image1=plt.imshow(Oceancurrent[0,:,:], extent=[longitude[:].min(),
longitude[:].max(), latitude[:].min(), latitude[:].max()], origin='lower')
plt.colorbar(image1, label='Ocean current speed [m/s]')
plt.scatter(lonShip, latShip, c='r')
plt.ylabel('Latitude')
plt.xlabel('Longitude')
plt.show()

# Visualise
plt.plot(dates, shipheading*180/np.pi, 'r-', label='Shipheading [deg]')
plt.plot(dates, currentdirection*180/np.pi, 'b-', label='Current direction [deg]')
plt.plot(dates, AngleShiptoCurrent*180/np.pi, 'm-', label='Angle ship to current
[deg]')
plt.plot(dates, ShipSpeedChange, 'g-', label='Ship Speed change due to current
[m/s]')
plt.ylabel('Angle (Degrees)')
plt.xlabel('Time')
plt.legend()
plt.show()

plt.plot(dates, ShipSpeedChange, 'go', label='Ship Speed change due to current
[m/s]')
plt.ylabel('knot')
plt.xlabel('Time')
plt.legend()
plt.show()

# Visualise
plt.plot(dates,Current, label='Ocean current speed [m/s]')
plt.xlabel('Time')
plt.legend()
plt.show()
fig = plt.figure(figsize=(10, 7))
ax = fig.add_subplot(1, 1, 1)

# Customizing the quiver plot
q = ax.quiver(
    longitude, latitude, u[0, 0, :, :], v[0, 0, :, :],
    color="blue",        # Color of the arrows
    scale=20,            # Scales the arrow sizes; smaller values result in bigger arrows
    width=0.001,         # Width of the arrow shafts
    headlength=5,        # Length of the arrow head
```

```
    headaxislength=4.5,  # Length of the axis for the arrow head
    headwidth=4,         # Width of the base of the arrow head
    alpha=0.8,           # Arrow transparency
    label="Ocean Currents"
)

# Add a colorbar to represent the magnitude of the currents
norm = plt.Normalize(Oceancurrent[0, :, :].min(), Oceancurrent[0, :, :].max())
plt.scatter(lonShip, latShip, c='r', s=50, label="Ship's Path")  # Making ship's path
dots a bit larger
plt.ylabel('Latitude')
plt.xlabel('Longitude')
plt.legend()
plt.show()
np.savetxt('ShipSpeedChange.txt',ShipSpeedChange, fmt='%10.16f')
np.savetxt('datesOcean.txt',dates, fmt='%str')
```

Appendix C: Python script for Solar irradiation data

```
# Solar data program

from netCDF4 import Dataset
import numpy as np
import matplotlib.pyplot as plt
import netCDF4

f = Dataset('solar.nc')

time = f.variables['time']
t_unit =f.variables['time'].units
latitude = f.variables['latitude']
longitude = f.variables['longitude']
solar = f.variables['fdir']

#Specifiy hourly location of ship
latShip=[6.41, 6.34, 6.18, 6.01, 5.78, 5.56, 5.35, 5.15, 4.95, 4.75, 4.58, 4.35, 4.12,
3.94, 3.59, 3.57, 3.38, 3.22, 3.11, 2.98, 2.82, 2.7, 2.58, 2.46, 2.35, 2.2, 2.05, 1.96,
1.86, 1.73, 1.62, 1.47, 1.39, 1.3, 1.21, 1.12, 1.05, 0.97, 0.87, 0.81, 0.75, 0.61, 0.61,
0.55, 0.49, 0.42, 0.4, 0.32, 0.28, 0.27]
lonShip=[3.4, 3.42, 3.42, 3.43, 3.45, 3.48, 3.5, 3.52, 3.55, 3.57, 3.59, 3.61, 3.64,
3.66, 3.69, 3.7, 3.74, 4.03, 4.18, 4.37, 4.6, 4.78, 4.94, 5.11, 5.28, 5.47, 5.69, 5.82,
5.96, 6.15, 6.32, 6.52, 6.64, 6.78, 7, 7.25, 7.45, 7.65, 7.91, 8.11, 8.27, 8.48, 8.68,
8.83, 9, 9.2, 9.33, 9.41, 9.45, 9.5]

# Create matrix of zeros for ocean current
Oceancurrent=np.zeros([len(time),len(latitude),len(longitude)])
```

```
Current=np.zeros([len(time)])
u_current=np.zeros([len(time)])
v_current=np.zeros([len(time)])
shipheading=np.zeros([len(time)])
currentdirection=np.zeros([len(time)])
AngleShiptoCurrent=np.zeros([len(time)])
SolarAtShip=np.zeros([len(time)])
ShipSpeedChange=np.zeros([len(time)])
Solar=np.zeros([len(time),int(len(latitude)),int(len(longitude))])
dates=netCDF4.num2date(time[:].squeeze(), t_unit,
only_use_cftime_datetimes=False, only_use_python_datetimes=True)

Latitude = np.zeros(len(latitude))
Longitude = np.zeros(len(longitude))

for j in range (1, len(Latitude)):
    Latitude[j] = latitude[j]
for j in range (1, len(Longitude)):
    Longitude[j] = longitude[j]

Solar = solar[:, 0:int(len(latitude)), 0:int(len(longitude))]/(60*60)

# Calculate resultant wind speed
for i in range (0, len(latShip)-1):

    indexLat=np.abs((latShip[i]-Latitude)).argmin()
    indexLon=np.abs((lonShip[i]-Longitude)).argmin()
    shipheading[i] = np.arctan2(lonShip[i+1]-lonShip[i], latShip[i+1]-latShip[i])
    print(shipheading[i]*180/np.pi)
    SolarAtShip[i] = Solar[i+18,indexLat,indexLon]

# Visualise the solar
image3=plt.imshow(Solar[11,:,:], extent=[longitude[:].min(), longitude[:].max(),
latitude[:].min(), latitude[:].max()])
plt.colorbar(image3, label='Solar irradiation [W/m2]')
plt.scatter(lonShip, latShip, c='r')
plt.show()

# Visualise solar at ship
plt.plot(dates, SolarAtShip, 'r-', label='Solar Power at Ship [W]')
plt.ylabel('solar irrradiation [W/m2]')
plt.xlabel('Time')
plt.legend()
plt.show()
```

```
np.savetxt('SolarPower.txt',SolarAtShip, fmt='%10.16f')
np.savetxt('datesOcean.txt',dates, fmt='%str')
```

Appendix D: Fuel consumption analysis for scenario 1

Name	IMO Number		SFOC	0.19	kg/kwh
Power	9480		time	1	hour
max speed	16.4				
c	2.149199808		speed	6.7	

Hours	Speed	power	mass of fuel	Optimised speed	new power	new fuel consumption
1	11.5	3268.66426	621.046209	6.7	646.399782	122.8159586
2	11.1	2939.31228	558.469334	6.7	646.399782	122.8159586
3	11.2	3019.47099	573.699488	6.7	646.399782	122.8159586
4	11	2860.58495	543.51114	6.7	646.399782	122.8159586
5	10.6	2559.73136	486.348958	6.7	646.399782	122.8159586
6	11	2860.58495	543.51114	6.7	646.399782	122.8159586
7	10.7	2632.86218	500.243814	6.7	646.399782	122.8159586
8	11.1	2939.31228	558.469334	6.7	646.399782	122.8159586
9	11.4	3184.13408	604.985475	6.7	646.399782	122.8159586
10	11.5	3268.66426	621.046209	6.7	646.399782	122.8159586
11	11.4	3184.13408	604.985475	6.7	646.399782	122.8159586
12	11.9	3621.7434	688.131246	6.7	646.399782	122.8159586
13	12	3713.81727	705.625281	6.7	646.399782	122.8159586
14	12	3713.81727	705.625281	6.7	646.399782	122.8159586
15	12.3	3999.375	759.88125	6.7	646.399782	122.8159586
16	11.7	3442.18635	654.015407	6.7	646.399782	122.8159586
17	11.3	3101.07396	589.204052	6.7	646.399782	122.8159586
18	11.6	3354.67738	637.388703	6.7	646.399782	122.8159586
19	11.5	3268.66426	621.046209	6.7	646.399782	122.8159586
20	11.5	3268.66426	621.046209	6.7	646.399782	122.8159586
21	12	3713.81727	705.625281	6.7	646.399782	122.8159586
22	12.2	3902.62017	741.497833	6.7	646.399782	122.8159586
23	12	3713.81727	705.625281	6.7	646.399782	122.8159586
24	12.1	3807.43856	723.413327	6.7	646.399782	122.8159586
25	12.7	4402.38435	836.453027	6.7	646.399782	122.8159586
26	12.2	3902.62017	741.497833	6.7	646.399782	122.8159586
27	12.4	4097.71594	778.566028	6.7	646.399782	122.8159586
28	12.3	3999.375	759.88125	6.7	646.399782	122.8159586
29	12.7	4402.38435	836.453027	6.7	646.399782	122.8159586
30	12.5	4197.65588	797.554616	6.7	646.399782	122.8159586
31	12.4	4097.71594	778.566028	6.7	646.399782	122.8159586
32	13	4721.79198	897.140476	6.7	646.399782	122.8159586
33	13.2	4943.09079	939.187249	6.7	646.399782	122.8159586
34	13	4721.79198	897.140476	6.7	646.399782	122.8159586
35	12.8	4507.19868	856.367749	6.7	646.399782	122.8159586
36	12.3	3999.375	759.88125	6.7	646.399782	122.8159586
37	6	464.227159	88.2031601	6.7	646.399782	122.8159586
38	0	0	0	6.7	646.399782	122.8159586
39	0	0	0	6.7	646.399782	122.8159586
40	0	0	0	6.7	646.399782	122.8159586
41	0	0	0	6.7	646.399782	122.8159586
42	0	0	0	6.7	646.399782	122.8159586
43	0	0	0	6.7	646.399782	122.8159586
44	0	0	0	6.7	646.399782	122.8159586
45	0	0	0	6.7	646.399782	122.8159586
46	0	0	0	6.7	646.399782	122.8159586
47	0	0	0	6.7	646.399782	122.8159586
48	0.2	0.0171936	0.00326678	6.7	646.399782	122.8159586
49	0	0	0	6.7	646.399782	122.8159586
50	0	0	0	6.7	646.399782	122.8159586
51	0	0	0	6.7	646.399782	122.8159586
52	0	0	0	6.7	646.399782	122.8159586
53	0	0	0	6.7	646.399782	122.8159586
54	0	0	0	6.7	646.399782	122.8159586
55	0	0	0	6.7	646.399782	122.8159586
56	0	0	0	6.7	646.399782	122.8159586
57	0	0	0	6.7	646.399782	122.8159586
58	0	0	0	6.7	646.399782	122.8159586
59	0	0	0	6.7	646.399782	122.8159586
60	3.3	77.2357935	14.6748008	6.7	646.399782	122.8159586
61	4.2	159.229915	30.2536839	6.7	646.399782	122.8159586
62	2.5	33.581247	6.38043693	6.7	646.399782	122.8159586
63	0	0	0	6.7	646.399782	122.8159586
64	0	0	0	6.7	646.399782	122.8159586
65	0	0	0	6.7	646.399782	122.8159586
66	0	0	0	6.7	646.399782	122.8159586
67	3.2	70.4249793	13.3807461	6.7	646.399782	122.8159586
68	3.7	108.863418	20.6840494	6.7	646.399782	122.8159586
69	2.2	22.8846796	4.34808912	6.7	646.399782	122.8159586
70	8.6	1367.01143	259.732172	6.7	646.399782	122.8159586
71	9.8	2022.80967	384.333837	6.7	646.399782	122.8159586
72	11.1	2939.31228	558.469334	6.7	646.399782	122.8159586
73	8.7	1415.25452	268.898359	6.7	646.399782	122.8159586
74	1.3	4.72179198	0.89714048	6.7	646.399782	122.8159586
			26603.39			9088.380935

Appendix E: Appendix D: Fuel consumption analysis for scenario 2

Name	IMO number	SFOC	0.1607	
		initial time	119	
Power	6480	Time	1	hour
Max speed	14			
c	2.36151603	new distance	487.59	new time

Hours	Speed	Power	mass of fuel
1	2.0	18.8921283	3.03596501
2	7.2	863.195215	138.715471
3	8.8	1591.08866	255.687947
4	6.8	748.009428	120.205115
5	2.1	22.3948579	3.59885366
6	0.2	0.03	0.004821
7	0.0	0	0
8	0.0	0	0
9	0.1	0.00236152	0.0003795
10	0.2	0.00797012	0.0012808
11	0.4	0.15113703	0.02428772
12	0.1	0.00236152	0.0003795
13	0.0	0	0
14	0.0	0	0
15	0.2	0.01889213	0.00303597
16	0.0	0	0
17	0.0	0	0
18	0.4	0.12453307	0.02001246
19	4.0	145.539938	23.388268
20	8.8	1609.30706	258.615644
21	7.2	872.281406	140.175622
22	7.0	792.766542	127.397583
23	7.3	899.922103	144.617482
24	3.2	73.81125	11.8614679
25	7.0	810	130.167

26	7.3	918.669883	147.63025
27	7.1	845.212566	135.825659
28	7.6	1036.64886	166.589472
29	7.4	969.932974	155.868229
30	7.8	1099.24882	176.649285
31	7.7	1078.11	173.252277
32	7.6	1036.64886	166.589472
33	7.2	881.431137	141.645984
34	7.4	944.069475	151.711965
35	7.5	996.264577	160.099718
36	7.6	1036.64886	166.589472
37	7.5	976.471826	156.919022
38	7.8	1120.66216	180.090409
39	7.5	1009.60723	162.243882
40	7.6	1036.64886	166.589472
41	7.6	1016.323	163.323106
42	8.0	1209.09621	194.301761
43	7.7	1078.11	173.252277
44	7.9	1164.3195	187.106144
45	7.9	1175.40819	188.888096
46	8.0	1216.66882	195.518679
47	8.0	1186.56705	190.681325
48	8.0	1186.56705	190.681325
49	8.5	1424.82336	228.969113
50	8.3	1350.28417	216.990666
51	8.3	1366.61808	219.615525
52	8.2	1311.61493	210.776519
53	8.4	1399.68	224.928576
54	8.4	1399.68	224.928576
55	9.0	1740.7444	279.737625
56	9.0	1702.48767	273.589768
57	8.9	1664.7956	267.532653
58	9.1	1756.20614	282.222327
59	9.2	1818.96866	292.308263
60	9.3	1869.02925	300.353
61	9.4	1930.30409	310.199868
62	9.6	2067.63	332.268141
63	9.7	2122.13417	341.026962

64	9.7	2133.14869	342.796994
65	9.9	2314.59988	371.956201
66	2.7	43.9469278	7.0622713
67	1.7	11.6021283	1.86446201
68	1.4	6.09130685	0.97887301
69	3.8	133.336852	21.4272321
70	2.8	51.050572	8.20382693
71	1.6	9.08072886	1.45927313
72	1.7	11.6021283	1.86446201
73	0.9	1.72154519	0.27665231
74	1.1	3.14317784	0.50510868
75	1.5	7.19937682	1.15693986
76	1.2	4.08069971	0.65576844
77	1.1	2.73375	0.43931363
78	1.0	2.36151603	0.37949563
79	3.7	119.617872	19.222592
80	10.5	2733.75	439.313625
81	10.7	2892.95869	464.898461
82	10.6	2812.60338	451.985363
83	10.6	2812.60338	451.985363
84	10.7	2892.95869	464.898461
85	10.9	3016.33875	484.725637
86	10.8	2933.70399	471.446231
87	10.8	2933.70399	471.446231
88	10.6	2812.60338	451.985363
89	10.7	2892.95869	464.898461
90	10.9	3058.23175	491.457842
91	11.0	3143.17784	505.108679
92	11.0	3100.51086	498.252095
93	11.0	3143.17784	505.108679
94	11.1	3229.68254	519.009984
95	11.0	3171.83886	509.714505
96	11.0	3143.17784	505.108679
97	10.4	2656.38437	426.880969
98	10.7	2852.59241	458.4116
99	10.8	3002.45991	482.495308
100	10.4	2675.58708	429.966843
101	6.6	668.691516	107.458727

102	1.0	2.02470481	0.32537006
103	1.3	5.18825073	0.83375189
104	1.2	3.5915707	0.57716541
105	1.2	4.08069971	0.65576844
106	1.0	2.36151603	0.37949563
107	0.5	0.2951895	0.04743695
108	0.7	0.81	0.130167
109	9.2	1818.96866	292.308263
110	10.9	3030.26029	486.962829
111	10.9	3086.37481	495.980432
112	10.8	2954.21933	474.743046
113	5.5	400.084198	64.2935307
114	2.7	45.2024795	7.26403846
115	1.6	9.67276968	1.55441409
116	2.0	18.8921283	3.03596501
117	6.6	685.117194	110.098333
118	4.4	199.643262	32.0826722
119	0.0	0	0
			22063.0947 kg

Appendix E: Fuel consumption analysis for scenario 3

Name	IMO number		SFOC	0.19	kg/kwh	Hatch Area	1720.4
						PV Efficiency	0.2
Power	9480	kW	time	1	hour		
max speed							
c	3.24190456		max speed	14.3			

Time	Speed	Power	mass of fuel consumed	speed chang	resultant speed d	new power	mass of fuel consumed with ocean current	solar irradiance	Solar Power	Power (kW)
1	5.7	600.3780307	114.0718258	0.02481612	5.7	608.2538268	115.5682271	22.53639242	7754.3219	7.7543219
2	10.6	3861.160198	733.6204377	-0.0097656	10.6	3850.498349	731.5946863	0	0	0
3	11.5	4930.531594	936.8010028	-0.0014336	11.5	4928.687834	936.4506885	0	0	0
4	12.0	5602.011075	1064.382104	-0.1649262	11.8	5374.19146	1021.096377	0	0	0
5	12.0	5602.011075	1064.382104	-0.059244	11.9	5519.448683	1048.69525	0	0	0
6	11.8	5326.552929	1012.045056	-0.0157398	11.8	5305.26639	1008.000614	0	0	0
7	12.1	5743.23168	1091.214019	0.04761407	12.1	5811.298492	1104.146714	0	0	0
8	12.2	5886.805907	1118.493122	0.00391132	12.2	5892.469653	1119.569234	0	0	0
9	12.1	5743.23168	1091.214019	-0.0509179	12.0	5671.032225	1077.496123	0	0	0
10	12.1	5743.23168	1091.214019	0.03799623	12.1	5797.506168	1101.526172	0	0	0
11	12.2	5886.805907	1118.493122	0.19567803	12.4	6174.6321	1173.180099	0	0	0
12	12.4	6181.093035	1174.407677	0.07586888	12.5	6295.244905	1196.096532	0	0	0
13	12.5	6331.844839	1203.050519	-0.0242647	12.5	6295.042634	1196.058101	0.192501217	66.2358186	0.06623582
14	12.7	6640.662183	1261.725815	-0.0438682	12.7	6572.085361	1248.696219	54.1340921	18626.4584	18.6264584
15	12.8	6798.766626	1291.765659	0.07162406	12.9	6913.536587	1313.571952	196.7087431	67683.5443	67.6835443
16	12.8	6798.766626	1291.765659	0.08836925	12.9	6940.553956	1318.705252	209.991327	72253.8158	72.2538158
17	13.1	7288.096458	1384.738327	-0.0184279	13.1	7257.382925	1378.902756	234.8652342	80812.4298	80.8124298
18	13.3	7627.024612	1449.134676	0.16684603	13.5	7917.679334	1504.359073	173.0173434	59531.8075	59.5318075
19	13.4	7800.359523	1482.068309	0.12310041	13.5	8017.316771	1523.290186	95.87935591	32990.1688	32.9901688
20	13.2	7456.276741	1416.692581	0.13258846	13.3	7683.226679	1459.813069	106.8656753	36770.3416	36.7703416
21	13.1	7288.096458	1384.738327	0.03900236	13.1	7353.386552	1397.143445	142.4234001	49005.0435	49.0050435
22	13.0	7122.464313	1353.268219	0.0578125	13.1	7217.910783	1371.403049	53.8178401	18517.6424	18.5176424
23	12.9	6959.360852	1322.278562	-0.0022057	12.9	6955.791565	1321.600397	25.90516371	8913.44873	8.91344873
24	12.8	6798.766626	1291.765659	-0.0173624	12.8	6771.13778	1286.516178	3.836274244	1319.98524	1.31998524
25	12.6	6485.028071	1232.155333	-0.0911716	12.5	6345.270299	1205.601357	1.498759471	515.693159	0.51569316
26	12.4	6181.093035	1174.407677	-0.1629496	12.2	5940.602215	1128.714421	0	0	0
27	12.5	6331.844839	1203.050519	-0.1694783	12.3	6077.774435	1154.777143	0	0	0
28	12.4	6181.093035	1174.407677	-0.1778907	12.2	5918.868851	1124.585082	0	0	0
29	12.6	6485.028071	1232.155333	-0.1211067	12.5	6299.824298	1196.966617	0	0	0
30	12.5	6331.844839	1203.050519	-0.0800119	12.4	6211.031982	1180.096077	0	0	0
31	12.8	6798.766626	1291.765659	-0.0439453	12.8	6728.981622	1278.506508	0	0	0
32	12.9	6959.360852	1322.278562	0.00541699	12.9	6968.1317	1323.945023	0	0	0
33	13.2	7456.276741	1416.692581	0.04600195	13.2	7534.504014	1431.555763	0	0	0
34	12.9	6959.360852	1322.278562	0.11507711	13.0	7147.274482	1357.982152	0	0	0
35	13.0	7122.464313	1353.268219	0.0059173	13.0	7132.194684	1355.11699	0	0	0
36	13.1	7288.096458	1384.738327	-0.1491831	13.0	7041.930197	1337.966737	0	0	0
37	12.8	6798.766626	1291.765659	-0.1450745	12.7	6570.206254	1248.339188	1.828761557	629.240277	0.62924028
38	12.7	6640.662183	1261.725815	-0.1561419	12.5	6398.727617	1215.758247	70.16669342	24142.9559	24.1429559
39	12.7	6640.662183	1261.725815	-0.097934	12.6	6488.218625	1232.761539	54.12034202	18621.7273	18.6217273
40	13.0	7122.464313	1353.268219	-0.1096118	12.9	6943.816184	1319.325075	156.8884915	53982.1921	53.9821921
41	13.1	7288.096458	1384.738327	-0.1663017	12.9	7014.042644	1332.668102	146.8234279	50519.0051	50.5190051
42	13.4	7800.359523	1482.068309	-0.1933593	13.2	7467.535708	1418.831784	82.98177441	28552.3689	28.5523689
43	13.3	7627.024612	1449.134676	-0.3260549	13.0	7079.725048	1345.147759	346.1034372	119087.271	119.087271
44	13.3	7627.024612	1449.134676	-0.3627761	12.9	7019.780093	1333.758218	305.7744324	105210.867	105.210867
45	13.3	7627.024612	1449.134676	-0.088625	13.2	7475.56956	1420.358216	405.0088095	139355.431	139.355431
46	9.7	2958.798758	562.171764	-0.0187102	9.7	2941.710234	558.9249445	293.9356075	101137.364	101.137364
47	7.5	1367.678485	259.8589122	0.0407415	7.5	1390.088292	264.1167754	147.1259298	50623.0899	50.6230899
48	5.6	569.3303107	108.172759	-0.0055243	5.6	567.6470787	107.8529449	20.32262843	6992.60999	6.99260999
49	2.1	30.02327811	5.70442284	0	2.1	30.02327811	5.70442284	1.086256865	373.759262	0.37375926
50	0.0	0	0	0	0.0	0	0	0	0	0
			56372.18382				55832.84148		1153988.82	1153.98882