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USE OF VARIABLE FREQUENCY DRIVE TECHNOLOGY IN SHIPS - APPLICATIONS

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Περίληψη

Η παρούσα διατριβή εξετάζει την τεχνική, λειτουργική και οικονομική σκοπιμότητα της εγκατάστασης μετατροπέων συχνότητας (VFDs) στις αντλίες έρματος ενός πλοίου Supramax bulk carrier. Στόχος της μελέτης είναι να αναλυθούν οι ενεργειακές απώλειες που συνδέονται με τον συμβατικό έλεγχο παροχής μέσω στραγγαλιστικών βαλβίδων και να εκτιμηθεί η δυνατότητα των VFDs να μειώσουν την κατανάλωση ενέργειας, τα καύσιμα και τις εκπομπές αερίων του θερμοκηπίου.Η μεθοδολογία βασίστηκε στη μοντελοποίηση της λειτουργίας των αντλιών και στην εφαρμογή των νόμων ομοιότητας, επιτρέποντας τη σύγκριση στραγγαλιστικού ελέγχου και ελέγχου μέσω VFD σε διαφορετικά σενάρια λειτουργίας. Τα αποτελέσματα δείχνουν ότι μπορούν να επιτευχθούν ενεργειακές εξοικονομήσεις της τάξης του 50–70% σε μερικά φορτία, οι οποίες αντιστοιχούν σε ετήσιες μειώσεις εκπομπών CO_2 της τάξης των 10–50 τόνων για τυπικές ποσότητες άντλησης έρματος. Η οικονομική ανάλυση καταδεικνύει ότι, ενώ η επένδυση δεν είναι ελκυστική για πλοία με χαμηλή ζήτηση έρματος και χαμηλές τιμές καυσίμων, καθίσταται ιδιαίτερα συμφέρουσα σε σενάρια μεσαίας και υψηλής χρήσης, με περιόδους απόσβεσης 2–6 ετών και έντονα θετικές Καθαρές Παρούσες Αξίες σε ορίζοντα δεκαετίας.

Εκτός από τα ποσοτικά οφέλη, η εγκατάσταση VFDs προσφέρει και ποιοτικές βελτιώσεις, όπως ομαλότερη λειτουργία, μειωμένη μηχανική φθορά, παράταση της διάρκειας ζωής των αντλιών και καλύτερη συμμόρφωση με κανονισμούς όπως ο Δείκτης Ενεργειακής Αποδοτικότητας Υφιστάμενων Πλοίων (EEXI) και ο Δείκτης Έντασης Άνθρακα (CII).

Η μελέτη αποδεικνύει ότι η εγκατάσταση VFDs στις αντλίες έρματος αποτελεί μια πρακτική και επεκτάσιμη λύση που βελτιώνει την ενεργειακή απόδοση, μειώνει τις εκπομπές και ενισχύει το περιβαλλοντικό προφίλ των bulk carriers. Τα ευρήματα παρέχουν τεχνική και οικονομική τεκμηρίωση για την ευρύτερη υιοθέτηση της τεχνολογίας VFD στη ναυτιλία.

Λέξεις-κλειδιά: Μείωση εκπομπών CO_2, ναυτιλιακή βιωσιμότητα.

Abstract

This thesis research examines the technical, operational and economic feasibility of the installation of Variable Frequency Drive (VFD) units on the ballast pumps of a Supramax bulk carrier. The paper focuses on the inefficiencies of traditional throttling-based pump control and the promise of VFD retrofits, with regards to energy savings, fuel saving, and greenhouse gas emissions.

The study integrated pump performance modeling and the use of affinity laws together to lead to a comparative study of throttling and VFD control in various flow regimes. The results show that at partial loadings, energy savings of 50-70 percent are possible, which means that for typical ballast water throughput, savings of 10-50 tonnes of CO2 can be achieved annually. The economic feasibility analysis revealed that although the investment is not attractive for vessels with low ballast demand and low fuel prices the investment is attractive under medium- to high-utilisation scenarios with payback periods of two to six years and strongly positive NPV horizons of 10 years.

In addition to measurable savings, VFD integration also provides qualitative advantages such as smoother operation, reduced mechanical wear, longer pump life, and greater compliance with the new environmental regulations, such as the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII).

In conclusion, the study shows that the VFD retrofits on ballast pumps are a viable and scalable energy efficiency measure, capable of reducing emissions and improving the sustainability profile of bulk carriers. The results not only provide technical justification, but also several economic reasons to favor the wider use of VFD technology in the maritime industry.

Keywords: Variable Frequency Drives, Energy Efficiency, Bulk Carrier, CO_2 Emissions Reduction, Maritime Sustainability

Contents

Chapter 1 Introduction

1.1. Contextual background

The shipping sector is one of the most pivotal for international trade, keeping in mind the volume estimate of about 80% of the total traded merchandise in the world (Smith et al., 2015). It provides big contributions to the global economy due to its role of transportation of goods while causing significant big environmental challenges. In respect to that, the other side of it also contains the biggest consumers of fossil fuels with high GHG emissions (Buhaug et al., 2009).

The International Maritime Organization has estimated that in 2012, the world fleet of ships consumed about 250 million tonnes of fuel and produced about 938 million tonnes of CO_2 emissions, accounting for about 2.2% of global CO_2 emissions in the same year (IMO, 2014). Without any mitigations, these emissions were projected to increase by 50% to 250% by 2050, assuming economic growth and pace of energy efficiency (Buhaug et al., 2009).

The IMO has been fast-tracking the adoption of environmental regulations to improve energy efficiency and reduce pollutant emissions. Among these, the Energy Efficiency Design Index (EEDI), effective since 2011, introduced stringent energy efficiency criteria for newly constructed vessels from beyond the above-mentioned date (IMO, 2011). In tandem with this, SEEMP was adopted, which pursues the principle of continuous energy performance improvement in ships already in service (IMO, 2012). Recently, this has been supported by the adoption of the Existing Ships Energy Efficiency Index and Carbon Intensity Index, EEXI and CII respectively, which align the performance of ships with the new environmental standard, established by the IMO in 2020 (IMO, 2020).

The integration of ballast water management systems (BWMS) has been identified as an essential component in ensuring compliance with these environmental regulations (David & Gollasch, 2015). Systems targeting aquatic invasive species, while underpinning international conventions-the 2004 IMO Ballast Water Management

Convention in this case-can be attained in application. Advanced water treatment technologies employed in BWMS not only reduce ecological impact caused by ships but also promote their operational sustainability (Doblin & Dobbs 2006).

Unfortunately, however, despite such moves and plans for rational improvement of the existing system, significant inefficiencies in traditional conventional ballast pump systems were still evident. The regular, everyday conventional systems make use of constant-speed centrifugal pumps, which usually run fully even when the requirement was for a much lesser flow rate (Wong et al., 2014). This leads to overconsumption of energy and mechanical wear and tear, hence raising the chances of reducing equipment life or increasing the operating cost on the whole (Mannan & Lees, 2012). Moreover, traditional flow governing approaches, for example through the use of throttle valves, result in more pressure loss, adding to system inefficiency (Wang & Taylor 2011).

There are also environmental concerns related to the risks of invasive species transfer through untreated ballast water, which further enhances disturbance in marine ecosystems. Likewise, technological innovations in current times, such as the use of variable frequency drives, increase the adoption of energy-optimizing and ecological minimalizing of ballast pump systems (David & Gollasch, 2015).

The combination of challenges related to energy consumption, GHG emissions and ballast water management highlights the need to adopt advanced technological solutions to meet growing environmental requirements. This study aims to assess the technical and economic feasibility of variable frequency drives as a means of improving ballast pump efficiency while reducing operating costs and environmental impacts.

1.2. Research problem and objectives

A critical problem in the marine sector is the high energy consumption of traditional ballast water pumping systems. Nevertheless, these systems run at constant speeds, regardless of need, and therefore lead to inefficient energy use and, hence, higher operating costs and greenhouse gas emissions (Mannan & Lees, 2012; Wong et al., 2014). The use of throttling valves for flow control increases observed energy inefficiency, adding hydraulic losses and accelerating mechanical wear of equipment (Wang & Taylor, 20111).

Constrained to these limitations, one promising means for the optimization of energy use and reduction of environmental impact is proposed to involve the integration of variable frequency drives (VFDs). Saidur et al., (2012) indicate that VFDs facilitate the dynamical adjustment of the speed of pumps electric motors and smooth their performance with the real demand. This technology may result in energy savings of up to 30% while minimizing energy losses and increasing the durability of the systems (Petrov & Gomez Diaz, 2020).

This study aims to achieve the following objectives:

- Evaluate the energy savings and CO_2 emissions reduction resulting from the installation of VFDs on ballast pumps. The analysis draws on mathematical models, real operating data and experimental evaluations to quantify energy gains (Su et al., 2013).
- Examine the operational and economic feasibility of integrating VFDs, taking into account installation costs, long-term economic benefits and regulatory compliance requirements (Petrov & Gomez Diaz, 2020).
- Quantify pump performance improvements in terms of hydraulic efficiency and operational adaptability, while identifying best practices for optimizing the use of ballast pumps (Su et al., 2015).

These objectives are designed to provide a solid evidence base for assessing the energy and environmental benefits of installing VFDs, while offering practical guidance for their widespread adoption.

1.3 Significance of the study

In response to obvious environmental concerns and demand for energy optimization in the sector (Räsänen & Schreiber, 2012; Su et al., 2015), this study seeks to contribute to the enhancement of energy efficiency in marine operations. The study focuses on integrating the VFDs in ballast pumps to provide a practical and innovative approach for decreasing energy consumption and limiting CO_2 emissions.

The outcome of this research is consistent with the international regulation adopted by the International Maritime Organization (IMO) with the guidelines of energy efficiency index order Existing Ships Energy Efficiency Index (EEXI) and Carbon Intensity Indicator (CII) which impose the ongoing improvement of vessel energy performance and continuous reduction of it CO2 emission (IMO, 2021). The study shows that when proposed solutions align with the requirements, it is possible to proactively guarantee compliance with regulation and to foster environmental sustainability.

In the economic terms, results on the reduction of fuel costs obtained as a result of the energy optimization are described. Lowering the energy requirements of ballast pumps can have benefits for ships by reducing their operational expenses, and increase their competitiveness on the global market. Moreover, energy saving and emission reduction contributes to the decreasing of the carbon footprint of maritime operation from the side of stakeholders, answering their expectations of the sustainability and environmental responsibility (Petrov & Gomez Diaz, 2020).

This study also has wider implication to industrial practice. It puts forward a replicable model to retrofit the older ships by incorporating energy efficient systems so that they can operate in more sustainably manner (Su et al., 2013). The model could be applied to other energy intensive onboard ship systems, such as fans and cooling systems, and would further strengthen integrated energy management strategies for shipping (Räsänen, & Schreiber, 2012).

This research provides an essential analytical and technical basis for assessing the economic and environmental impacts of VFDs in ballast pump systems. It highlights applicable and reproducible solutions to the energy challenges of the marine sector, while ensuring compliance with global environmental regulations.

1.4. Research Questions

The aim of this study is to investigate the impact of variable frequency drives (VFDs) on the energy efficiency of ballast pumps and to assess their effects in terms of CO_2 emissions and fuel consumption. Several key questions guide this research:

- What is the impact of VFD units on the energy efficiency of ballast pumps?

This question explores the ability of VFDs to optimize energy consumption, by dynamically adjusting pump speed according to operational needs (Saidur et al., 2012).

- How does the installation of VFDs influence CO_2 emissions and fuel consumption?

The focus is on reducing pollutant emissions by improving energy efficiency, in line with the environmental objectives of the International Maritime Organization (IMO, 2021).

- What are the operational and economic gains resulting from the integration of VFD units?

The aim is to assess cost savings and improvements in operational performance through concrete examples taken from the case study (Petrov & Gomez Diaz, 2020).

- What are the main technical and economic challenges of implementing VFDs in ballast pumping systems?

This question addresses installation constraints, initial costs, and maintenance requirements, while identifying potential obstacles to the adoption of this technology in the existing fleet (Su et al., 2015).

1.5. Structure of the Dissertation

The structure of this dissertation is intended to provide a complete analysis of the technical and economic impacts to the use of variable frequency drives (VFDs) on the ballast pumping system.

We then provide a detailed analysis of global consumption trends in shipping fuel. Technological advances in ballast water management system (BWMS) (Smith et al., 2015; IMO, 2020) and regulatory frameworks that set the stage for industrial practices prioritising energy efficiency and emissions reduction are reviewed.

Chapter 3: Methodology

Data collection methods and analytical frameworks that were used to assess energy consumption and emissions are described. Specific pump affinity laws and simulations are explained to provide rigorous analysis (Stepanoff, 1957; Dixon & Hall, 2010).

Chapter 4: Case study analysis

An in-depth analysis of the technical characteristics of the vessel being studied, pump performance and procedures for VFD integration are presented in this chapter. Results are validated with technical diagrams and pump performance curves (Karassik et al., 2001).

Chapter 5: Economic feasibility study

The energy savings, operating costs and return on investment are analyzed using an economic analysis. To ascertain the financial viability of this technology, installation costs, maintenance costs and the emission reductions are studied (Su et al., 2015; Petrov & Gomez Diaz, 2020).

Chapter 6: Also, conclusions and recommendations.

Key points from the study are concluded, and recommendations are made aimed to promote the using of this technology into the marine industry. Furthermore, the implications of the results for future research pertaining to improving the accuracy of estimates, and identifying further applications of VFDs in different pumping systems are discussed (Räsänen & Schreiber, 2012).

Chapter 2 Literature review

2.1. World Shipping Fuel Consumption Trends

The maritime transportation sector represents the backbone of international trade since it is responsible for about 80% of the volume of commodities exchanged around the world. At the same time, the shipping industry is actually one of the large consumers of fossil fuel resources, which leads to the generation of substantial GHG emissions. Consumption of fuel by shipping is on an upward trend because of the expansion in international trade and the increase in the global container fleet (Smith et al., 2015).

It is estimated that the world fleet consumed about 250 million tonnes of fuel in 2012, giving rise to about 938 million tonnes of CO_2 emissions, accounting for about 2.2% of worldwide CO_2 emissions that year (IMO, 2014). Without any mitigation, emissions will increase to as much as 50 % to 250 % above the levels in 2012 by 2050, depending on economic growth and any improvements in energy efficiency (Buhaug et al., 2009).

Technology advances and economies of scale that have moved towards greater ship size result in a higher absolute fuel consumption values due to greater carrying capacity and consequently operating requirements, despite being more efficient per tonne-mile (Psaraftis & Kontovas, 2012). Moreover, slow sailing that was widely followed as a way of saving fuel costs after the financial crisis in 2008 started to decline mainly due to positive changes in the macroeconomic environment and may, therefore, allow for the introduction of higher speeds in maritime transport and higher fuel consumption (Notteboom & Vernimmen, 2009).

Another element that influences the consumption patterns discussed above is fuel price volatility. High fuel costs, in particular, incentivize shipowners to invest in energy-efficient technologies and operational strategies to reduce such consumption.

Rather, lower fuel prices depress this kind of related investment; hence the establishment of regulatory frameworks becomes very important to stir energy efficiency, regardless of market fluctuations in fuel prices (Poulsen & Johnson, 2016).

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2.2. Regulatory frameworks promoting energy efficiency in the shipping sector

Accordingly, in response to the environmental impact of fuel consumption in maritime transport, a regulatory framework has been developed by regulatory bodies, particularly the International Maritime Organization, aimed at improving energy efficiency and reduction of greenhouse gas emissions from ships.

In this respect, the Energy Efficiency Design Index (EEDI) is the mandatory measure taken by the IMO in 2011, targeting ships from then on, having put into practice the use of more energy-efficient equipment onboard a maritime vessel (IMO, 2011a). This requires new ships to meet a minimum energy efficiency level per tonnage mile that is progressively tightened over time. For example, the incoming EEDI Phase 3 in 2025 has a more green-friendly approach, with a 30% reduction in CO_2 emissions per tonne-mile for most vessel types, considering the baseline of 2013. IMO (2020).

Complementary to EEDI, the Ship Energy Efficiency Management Plan (SEEMP) is an operational standard that came into force in 2013, which requires all ships (newbuilding and existing) to develop a plan to improve their energy efficiency during operation (IMO, 2012). The SEEMP encourages ship owners and operators to consider best practices for fuel efficiency, such as optimized voyage planning, speed optimization and regular cleaning of ships' hulls and propellers.

The Energy Efficiency of Existing Ships Index (EEXI), adopted in June 2021, extends the principles of the EEDI to existing ships, with the aim of bringing their energy efficiency closer to that of newer ships (IMO, 2021a). Ships are required to identify their achieved EEXI and ensure that the performance they record meets the required EEXI value, which may require technical modifications such as power curtailment, engine retrofit or installation of energy-saving devices.

The Carbon Intensity Index (CII) is a measure established to assess and rate the operational carbon intensity of ships on an annual basis (IMO, 2021a).

Ships would be required to calculate the attained annual operational CII and implement a continuous performance improvement plan. The CII scale would be A ; corrective action should be necessary for ships ranked D for a period of three consecutive years or for those ranked E for any year (IMO, 2013b).

MARPOL Annex VI sets limits for nitrogen oxides (NO_x) and sulphur oxides (SO_x) emissions from ships' exhaust gases and prohibits intentional ozone-depleting substances emissions. Through amendments, Annex VI has progressively tightened these limits and introduced various measures that deal with GHG emissions. The 2020 global sulphur cap, which cut the maximum sulphur content in marine fuels to 0.50%, will vastly impact fuel choices and resulting emissions. (IMO 2016).

Hence, in 2018, IMO adopted an initial strategy for the reduction of GHG emissions from ships to reach a total annual GHG emissions by ships reduced by at least 50% by 2050 compared to 2008, while pursuing efforts toward phasing out GHG emissions entirely (IMO 2018). In this strategy, the development of new technologies and alternative fuels and energies is considered one of the priorities for use with the view to enhancing the energy efficiency of ships.

It also encourages the regulatory frameworks towards the inclusion of both technological and operational metrics for the improvement in energy efficiency. The technological metrics include adoption of ESD, optimization in the morphology and design of hull, upgrade of propellers and integration of advanced propulsion systems (Bouman et al., 2017). The key focuses regarding the operational metrics are route optimization, weather-based routing, just-in-time arrival, and better maintenance practices.

Energy efficiency as a regulatory focus has accelerated the adoption of VFDs and similar technologies in marine service. These allow for precise control over the rotational speed of electric motors, which locks in tremendous savings for systems - such as ballast pumps - for which operation at or near full capacity is standard.

By adjusting the pump speed to meet the required flow efficiency, VFDs reduce wasteful energy consumption, contributing to compliance with EEXI and CII indicator requirements.

Although the regulatory frameworks provide clear direction in terms of improving energy efficiency, shipowners face challenges in implementing the envisaged reforms, which may affect the adoption path of the envisaged changes. Capital investment requirements, technology compatibility and potential operational disruptions are important aspects in the compliance process for any shipowner (Rehmatulla et al., 2017). However, long-term operational cost savings and direct and indirect significant environmental benefits are attractive incentives for the adoption of energy efficient technologies.

In addition, access to finance and fiscal incentives introduced at the state level in the context of the green transition in the maritime transport sector can facilitate the transition process. With initiatives such as the Poseidon Principles and the Marine Cargo Charter, climate change considerations are incorporated into lending decisions, encouraging investment in more environmentally friendly technologies in the shipping sector (Poseidon Principles, 2019).

2.3. Traditional ballast pump systems and their disadvantages

Ballast water is essential to maintain weight distribution ensuring stability, and structural integrity of bulk carriers during voyages and becomes a necessary condition for ships handling a fluctuating volume of goods in transit (Endresen et al, 2004). Traditional Ballast Pump Systems Traditional ballast pump systems use constant speed centrifugal pumps, which operate inflow and discharge large volumes of seawater in order to adjust the buoyancy and balance of the ship, depending on the circumstances. Large pumps are generally running at constant speed without regard for actual demand for ballast. This results in the following inefficiencies and disadvantages.

A major disadvantage of traditional ballast pump systems is excessive energy consumption. Operating at constant maximum capacity means that the pumps often deliver more flow than is needed in a given situation, resulting in unnecessary energy use and increased operating costs (Wong et al., 2014).

The flow rate is usually controlled by the use of flow choke valves, which have further pressure losses and decrease the overall efficiency of the system even more. This kind of flow control method wastes not only energy but also accelerates wear and tear on pumps and associated piping because of increased mechanical stress and a risk of cavitation associated with this type of application (Mannan & Lees, 2012).

Moreover, since pumps operate at maximum power continuously, fuel consumption by the auxiliary engines driving these pumps is increased in ships where these are fitted (Wang & Taylor, 2011). This increase in fuel consumption not only increases operating costs but also leads to higher emissions of greenhouse gases and other pollutants, which conflict with the International Maritime Organization's regulations on the purpose of reducing emissions of polluting gases by the shipping sector. Inefficient performance of the conventional ballast pump system thus has economic and ecological consequences (Wong et al., 2014)..

Another important issue is the environmental effect that happens to go along with ballast water discharge. Traditional systems can easily pave the way for invasive water species to move to other marine ecosystems, creating ecological disturbances of the actual ecosystems where they end up docking (David & Gollasch, 2015).

Although the primary function of ballast pumps is not directly related to ballast water treatment, the lack of integrated treatment solutions in traditional systems exacerbates the spread of non-indigenous species (Endresen et al., 2004).

In addition, the inelasticity that characterises the operation of fixed-speed rotary pumps limits the operational response of the ship. Speaking to the issue of where exact control of the ballast operation is vital, such as in cases of loading/unloading in ports, traditional systems are not capable of giving them such adaptability (Parise et al., 2008). This could result in longer exchange times of ballast and lower efficiency on the whole. This unavailability for adaptation might also raise some safety risks since the vessel would not get optimum stability in time (IMO, 2011).

Their maintenance requirements are also high in conventional or traditional ballast pump systems. The continuous running at high speeds imparts enormous stress on the mechanical parts of machinery, thereby increasing the chance of wear and tear on machine parts, necessitating its maintenance more often, hence leading to possible downtime (Papanikolaou, 2009).. As explained, this results not only in added cost, but it may affect the overall operational planning of the vessel (Mannan & Lees, 2012).

Toward all these challenging dimensions, traditional ballast water pump systems face significant technological advances, especially in the BWMS. This is because of the demand for tougher environmental regulations. For instance, by the 2004 IMO Ballast Water Management Convention, BWMC, it is demanded that ballast water should be treated to avoid spreading harmful aquatic organisms (IMO, 2004).

With the advancements, the installations of BWTS are one of them, which performs physical, chemical, or combined methods of treatment to remove invasive species from the ballast water. The typical treatment technologies used are (Lloyd's Register, 2016):

Filtration systems, which would make use of mechanical filters in order to remove larger sized organisms along with sediment from ballast water, reducing the load of potential invasive species (David & Gollasch, 2015).

to ultraviolet radiation, where UV treatment annihilates the DNA of the microorganisms and they cannot reproduce anymore {Rose & O'Connell, 2009}. This method has a broad spectrum of microorganisms and is devoid of chemicals.

o Chemical disinfection: where oxidising agents like chlorine, ozone or peracetic acid are introduced to the ballast water in order to inactivate or kill the organisms (Doblin & Dobbs, 2006). In Chemical treatment has to be well handled and neutralised prior to its discharge.

o Deoxygenation-the process of decreasing oxygen levels in ballast water, thus creating an environment unsuitable for the survival of aerobic organisms; this is an effective way to eliminate such organisms (David & Gollasch, 2015).

The systems struggle with the need for precise regulation of flow rates and pressure of ballast water. This need has brought about the adoption of variable frequency drives in ballast pump systems (Doblin & Dobbs, 2006). VFDs allow for modulation of the rotational speed of electric motors of the pumps, which allows adjustment of the flow rate to the exact needs of the treatment process.

By adjusting the pump speed, VFD units improve energy efficiency by reducing unnecessary energy consumption at times when the use of maximum pump power is not required (Petrović et al., 2019).

The application of VFD units offers a number of advantages, such as:

- Energy efficiency, as by ensuring that pumps operate over a range of variable speeds, VFD units reduce energy consumption in proportion to the flow rate (Wang et al., 2022).
- Operational flexibility, in that VFD units provide capabilities to precisely control the operation and performance of the pumps, offering operational flexibility.
- Reduced mechanical stress, in that through operating the devices at a lower number of rotations, wear and tear on pump components is reduced, extending equipment life and reducing maintenance costs (Mannan & Lees, 2012).
- Integration with automation systems: where VFD units may be integrated into the ship-wide automation and energy management systems, thus allowing for optimization of operating and monitoring of the ship's operational processes (Barreiro et al., 2022)..
- There have also been developments regarding design and materials applied for the ballast pumps themselves (Kim et al., 2012). Modern pumps are manufactured with impellers and casings of higher efficiency in order to minimize hydraulic losses. Materials used which resist corrosion and biological contamination raise the reliability of pumps and reduce maintenance needs (Mokhtari & Arabkoohsar, 2021).

Another technological development in the last few years includes the CFD and simulation-based design and optimization for BWMS. CFD models have helped in ascertaining the flow characteristics within the ballast water system, finding out the potential areas for efficiency improvements, and predicting the performance of different treatment technologies under various operating conditions (Sarkar et al., 2012)..

Some BWMS are incorporated with energy recovery technologies. For instance, the application of energy-efficient component and waste heat recovery from ballast handling operation contributes to the overall reduction of the energy footprint of the ship. The same has been discussed by Lakshmi et al. (2020).

In spite of such development, difficulties can still be witnessed in the implementation of modern BWMS on ships serving global maritime transport. The high cost of initial installation, especially because of the retrofitting of ships, can be one of the major barriers against advanced systems' installation in the ships (Jee & Lee, 2017). The diversity of processing technologies and various international regulations within this regard can further complicate the compliance efforts by ship operators (David & Gollasch, 2015).

Nevertheless, the long-term benefits of adopting advanced ballast water treatment technologies are enormous since they guarantee better energy efficiency, reduced operating costs, improved environmental compliance, and ecological damage owing to preventing the transportation of invasive species (Sayinli et al., 2021).

With environmental legislation becoming ever more strict, the drive for sustainability from the maritime transport sector looks set to inspire further growth in advanced BWMS adoption, along with the integration of VFD modules into the operation of ship pumps.

2.4. The importance of energy efficiency in shipping operations and seawater pumping systems

An important topic that arises in the study of the relevant literature regarding the application of variable frequency drives in ballast pumps is the improvement of the energy efficiency of the devices and the ships where these drives are installed. Pumps rank among the largest power consumers in all ship operation systems. They form parts of key applications, such as central cooling, seawater handling, and ballast management. Optimization of these pumps by VFD technology may bring about substantial savings in total energy consumption and, consequently, fuel consumption.

Energy efficiency has emerged as one of the major concerns in maritime operations for its huge implication on fuel consumption, operating cost, and environmental endurance. The shipping industry carries about 90% of the merchandise traded around the world, while this industry has been under increasing pressure to cut greenhouse gas emissions and adhere to international regulations fostering energy-efficient practices (IMO, 2021).

It is defined as energy efficiency in shipping, referring mainly to the use of less energy without necessarily affecting the quality of the service provided or the operational performance. Energy efficiency has cropped up as an important principle in cost-saving purposes and also reduction of environmental impacts emanating from shipping activities. Relevant research highlights that energy efficiency will continue to have the most significant role in reducing carbon dioxide emissions - up to as much as 53% in total CO_2 emission reductions; this shows the need to integrate energy-efficient solutions into the design and operation of ships to meet globalised environmental problems, such as climate change (Kocak & Durmusoglu, 2017; İnal & Koçak, 2023; Räsänen and Schreiber, 2012).

According to Kocak and Durmusoglu (2017), pumps occupy almost 50% of ship's total electricity consumption. The huge energy savings potential associated with improved operational efficiency of pumps is evident at this magnitude. Many marine systems have traditionally operated pumps at constant speed, independent of fluctuating demand — wasting energy. However, VFDs can be integrated into these systems for a more adaptive control system in which the operating speed of the pumps may be modulated with real time demand as seawater temperatures vary or load conditions change. This result is consistent with findings by Inal and Koçak (2023) that specify that generator load, in the case of electric motors for ship ventilation and pumping systems, can constitute up to 87.9% of the total. VFDs are installed to optimise the speed of these electric motors based on demand leading to reduced energy consumption and higher energy system efficiency.

In line with the regulations set by the International Maritime Organization (İnal & Koçak, 2023) like the Design Energy Performance Index and the Ship Energy Efficiency Management Plan (SEEMP) initiatives are stimulated for energy related measures for older and newer ships. Also, these regulations are aimed to force ships to gradually improve their energy efficiency in time as targets get increasingly stringent. For example, the requirement was to be 10% more efficient for ships built between 2015 and 2019 while the requirement was to scale up the 30% energy efficiency threshold for ships built after 2024 (Räsänen & Schreiber, 2012). These regulations are only complied with if energy efficiency is maintained during the design and operation phase of a ship. The application of VFD units in closed-system pumps, such as those used for boiler feed water, further highlights their beneficial role in improving energy efficiency. Su et al. (2015), highlight that closed system pumps are particularly suitable for variable speed regulation. These systems are often operated under high pressure and temperature conditions, and the use of VFDs to adjust the operating speed of the pumps based on actual pressure and flow requirements prevents the frequent overloads and wear associated with constant speed operation of the pumps. This also avoids unnecessary waste of energy, as the system is not forced to operate at maximum capacity when demand requirements are at low levels.

Kocak and Durmusoglu in the year 2017 consequentially cited that the energy efficiency and environmental impact are the two most salient features which seriously affect the design process of ships and engineering operation processes in every aspect.

The case study they carried out on a ship's Central Water Cooling System mentioned that the attained reduced energy consumption and lower CO_2 emissions by the application of VSP function can enhance the operational energy efficiency (Kocak & Durmusoglu, 2017).

According to the findings of Su et al., (2013) seawater cooling pumps, which are one of the most important components of a ship's central cooling system, benefit greatly from VFD technology. The cooling requirements on ships vary significantly depending on environmental conditions, such as seawater temperature and the load of auxiliary and main engines.

As compared to traditional fixed speed pump systems, during periods of low cooling demand, the cooling pumps run continuously and at complete power, while operating with VFD units will allow these pumps to run at variable speeds conforming to the prevailing actual demand by saving huge amounts of energy.

İnal and Koçak (2023) refer to the big share of maritime transport in global greenhouse gas emissions, which is about 3-4% of the total global pollutant emissions. The authors believe that energy efficiency improvement is crucial for accomplishing these reductions and indicate electric motors as important energy-intensive devices in model ships.

Extensively used in systems such as pumps, fans and ventilation, electric motors account for 84-88% of a ship's generator load (İnal & Koçak, 2023). Improving the efficiency of these engines through technologies such as VFD technology has the potential to lead to significant reductions in fuel consumption and emissions on ships.

Petrov and Gomez Diaz (2020) further confirm these findings by demonstrating that the installation of VFD units in centrifugal pumps can reduce energy consumption by up to 50%. Centrifugal pumps are commonly used in a wide range of ship systems, such as HVAC and refrigeration systems. Without the use of VFD technology, these pumps operate under continuous operation at constant speed (most commonly at maximum speed) which often leads to energy waste when the system is operating at levels below maximum capacity. By controlling the speed of rotation of these pumps through the VFD units, energy consumption is aligned with real-time operational requirements, ensuring that energy is used only when and where it is needed and of course to the extent required.

Su et al. (2015) point out that the electrical loads of ship pumps which cover various types of electrical equipment make up about 70% of the total power consumed on board. They note that the application of variable frequency control technology to these power pump loads can meet international maritime laws and energy saving requirements.

The benefits coming from this approach are not only related to the improved energy efficiency but also to a reduction of the workload for maintenance engineers and, consequently, further risks that might occur for the equipment.

Also, VFD systems can reduce energy consumption by 60% according to Räsänen and Schreiber (2012) in both seawater pumping systems and ship ventilation systems. It naturally goes without saying that existing ships-even the newer ones-operate under the outdated control principles of throttling and bypass loops, which use and force pumps to run continuously at full load independent of the real needs of the system. VFDs eliminate the inefficiencies of these traditional systems by allowing pumps to operate at their own optimal speeds for significant energy savings in a wide range of applications that include ballast, cooling, and ventilation systems.

Furthermore, Su et al. (2013) point out that significant opportunities exist to reduce the energy consumption of pumping systems through smart design, retrofit and operational processes. They propose an energy savings evaluation method for VFD applications in centralized ship cooling systems, demonstrating that such applications can improve performance, reliability and reduce life cycle costs. Their analysis shows that energy savings are significantly influenced by factors such as seawater temperature and ship routes, which affect the cooling requirements of ship systems (Su et al., 2013).

Räsänen and Schreiber (2012) further confirm the critical role of energy efficiency in reducing emissions. They report that the shipping industry is responsible for 3-4% of total GHG emissions and that in the absence of interventions to improve energy efficiency, emissions from shipping could increase by 150-250% by 2050. They advocate the use of VFD units in pump and air system applications on ships, as their research highlights the importance of integrating energy efficiency into both newbuild and existing ships to achieve emission reduction targets.

Petrov and Gomez Diaz (2020) discuss the application of variable speed control in centrifugal pumps for closed systems such as heating, ventilation and air conditioning (HVAC) systems.

Although the researchers have put a bias on building systems, the principles applied can be related to marine activities. They reason that due to control of rotational speed of a centrifuge pump with VFD units leads to considerable energy saving in the system, especially those characterized by variable load conditions. Their conclusions showed that, by reducing the rotation speed of the pumps, it is possible to save 50% of the energy consumption. This approach is able to provide the required flows at the necessitated pressure while optimizing energy consumption (Petrov & Gomez Diaz, 2020).

The literature points out that energy efficiency is part of sustainable shipping operations. Energy efficiency technologies and practices in shipping would have the result, on one hand, of saving costs and compliance with more stringent environmental regulations, but would also contribute, on the other hand, to world-wide efforts to mitigate climate change. Special attention should be given to high energy-demanding systems such as pumps and electric engines since these kinds of systems are among the biggest ones in a ship's energy use.

2.5. Operational and engineering benefits of variable frequency drives

In addition to enhancing energy efficiency and reducing emissions, variable frequency technology offers significant operational and mechanical benefits, mainly by extending the lifetime of mechanical systems and improving the overall reliability of a system. These benefits derive from the precise control that VFD units offer over the operation of pumps and motors, limiting equipment wear, preventing common mechanical problems and optimising system performance under varying loads.

These variable frequency drives and variable speed pumps are highly advanced technologies that permit the precise adjustment of the electric motor speeds to actual operating requirements, thus ensuring the best energy efficiency and least unnecessary energy consumption. Changing the frequency of the electric power feeding the motors, these systems regulate rotational speed and torque of the pumps to evade energy waste when operating at full capacity is not needed. In fact, in their respective studies, Kocak and Durmusoglu (2017) and İnal and Koçak (2023) confirm that through change of frequency of the electric power which feeds the motors, the system regulates the rotational speed and torque of the pumps to prevent energy loss when working at full capacity is not needed.

Su et al. (2015) investigate the application of VFD units in closed systems, such as boiler feed water pumps, in which they play a critical role in terms of mitigating overheating, cavitation incidents and excessive wear of key pump components, especially impellers and orifice rings. The closed systems have potential direct exposure to mechanical wear under high pressure conditions for continuously operating pumps at maximum torsion, even at low load conditions. These units allow the systems to vary the pump speed with the actual load, thereby avoiding unnecessary mechanical stress that would lead to potential cavitation-a destructive situation where steam bubbles are formed and depressed within the pump, which causes damage to the impeller. VFD units improve operational efficiency by avoiding this mechanical stress, reducing maintenance requirements and prolonging life for key components.

According to Kocak and Durmusoglu, (2017), traditional ship systems rely on pumps that operate at a constant speed with maximum capacity regardless of actual demand for cooling or liquid transfer. At least energy inefficiency during partial loading conditions is unavoidable. The use of VFDs can vary the pump rotation speed depending on the demand for cooling time, hence bringing huge energy savings. The optimization of energy consumption in the central cooling water system of a tanker, as studied by the authors, reveals that the application of the VSP unit reduces energy consumption by regulating the flow rate of seawater instead of bypassing excess potable water. This mainly occurs during any variation in the temperature of the seawater.

Räsänen and Schreiber, (2012) also point out that the VFD unit helps to eliminate the danger of cavitation in oversized pumps. This is a common problem in marine systems, since quite often pumps are designed for peak conditions in such a way that only seldom would the actual demand require operation under full capacity. In such cases, the pumps operating under full load without any such demand therefore have a greater risk of being subjected to cavitation, which badly affects pumps' performance, efficiency, and lifespan. The VFD units provide closer control to the operating speed of the pump, hence the operational possibility of running the pump closer to BEP. Since optimization reduces wear and tear on components, it results in fewer repairs or hardware replacements, leading to extended useful life. The VFD modules are, therefore, able to manage variable loads by pumps effectively for smooth operation without sudden stress or overloading, thus adding more to the durability of the pumps.

İnal and Koçak (2023) highlight the effectiveness of VFD units in enhancing energy efficiency in ship engine room ventilation systems. Traditional ventilation fans on ships usually operate at constant speeds, ignoring ambient temperature variations or ventilation requirements, which leads to energy waste. These VFD units allow air system motors to adjust their speeds according to actual temperature values, thus minimizing energy consumption by a great deal. In fact, the authors have reported in their case study of crude oil tankers that the consumption of energy by the use of VFD-controlled fans is more than 80% less, hence indicating impressive advantages of VFDs in variable-load devices.

The same idea with regard to the integration of VFD units normally increasing the effectiveness of operational reliability for HVAC systems and in closed-loop pumping systems is discussed by Petrov and Gomez Diaz (2020). The VFD units here manage the load with precision, as the speed of the pumps can be varied to respond to demand in real time. This flexibility avoids the common operational problems of pipeline blockages that are generally experienced with pumps operated at constant speed irrespective of demand fluctuations. The VFD units, while dynamically regulating pump speed, maintain optimum flow rates. Thus, such blockages occur rarely and add positively to the overall system reliability. Also, fewer failures and less resulting downtime stem from systems operating under less mechanical stress with VFD units installed. Accordingly, the capability of VFD units to avoid blockages in the pipeline and keep providing stable performance under different conditions points at the contribution of these drives to system stability and general operational resilience.

Su et al. (2015) discuss the application of variable frequency constant pressure technology to closed system pumps on marine vessels. They indicate that such control methods in the closed system pumps, for instance, running at full capacity continuously, are energy-inefficient and give rise to mechanical wear resulting from events such as overpressure. With the VFD module constant pressure control, the rotation speed of the pump is varied depending on the system requirements of pressure for an optimized operation that results in reduced energy consumption. On-site application to the auxiliary boiler feed water pump in a bulk carrier vessel showed possibilities of up to 40-50% reduction in the consumption in the consuming engine during idling of the water supply system and up to 68.25% when combined with improvements in the pump mechanism.

Su et al., (2013) go further to present a method to quantify the energy savings for the application of VFDs in centralized ship cooling systems. The studies compared the energy efficiency of two identical commercial ships on different routes and found considerable energy savings with the application of VFDs; the magnitude of savings varied according to several factors, including seawater temperature and sea routes.

Räsänen and Schreiber (2012) point out that the use of VFD in pump and air system applications on ships can reduce energy consumption by up to 60%, arguing that pumps and air systems are often oversized to respond to extreme conditions, which are rarely encountered during normal ship operation. As a result, these systems are constantly operating at full power, leading to excessive energy consumption and mechanical wear and tear. VFD units allow engine speeds to be adjusted to meet actual demand, providing significant energy savings and reducing emissions. The authors' research shows that, in many cases, the return on investment for retrofitting existing ships to carry VFDs is less than one year, making the investment an economically attractive solution for shipowners.

Petrov and Gomez Diaz (2020) discuss the benefits gained from adaptive speed control on centrifugal pumps for closed loop HVAC type systems. They point out that VFDs regulate the rotational speed of electric motors in centrifugal pumps to bring about energy gain with regard to adapting the pump performance to the given demand of the system. It was established that changes in the rotation of the pumps relative to the required volumetric flow rate would lead to significant savings of energy. The analysis made by the researchers shows that it's possible to save up to 50% of energy consumption by reducing the speed of the pump, and the flow and pressure from results produced are enough to operate the system. From the studies reviewed, VFD and VSP are quite efficient technologies in marine applications in enhancing energy efficiency related to pumps. Since speed and torque from the motor can be precisely controlled by VFD units alone, this eliminates the waste of energy associated with operating pumps or air systems at constant speeds unrelated to demand for the same. This feature partly finds great application areas where the operation of pumps is required to be invariable at full, such as cooling systems, ventilation, and ballast processes.

The application of VFD units not only leads to significant energy savings, but also reduces mechanical wear and tear on equipment, lowers operating costs and helps to reduce polluting gas emissions, in line with international efforts to enhance the sustainability of processes in the shipping sector.

Chapter 3 Methodology

3.1. Introduction

This chapter aims to present in detail the methodology adopted in this study to answer the research questions posed. It describes the methodological approaches chosen, the data collection and analysis techniques, and the tools used to validate the results obtained. The main objective is to ensure the transparency and reproducibility of the methods employed, in line with the principles established by Creswell (2014) and Yin (2018).

The methodology adopted is based on a combination of analytical and experimental approaches to assess the energy savings and CO_2 emissions reduction achieved by installing variable frequency drives (VFDs) in the ballast water pumps of the ship under study. This approach is justified by the need to precisely quantify the energy and environmental performance of a complex technical system (Silverman, 2013).

This chapter ensures that the methods employed are suitable for testing the hypotheses and achieving the objectives set. Consequently, calculations of energy consumption, pump performance and emission reductions are rigorously investigated through quantitative analysis based on theoretical models and numerical simulations (Saunders et al., 2019).

The approach adopted in this research is based primarily on a qualitative content analysis research methodology. This strategy is chosen to enable accurate and objective measurement of the energy performance of ballast water pumps and the impact of VFD units on energy consumption (Bryman, 2012). Quantifying the results is essential to assess the relevance of the proposed improvements and determine their applicability to other similar vessels.

The case study method was selected as the main framework for this research. Yin (2018) argues that this approach is particularly appropriate for in-depth investigations of complex phenomena in their real-life context. In this case, the vessel studied, a bulk carrier equipped with a ballast water management system (BWMS) using VFD units, provides an ideal setting for examining the effects of energy-saving technologies in an operational maritime environment.

The case study also makes it possible to take into account the specific technical characteristics of the vessel, such as pump capacity, water flow rates, and operational profiles, thus ensuring that the conclusions drawn are directly applicable to similar situations (Stake, 1995). By combining real operational data with simulations based on pump similarity laws, the analysis aims to provide reliable and generalizable results while taking into account the inherent limitations of marine systems (Miles & Huberman, 1994).

Finally, this methodological design enables quantitative data obtained from sensors and ship's logs to be combined with theoretical assessments derived from pump performance curves and energy-saving models. This integrated framework facilitates the assessment of energy savings and emissions reductions by taking into account operational parameters and environmental variables (Robson, 2011).

3.2. Data sources

Primary data acquisition relies on several essential sources that guarantee the accuracy and relevance of the information collected for the study. Foremost, the technical specifications of the equipment installed on board the vessel are provided by the manufacturers (David & Gollasch, 2015). These include details of pump capacity, performance curves and variable frequency drive operational parameters. Subsequently, operating logs and energy consumption data recorded on board are analyzed to assess performance under real-life conditions (Smith et al., 2015). These logs include information on ballasting and de-ballasting cycles, duration of operations and electricity consumption levels.

In addition, real-time monitoring data is extracted from the VFD systems and pumps. Integrated sensors measure power input, flow rate, and pressure (Poulsen et al., 2021). This data is used to verify predicted theoretical models and assess the actual reduction in energy consumption.

Secondary data sources complete the analysis by providing a theoretical framework and industry standards. A literature review was conducted to examine previous studies on pump performance, energy efficiency and VFD optimization (Räsänen & Schreiber, 2012). These works provide essential references for understanding the hydraulic laws governing flow and power variations (Su et al., 2015).

Assessing the energy and hydraulic performance of pumps relies on advanced measurement tools. Digital wattmeters and flow sensors are used to monitor pumps' power consumption and volumetric flow (Petrov & Gomez Diaz, 2020). These instruments offer high accuracy and enable real-time readings.

Calibration procedures were applied prior to data collection to ensure measurement reliability (ISO, 2017). Measuring devices are regularly checked in accordance with manufacturers' recommendations and international standards.

3.3. Analytical framework

Pump performance analysis in this study is based on the application of affinity laws for centrifugal pumps, which model performance variations as a function of load changes. These laws, as stated by Stepanoff (1957) and confirmed by Dixon and Hall (2010), are essential for predicting the relationship between flow rate, head and power input.

These relationships can be used to analyze pump performance curves as a function of optimized operating conditions. Efficiency and performance curves (flow vs. head) are interpreted to determine optimum operating points and detect potential drifts due to hydraulic losses (Karassik et al., 2001). This study also takes into account the integration of variable frequency drives (VFDs), which enable dynamic adjustment of pump performance, thus improving their energy efficiency (Pumpe, 2015).

Energy consumption is assessed using standardized formulas that integrate data on power input, flow rate and operating time. The basic equation used to estimate energy consumption is :

$$E = P \cdot T$$

Where :

represents energy consumed (kWh)

is power input (kW)

is operating time (hours)

A comparison between baseline energy consumption (before VFD installation) and optimized energy consumption (after VFD installation) is carried out to measure the savings achieved. According to Saidur et al (2012), the use of VFDs can reduce pump energy consumption by up to 30% by dynamically adjusting rotation speed.

The calculations also include an analysis of efficiency losses due to hydraulic friction and load fluctuations, as specified by Neale and Associates (2010). These analyses guarantee an accurate estimate of energy efficiency.

The reduction in CO_2 emissions is calculated from the fuel savings achieved through increased energy efficiency. The formula used is:

$$\mathrm{CO_2} = E \cdot SFC \cdot EF$$

Where:

$\mathrm{CO_2}$ represents emissions avoided (kg)

E is energy saved (kWh)

SFC is the specific fuel consumption (g/kWh)

EF is the emission factor (kg CO_2/kg fuel)

For the purposes of this study, an average SFC of 200 g/kWh and an emission factor of 3.15 kg CO_2/kg are adopted, in line with International Maritime Organization (IMO) guidelines (IMO, 2021).

Calculation assumptions are based on operating data and benchmarks established by Ship & Bunker (2024) for marine fuels. Preliminary results indicate a significant reduction in CO_2 emissions, contributing to compliance with environmental regulations and sustainability goals.

The analytical framework presented provides a structured methodology for assessing pump performance, energy savings and emission reductions associated with VFD installation. Using pump affinity laws, established formulas and recognized standards, this analysis ensures a rigorous and quantitative assessment of operational and environmental impacts.

3.4. Key assumptions

The analytical model used in this study is derived from some assumptions that assure the consistency between the theoretical model and the actual evaluation of pump performance under VFD operation. First, the analysis is repeated for steady-state operation of the ballast pumps so that the pump transient effects are not considered during start-up and shut-down phases. This approximation was essential in order to be able to use pump affinity laws and performance curves, which relate flow, head and power under predominantly steady-state operating conditions (Stepanoff, 1957; Dixon and Hall, 2010).

Second, the calculations were made based on manufacturer pump curves for EMD-300C centrifugal pump model because no direct full-scale measurement data were available. It was therefore assumed that the performance characteristics supplied by the manufacturer in fact approximates the actual operation of the pumps inside the design envelope. In this context, operating points were chosen inside the stable region of the operating curves, which guarantees the technical validity and avoids the risk of cavitation. For example, the filling condition was simulated at a flow rate of 800 m3/h and a total head of 22.5 m whereas the emptying scenario was simulated with two pumps in parallel each with a flow rate of 800 m3/h (1600 m3/h total).

Third, the density of seawater was assumed to be constant (r = 1025 kg/m^3) without considering the temperature and salinity effect. For the purposes of engineering analysis of ballast systems such a variation is generally small compared to the overall changes in flow and head and is therefore often neglected. Also, the gravitational acceleration was assumed to be g = 9.81 m/s^2.

Fourth, steady-state efficiency values of the pump were assumed in the calculation of the electrical input power. Efficiency was removed from the reference operating point of the pump curve and assumed to be nearly constant for the operating range of interest. Although, in practice, variable efficiency may be present, this assumption is valid for a comparison between throttling and VFD operation, since the relative performance differences are still valid in the frame of a constant efficiency approach (Su et al., 2015; Petrov & Gomez Diaz, 2020).

Fifth, system losses (frictional resistance through piping and valves, etc.) were assumed to scale as the square law of flow. The zero-flow static head was therefore used to construct the system characteristic curve (SIC) which was then fitted at the chosen operating point to give a representative curve of system resistance. This allowed throttling (increasing resistance at constant speed) and VFD operation (pump speed reduction with a constant system demand) to be compared.

Sixth, energy estimates assumed that the pumps were operated continuously throughout ballasting and de-ballasting cycles and do not account for possible operational shutdown or idling times. Operating time was thus proportional directly to the calculated energy consumption at the flow conditions selected. Fuel savings and reduction of CO2 emissions were then calculated using standardized conversion factors for specific fuel consumption and emission factors according to IMO (2021) regulations.

Finally, it was assumed that the installation of VFDs has no effect on the baseline mechanical condition of the pumps other than providing for variable speed operation. In addition, secondary benefits such as decreased mechanical wear, a smoother start-up and low vibration, were recognized but not explicitly or directly measured in the numerical analysis. The intention behind the assumptions was to give a clear and conservative estimate of the energy efficiency savings directly attributable to the use of VFD control, and not to take account of secondary operational effects.

Through this specification, the study provides a repeatable and replicationable methodological framework. Although approximations are made, including constant efficiency and idealised seawater density, to allow the simplified analysis to be meaningful and to allow a comparison between conventional throttling and VFD control, the overall conclusions remain valid. These assumptions allow the results of energy savings and emissions reductions to be robust enough to be used to inform technical and economic feasibility studies of VFD integration into ballast pump systems.

3.5. Limitations

Despite the rigor of the analytical framework applied, however, there are several limitations to this study that need to be acknowledged when interpreting the study results. These limitations are the result of the dependence on theoretical models, availability of data, and the simplifications necessary to perform the analysis in a practical and reproducible manner.

The first limitation is that manufacturer-supplied pump curves are used directly as the source of information for performance modeling. While these are good curves for normal conditions, they may not adequately represent the variation in pump operation under actual shipboard conditions. Factors such as pump wear, pump fouling or variations in the quality of the seawater can have a significant impact on actual performance. The lack of a large amount of field measurement data limits the accuracy of the results especially in long-term operational applications (Karassik et al., 2001).

Second, this assumption of constant pump efficiency at different operating points makes an inherent simplification. In reality pump efficiency generally declines when operating away from the best efficiency point (BEP). Although this assumption makes it easier to compare the throttling and VFD scenarios, it can result in over or underestimation of the actual energy consumption and energy savings (Petrov, & Gomez Diaz, 2020).

Third, environmental and operational variables like seawater temperature and salinity and ship motion (e.g. rolling and pitching) were not included in the hydraulic modeling. These can affect pump performance and energy demand, but were not considered in order to keep the calculations clear and tractable. This is a limitation that demonstrates that the results obtained should be interpreted as indicative and not absolute predictions of the savings in the real world (Su et al., 2015).

Fourth, the analysis assumed continuous and uninterrupted ballasting and de-ballasting cycles with no allowance for possible changes in operating practices. In reality, operational pauses, partial cycles and time periods of idling can change total energy consumption. This creates a difference between the modeled and actual ship operations that may impact the overall magnitude of estimated savings.

Another limitation relates to the estimation of CO2 emission reductions, which was based on standard specific fuel consumption values and on generalised emission factors, as recommended by the International Maritime Organization (IMO, 2021). These conversion factors are a standardized way to do estimation but may not accurately reflect the actual fuel type, combustion or operating conditions of the auxiliary engines onboard the case study vessel.

Further, the study did not include the possible secondary effects of VFD installation such as reduced mechanical wear, smoother pump start-up or vibration. While these benefits are recognized qualitatively and supported by literature (Rasanen and Schreiber, 2012) they were not included in the quantitative framework. Excluding these factors is conservative in nature but could underestimate the greater operational and economic value of VFD technology.

Finally, the case study design makes it difficult to generalize the results. The results can be directly applied to the EMD-300C ballast pump and the particular operational profile of the vessel being examined. Although the approach can be used for other vessel types and pump types, the results may differ due to the different pump design, system configuration and different operating regimes. Thus, care should be exercised when applying the findings to other settings (Yin, 2018).

In sum, these limitations point out the trade-off between analytical precision and practical feasibility. The results are not explicit predictions of performance in all operational situations, but instead should be considered as representative of the gains in efficiency that can be obtained by integrating VFDs under the assumptions and conditions used in their development. Acknowledging these constraints helps ensure transparency and provide a basis for further improvement of future research by way of empirical verification, much larger data sets, and more comprehensive modeling approaches.

Chapter 4 Installation of VFD units on ballast pumps on the case study vessel

4.1. Presentation of the characteristics of the case study vessel

The vessel considered as the case study for this research is a bulk carrier representative for the medium-size portion of the worldwide dry bulk fleet. Bulk carriers are one of the most common types of ships in the world, handling major cargoes such as coal, iron ore, bauxite, and grain and their energy efficiency is of crucial importance because of their high operational frequencies and high auxiliary power requirements (Stopford, 2009). The particular ship used in the study was selected because it has typical trading patterns for its class, involving frequent loading and unloading operations, requiring extensive operation of ballast water systems. This operational profile makes it a good subject to analyze the potential benefits of Variable Frequency Drive (VFD) installations on ballast pumps.

The vessel is of around 56,000 tonnes deadweight tonnage, making it a Supramax bulk carrier (one of the significant share of the global fleet, UNCTAD, 2023). Its principal dimensions are: length overall (LOA) 190 meters, beam 32 meters and draft 12 meters. These dimensions are common for this size of vessel allowing them to be able to call at a wide variety of international ports, including those with draft restrictions. The form of the hull is optimised for cargo-carrying efficiency, but as in most bulk carriers, auxiliary systems such as ballast water management play a critical role in ensuring operational stability and safety during voyages with varying cargo loads.

The ballast water capacity of the vessel is around 20,000 cubic meters and is located in multiple tanks fore, aft and along the double bottom. The management of this ballast water is not only required for maintenance of the vessel's trim and stability; it is also required in order to comply with international regulations, including the Ballast Water Management Convention (IMO, 2004). During cargo operations, ballasting and de-ballasting cycles are frequent and energy intensive, requiring pumps to be operated at high capacities to achieve rapid movement of large amounts of water. As such, ballast pumps are one of the most energy-hogging auxiliary systems on board.

The engine room of the ship is equipped with two centrifugal ballast pumps of type EMD-300C, each having an electric motor rated at 75 kW at 1800 rpm. These pumps are designed to provide seawater flow rates of between 500 to 850 m3/h with between 20 and 30 meters total dynamic head values, depending on operating conditions. In conventional operation, these pumps are run at constant speed, regardless of demand on the system, resulting in inefficiencies when less flow is demanded than the design capacity of the pump(s). The integration of VFD units allows for dynamic adjustment of pump speed, aligning energy consumption with operational requirements and creating a more sustainable solution.

The power generation system on the vessel consists of four auxiliary diesel powered generators, which can each provide electrical power to shipboard systems, such as the ballast pumps. The need for auxiliary power is especially great during port operations when both cargo handling equipment and ballast pumps are in operation. Reducing the electrical load of the pumps by the use of VFDs can therefore have a direct impact on the fuel consumption on auxiliary generators, contributing to lower operating costs and reduced CO2 emissions.

From an operational standpoint, the vessel experiences frequent ballast water operations during voyages and port stays and during cargo handling. Typically, ballasting is done during cargo discharge and de-ballasting is done during cargo loading. Each cycle includes several thousand cubic meters of seawater and may take several hours depending on the port infrastructure and operational needs. Given the total amount of energy used in multiple voyages per year, even moderate gains in pump efficiency can result in substantial annual savings in fuel and emissions.

The vessel is also subject to increasing stringent international environmental rules such as Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations which require continuous improvements in energy performance (IMO, 2021). As a result, the use of VFDs in auxiliary systems like ballast pumps makes sense from a compliance with the environment as well as a competitive point of view. The case study vessel is thus a realistic example of how the retrofitting of existing ships with advanced energy-saving technologies can simultaneously address regulatory, operational and environmental challenges.

In conclusion, the chosen bulk carrier offers a suitable platform to analyze the technical and economic viability of installation of VFD for ballast pumps. Its operational profile, the configuration of ballast systems, and the regulatory environment make it representative of a large segment of the global bulk carrier fleet, while the pump specifications are sufficiently detailed to permit rigorous analysis of performance under VFD conditions.

4.2. Technical characteristics of the vessel

The case study vessel is a Supramax bulk carrier used for the carriage of dry commodities with a deadweight tonnage (DWT) of about 56,000 tonnes. The ship's hull is built on a conventional single deck layout, with five cargo holds, and four deck cranes for self-loading and unloading operations. The overall length of the vessel is 190 meters with a beam of 32 meters and a fully loaded draft of 12 meters with dimensions that allow access to a wide range of medium and large size ports in the world.

The propulsion system of this vessel consists of a two-stroke, slow-speed diesel engine with a fixed-pitch propeller. This configuration is common for bulk carriers of this class and offers good propulsion efficiency on long-haul voyages. Complementing the main engine, the ship is fitted with four auxiliary diesel generators rated at about 750-1000 kW each providing electrical power for hotel loads, cargo loads and auxiliary machinery. During ballast water operations, these generators provide the power needed to run the ballast pump motors, so their performance and energy consumption is vital to the overall energy balance of the vessel in terms of fuel.

The ballast water system is a key to the operational flexibility of the vessel. It is a system of several tanks in the forepeak, afterpeak, double bottoms and wing sections of the hull. The total ballast capacity is about 20,000 m3 and the system is designed for gravity - and pumped ballast operations depending on port requirements. The pumps system is stratified into two EMD-300C centrifugal ballast pumps with a capacity of 75 kW and a constant nominal speed of 1800 rpm.

These pumps have a design flow capacity of 800 m3/h, at a total head of about 22.5 meters. Under conventional operation, the pumps are started and stopped directly on line, causing high starting currents and mechanical stresses that can accelerate the wear of electrical and hydraulic components.

The pump room layout allows the redundancy to be done, when either pump can perform partial operations by itself, while both pumps can be operated simultaneously during peak demand, such as de-ballasting during loading of cargo. The discharge piping is equipped with valves for manual flow regulation, however as shown in the analysis of performance, this is based on throttling, which results in large hydraulic losses and inefficient operation. The installation of the Variable Frequency Drive (VFD) units would enable the control of the speed of the pumps based on actual flow requirements, thus eliminating unnecessary energy losses and optimizing the system performance.

In terms of auxiliary systems, the vessel is equipped with a seawater cooling system and central air-conditioning units as well as freshwater generation plants, all of which have an impact on the auxiliary power demand. Pumps and fans are the clear winners in this category with ballast pumps making up a significant portion during ballasting cycles. Studies suggest that pumps can account for up to 50% of auxiliary power consumption in bulk carriers (Kocak & Durmusoglu, 2017), which makes it important to optimize their operation.

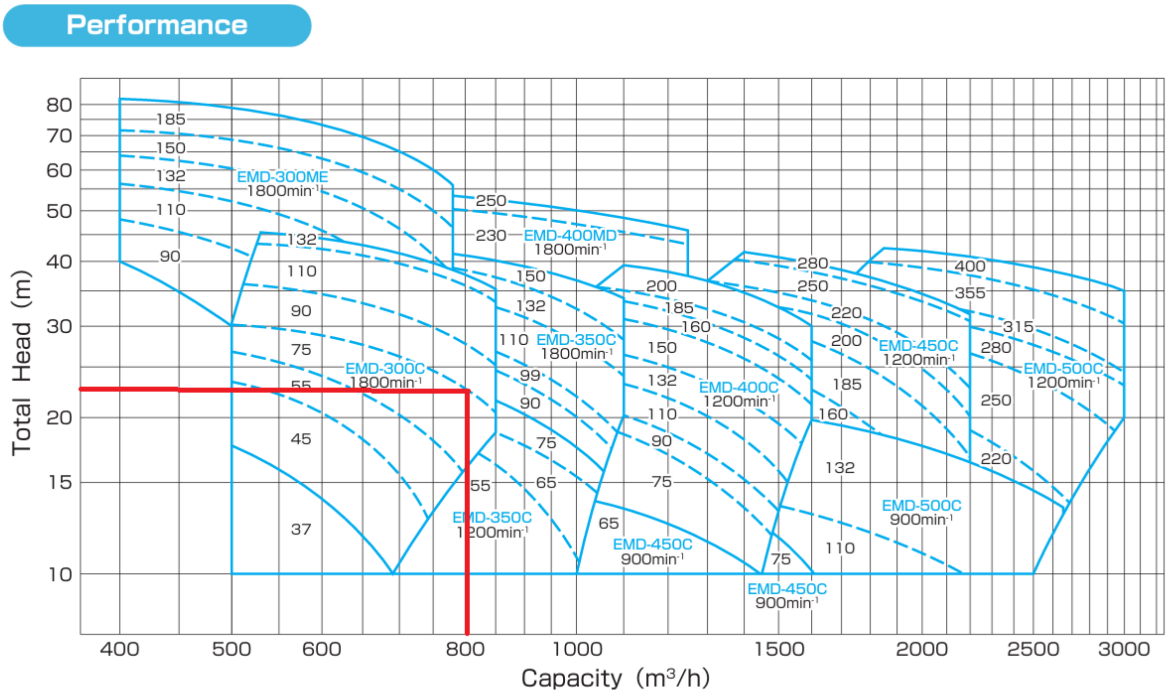
The ship is certified as compliant with the International Maritime Organization's (IMO) Ballast Water Management (BWM) Convention and the MARPOL Annex VI regulations on air pollution. However, with the introduction of the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) requirements, retrofitting with energy-saving technologies has become necessary to keep-up compliance and prevent penalties or restrictions on operations (IMO, 2021). The integration of VFD units into the ballast system is a direct way to improve the vessel's energy efficiency profile to reduce greenhouse gas emissions and improve the reliability of the system.

Electrically, the vessel is 440V AC powered with auxiliary systems. The ballast pumps are connected through motor control centers (MCCs) which presently use direct-on-line starters. The proposed retrofit would be done by replacing these starters with VFD modules capable of taking on the rated power of the motor, at the same time having built-in safeguards against overcurrent, overheating, and harmonic distortion. Integration into the ship's power management system would allow load distribution to be more even, and generators to avoid being overloaded when pumps are simultaneously operating.

Finally, the technical design of the vessel shows the typical balance between the efficiency of the cargo-carrying system and the performance of the auxiliary systems. While optimized structurally for maximum payload, the auxiliary machinery (especially the ballast pumps) offers opportunities for energy-saving retrofits. The technical specifications described above provide confirmation that the case study vessel is a realistic and appropriate platform for determining the feasibility of VFD technology in marine ballast applications.

4.3. Pump Description, Performance and Diagram - Technical Analysis

Pumps were assumed to operate at 1800 rpm with an impeller power 75 kW, based on the manufacturer's specifications. As no real measurement data were available, the selection of operating points was carried out exclusively through interpretation of the pump's performance curves. For the filling scenario, a flow rate of 800 m^3/h at 22.5 m of total head was used, while for the emptying scenario, two pumps are operating at 800 m^3/h (800*2=1600 m^3/h). These points were chosen to lie clearly within the characteristic curves of the EMD-300C pump, ensuring technical validity.



- Pump: EMD-300C
- Speed: 1800 rpm
- Flow: $Q = 800\ \mathrm{m^3/h}$
- Head: $H = 25\ \mathrm{m}$
- Electrical (motor) input power: $P_{\text{electric}} = 75\ \mathrm{kW}$
- Fluid: seawater, $\rho \approx 1025\ \mathrm{kg/m^3}$
- Gravity: $g = 9.81\ \mathrm{m/s^2}$

Convert flow to $\mathrm{m^3/s}$:

$$Q = \frac{800}{3600} = 0.222\ \mathrm{m^3/s}$$

1. Hydraulic power

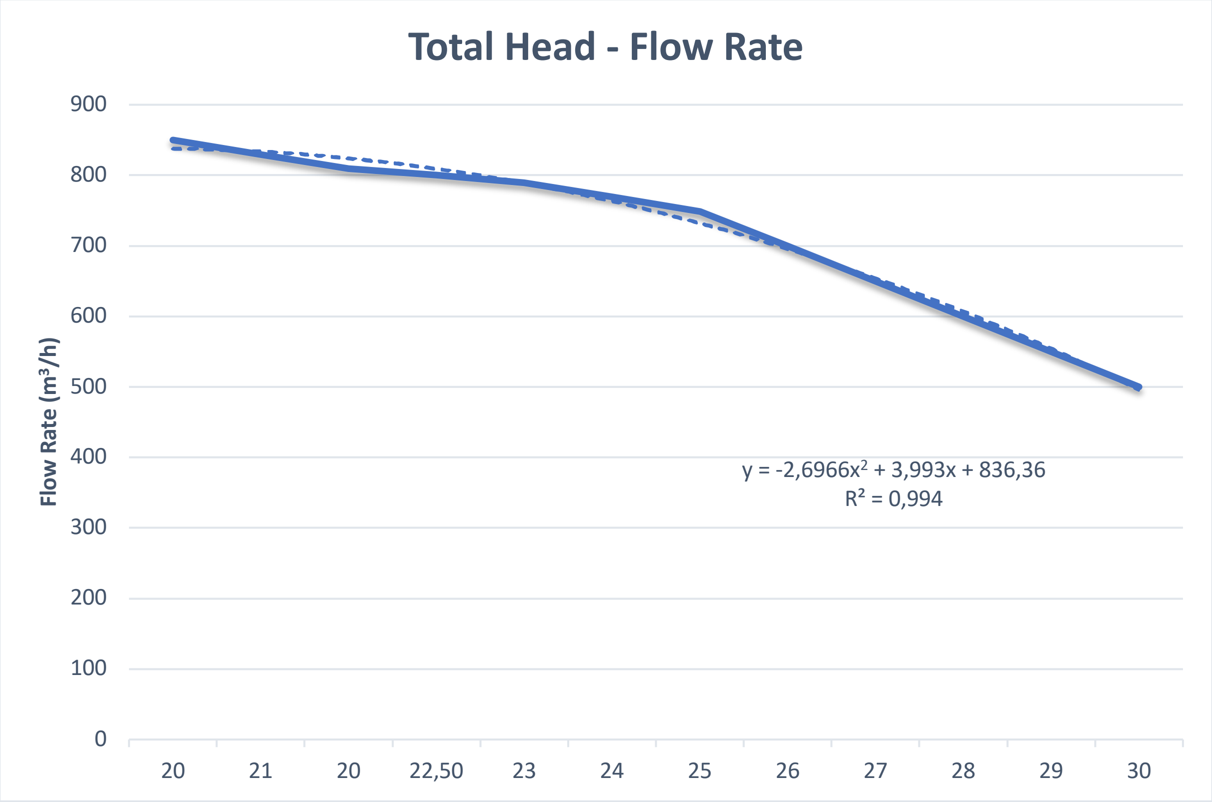
$$P_{\text{hydr}} = \rho g H Q = 1025 \times 9.81 \times 22.5 \times 0.222 = 50.276\ \mathrm{kW}$$

2. Pump efficiency at this point

$$\eta_{\text{pump}} = \frac{P_{\text{hydr}}}{P_{\text{electric}}} = \frac{50.276}{75} \approx 0.67(\mathbf{67}\%)$$

Total Head (m)	**Flow Rate (m’/h)**	**Power Hydraulic [kW]**	**Power Electric [kW] (Estimated with Constant Efficiency)**
20	850	47,48	70,83

21	829,8	48,67	72,61
20	809,6	45,23	67,47
22,50	800,0	50,28	**75,00**
23	789,4	50,71	75,65
24	769,2	51,56	76,92
25	749	52,30	78,02
26	699,2	50,78	75,75
27	649,4	48,97	73,06
28	599,6	46,89	69,95
29	549,8	44,53	66,43
30	500	41,90	62,50



Derive the system (piping) characteristic in the form

$$\Delta H(V) = C_1 + C_2 V^2$$

with ΔH in meters of head and V in m^3/h.

Assumptions / Points used

- Operating point A (from the pump curve):
$$V_A = 800\ \mathrm{m}^3/\mathrm{h}, \Delta H_A = 25\ \mathrm{m}$$
- Static head (zero-flow intercept) B:
$$V_B = 0\ \mathrm{m}^3/\mathrm{h}, \Delta H_B = H_{\text{static}} = 12\ \mathrm{m}$$

Solve for the constants

1. From the zero-flow condition:
$$C_1 = H_{\text{static}} = 12\ \mathrm{m}$$
2. Fit the curve through point A :
$$\Delta H_A = C_1 + C_2 V_A^2 \Rightarrow 22.5 = 12 + C_2(800)^2$$
$$C_2 = \frac{22.5 - 12}{800^2} = \frac{10.5}{640000} = 1.641 \times 10^{-5}$$
$$\frac{\mathrm{m}}{(\mathrm{m}^3/\mathrm{h})^2}$$

System characteristic (final)

$$\Delta H(V) = 12 + 1.641 \times 10^{-5} V^2 \text{ (H in m, V in m}^3\text{/h)}$$

For example at $V = 450\ \mathrm{m^3/h}$:

$$\Delta H = 12 + 1.641 \times 10^{-5}(450)^2 = 15.323\ \mathrm{m}$$

New pump speed from the affinity laws

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \quad \text{(Flow)}$$

$$\frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2 \quad \text{(Head / Manometric head)}$$

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3 \quad \text{(Power)}$$

With the same impeller diameter, pump head scales with the square of speed:

$$\frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2$$

Take $H_1 = 22.5\ \mathrm{m}$ at $N_1 = 1800\mathrm{rpm}$ (point A) and $H_2 = 15.323\ \mathrm{m}$ (system at $450\ \mathrm{m^3/h}$):

$$N_2 = N_1 \sqrt{\frac{H_2}{H_1}} = 1800 \sqrt{\frac{15.323}{22.5}} \approx 1485.43\mathrm{rpm}$$

Electrical power at $V = \frac{450\ \mathrm{m^3}}{\mathrm{h}}, H = 15.323\ \mathrm{m}$

Use seawater density $\rho = \frac{1025\ \mathrm{kg}}{\mathrm{m^3}}, g = 9.81\ \mathrm{m/s^2}$.

Convert flow: $Q = 450/3600 = 0.125\ \mathrm{m^3/s}$.

Hydraulic power:

$$P_{\mathrm{hydr}} = \rho g H Q = 1025 \times 9.81 \times 15.323 \times 0.125 \approx 19.26\ \mathrm{kW}$$

Using the pump efficiency taken from point A ($\eta_{\mathrm{pump}} \approx 0.67$):

$$P_{\mathrm{electric}} = \frac{P_{\mathrm{hydr}}}{\eta_{\mathrm{pump}}} \approx \frac{19.26}{0.67} \approx 28.73\ \mathrm{kW}$$

If we had estimated the required power only using the affinity laws, we would have:

$$\frac{N_2}{N_1} = \frac{V_2}{V_1} \Rightarrow N_2 = N_1 \cdot \frac{V_2}{V_1} = 1800 \cdot \frac{450}{800} \Rightarrow N_2 = 1012.5\mathrm{RPM}$$

and similarly:

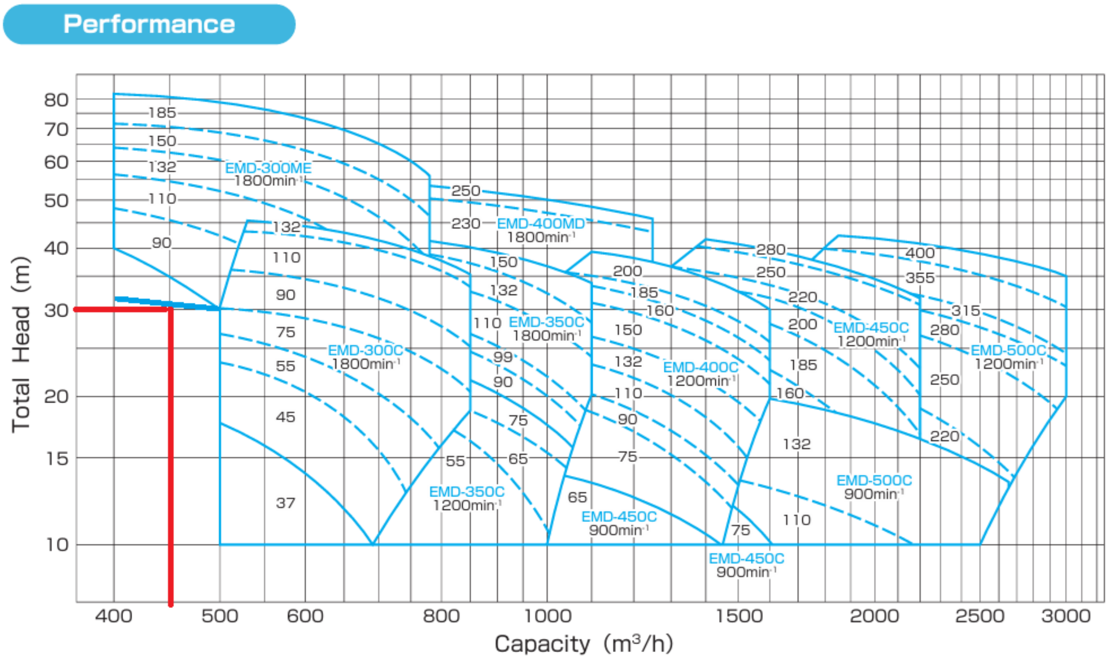
$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3 \Rightarrow P_2 = P_1\left(\frac{N_2}{N_1}\right)^3$$

$$P_2 = 75 \cdot \left(\frac{1012.5}{1800}\right)^3 \Rightarrow P_2 = 75 \cdot 0.1779 \Rightarrow P_2 = 13.34\ \text{kW}$$

Thus, we see that the power is significantly lower than the one we calculated earlier. Therefore, from this calculation we can refer to a required power reduction from $800\ \text{m}^3/\text{h}$ to $450\ \text{m}^3/\text{h}$ using VFD, which results in:

$$\frac{28.73}{75} = 0.383 \Rightarrow \text{Power reduction} = (1 - 0.383) = 61.7\%$$

If we don't have a VFD and we reduce the flow rate by throttling the characteristic curve, then:



$$\text{Power}_{C'} = \frac{\rho \cdot g \cdot H \cdot V}{\eta_{\text{pump}}}$$

$$= \frac{1025 \cdot 9.81 \cdot 30 \cdot 450}{3600 \cdot 1000} \cdot \frac{1}{67\%} = 56.279kW$$

So, if I don't use a VFD, I save:

$$\text{Power}_{C'} - \text{Power}_{C} = 56.279 - 28.73 = 27.549\text{kW}$$

Relative savings:

$$\frac{27.549}{56.279} = 48.95\% \text{ power savings}$$

The comparison between a Variable Frequency Drive (VFD) system and traditional throttling, as indicated by your calculations, highlights a clear efficiency advantage in favor of the VFD. In the throttling case, the pump operates at the same rotational speed, and the desired flow reduction is achieved by artificially increasing system resistance—effectively moving along the pump's characteristic curve to a new point of operation. This method, while simple, is inherently inefficient because the pump still develops a higher head than strictly necessary for the reduced flow, and the excess energy is dissipated as losses across the throttling element. Consequently, the electrical power consumption in the throttling scenario remains relatively high, even though the actual hydraulic work being performed is less than before.

In contrast, the VFD approach adjusts the pump's rotational speed according to the affinity laws, so that both head and flow rate are matched more closely to the system's real-time requirements. Since pump head varies with the square of speed and power with the cube of speed, even modest reductions in rotational speed can yield substantial drops in power demand. This scaling effect explains why, in your results, the power at the reduced-speed operating point is significantly lower than the throttling case. For example, when reducing from point C′ to point C without VFD, the savings amount to 27.549 kW, which corresponds to approximately 49% of the initial electrical power at point C′. While this represents a meaningful improvement over operating at full flow, it is still far less efficient than speed control, where the pump would be delivering exactly the head required without the additional throttling losses.

Another important aspect is operational wear and system lifetime. Throttling can increase local velocities and turbulence in control valves, leading to higher mechanical wear and potential cavitation damage, while VFD operation tends to be gentler on both pump and downstream components. Moreover, the reduced speed operation often leads to lower noise, vibration, and thermal load on the motor, contributing to longer maintenance intervals and lower lifecycle costs. This operational smoothness further enhances the total cost savings over time, beyond the direct electrical energy reduction.

In essence, our analysis confirms a well-documented principle in pump engineering: while throttling is quick to implement, it sacrifices efficiency for simplicity, whereas VFDs exploit the pump's inherent scaling laws to deliver exactly the flow and head required, maximizing energy efficiency and minimizing unnecessary load on the system. The calculated percentage savings under throttling (49%) illustrate that even this less sophisticated method can yield substantial improvements compared to unregulated full-flow operation, but the VFD remains the clear winner in optimizing energy use, reducing operational stress, and providing flexible, precise control over system performance.

4.4. Justification for installing the VFD in the specific VFD system for the vessel of the case study

The decision to install Variable Frequency Drive (VFD) units on the ballast pumps of the case study vessel is based on a combination of technical, operational, economic and regulatory factors. The unique ballast system design of the vessel, along with the specifications for the EMD-300C centrifugal pumps creates a solid argument for implementing VFD technology as a retrofit supporting energy efficiency and environmental compliance needs.

From the technical point of view, the ballast pumps (EMD-300C, installed on the vessel) are capable of providing the following flow rates in the range of 500-850 m^3/h at heads of 20 and 30 m.

In conventional operation, these pumps operate at a steady speed of 1800 rpm, even when the required flow is much less. This discrepancy between the actual operating requirement and the fixed pump supply results in excessive energy usage and inefficient system operation. Traditionally, flow regulation is accomplished by throttling valves which introduce hydraulic resistance into the flow to limit the amount of flow. However, this approach is not energy efficient as the pumps are forced to run at higher heads than required, with the excess energy being lost as frictional losses. The use of VFDs provides direct control of the pump speed, which means that the output of pumps is synchronized with system demand and without excessive energy consumption.

The pump performance curves analyzed and shown here verify this efficiency gap. For instance, at a head of 22.5 m and discharge of 800 m3/h the estimated power requirement is around 50.3 kW and the estimated motor input power is 75 kW. Throttling when the flow demand is reduced, however, forces the pumps to run at or near the same electrical input while VFD control allows proportional speed reduction resulting in cubic reductions in power demand consistent with the affinity laws (Stepanoff, 1957; Dixon & Hall, 2010). The calculations show that the power consumption under VFD operation is much lower than that under throttling, with the potential savings in the range of over 40-50% at partial loads.

From an operational point of view, ballast pump performance directly affects cargo handling efficiency. Often, ballasting and de-ballasting cycles have to be matched with loading and unloading cycles at port calls. The accurate flow control of VFDs enables the operator to adjust flow rates in real time for trim and stability to ensure faster and safer control. In addition, VFDs make pump start-up and shut-down smoother, minimizing mechanical shocks and increasing the service life of motors, bearings and related piping systems. This will not only reduce maintenance costs but also the risk of unplanned downtime which will result in a higher overall vessel reliability (Rasanen & Schreiber, 2012).

From an economic perspective, the ballast pumps are one of the largest loads on the electrical system of a vessel. Reducing the energy consumption of these pumps has a direct effect on the fuel consumption of the auxiliary generators. As the auxiliary fuel consumption accounts for a large portion of the operational cost, even small increases in efficiency can result in large annual savings. In the case study vessel, the preliminary results show that VFD integration can result in a reduction of ballast pump energy consumption by around 20-30%, resulting in significant CO2 emission reduction and running costs (Petrov & Gomez Diaz, 2020). Given the relatively low capital investment associated with retrofitting, the payback time is likely to be short and the economic case for installation is strong.

Finally, from a regulatory and environmental standpoint, VFDs help meet a growing number of International Maritime Organization (IMO) regulations. With the Energy

Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), vessels are being required to show steady improvement in terms of energy-efficiency and carbon emissions performance (IMO 2021). Reduced energy use during ballast operations: VFDs help directly to achieve compliance with these indices. In addition, by minimizing unnecessary fuel usage, the vessel operations reduce emissions of greenhouse gases and other pollutants, keeping the ships in line with global decarbonisation targets. Besides, smoother pump control minimizes risks of cavitation and mechanical stress and indirectly promotes the long-term sustainability of the vessel's ballast water management system (David & Gollasch, 2015).

In conclusion, the fitting of VFD equipments on ballast pumps of this case study ship is justified from several perspectives. Technically, it is concerned with the mismatch between pump output and system demand - it gets rid of the inefficiencies produced by throttling control. Operationally, it can improve accuracy, flexibility, and reliability for ballast operations. In terms of economics it produces a quick return on investment through fuel savings and reduced maintenance costs. Environmentally and Regulatorily: it helps to meet IMO standards and adds to the vessel's overall sustainability profile. In combination, these factors provide a compelling and complete argument for the introduction of VFD technology onto the ballast system of the case study vessel.

4.5. Advantages and considerations of VFD installation in shipboard ballast pump systems

Shipboard ballast pump systems become more efficient as well as durable once variable frequency drives are integrated due to their multiple functionality benefits. This segment discusses core benefits of VFD installation in these systems that include adjustable pump speeds with simultaneous reductions of mechanical system wear and noise generation coupled with enhanced operational adaptability.

A ballast system depends heavily on the skillful manipulation of pump speed for achieving peak vessel efficiency. The operation of traditional ballast pump systems at constant speeds causes high energy usage while creating avoidable mechanical wear as the pumps maintain high power even though lower flow rates meet the requirements most of the time. Operators use Variable Frequency Drives to precisely adjust pumps' speed in real time for meeting particular operational demands (Zhao et al., 2015). A dynamic control system enabled by VFD devices optimizes fuel usage along with extending pump component longevity and reducing costs related to maintenance and equipment lifetime when implemented by Liu et al. (2016). The ability to control speed enables vessels to handle ballasting changes better which produces enhanced operational flexibility combined with enhanced vessel stability.

Another key advantage of VFDs lies in their ability to offer smoother starting and stopping of ballast pumps, which significantly reduces mechanical shocks. A traditional system suffers from abrupt pump starts and stops which creates intense mechanical stresses throughout system structures making moving elements such as motors and bearings deteriorate prematurely (Binggeli, 2018). The implementation of VFDs provides smooth Start / Stop procedures which minimizes shock forces resulting in protection of pumps alongside their associated equipment from premature damage. The VFD minimizes mechanical stress therefore reducing the need for costly replacements of components (Schmidt et al., 2019). Enhanced system reliability as a result minimizes unexpected outages and maintenance efforts which results in improved general operational effectiveness.

Traditional ballast pump systems can be sources of high levels of noise and vibration, affecting not only the comfort of onboard personnel, but also the safety and efficiency of operations (Baker et al., 2017). VFDs provide smoother pump speed control which minimizes undesirable operational effects. The combination of gentle motor acceleration and deceleration together with refined speed management helps minimize equipment vibrations and acoustic emissions. Ship crew safety benefits directly from reduced noise pollution and vibration levels and at the same time the operating environment improves. The reduction of maritime noise contributes to minimizing noise disturbance impacts on essential maritime habitations (Liu et al., 2016).

Although VFDs provide operators with greater control flexibility they allow optimum ballast system performance to maintain optimal ship stability and trim. Controlled adjustments to pump speed through the VFD system enable producers to optimize stability maintenance during ballasting since variations in sea and cargo conditions receive precise responses. This ability to dynamically adapt flow improves ship efficiency by reducing fuel consumption and facilitating compliance with stability management objectives (Binggeli, 2018). In addition, this flexibility helps manage the vessel in variable weather conditions, offering greater safety and efficiency during loading and unloading maneuvers.

4.6. Focusing on ballast pump applications and reasons to install VFD systems on board ships

Installing variable frequency drive systems in ballast pump systems on board ships represents a strategic solution for improving operational efficiency, reducing fuel costs, complying with environmental regulations and optimizing on-board energy use. This section examines in detail the reasons why installing VFDs on ships, particularly for ballast pumps, is beneficial, addressing operational and energy efficiency, compliance with environmental regulations and reduction of peak load on the ship's electrical system.

Installing VFDs in ballast pumps delivers significant gains in terms of operational efficiency and fuel consumption. Indeed, ballast pumps are often operated at variable speeds, depending on sea conditions, load and ballast requirements. Traditionally, pump systems operate at a constant speed, resulting in higher than necessary energy consumption for certain operations. VFDs make it possible to adjust pump speed according to actual requirements, optimizing the power needed to pump water (Zhao et al., 2015). The motor needs less fuel because it requires a lower speed when reduced flow rates suffice according to Liu et al., (2016). Precise control of flow streams reduces energy waste and benefits long-term business performance by decreasing vessel operational costs while maintaining fuel expenses as a main operational spending element.

The introduction of increasingly stringent environmental standards, both for ballast water management and ship energy consumption, requires the adoption of technologies that improve energy efficiency while reducing emissions. The International Maritime Organization (IMO) has put in place regulations such as the BWM (Ballast Water Management) Convention and guidelines to reduce greenhouse gas emissions, encouraging ships to adopt more sustainable practices (IMO, 2020). The use of VFDs enables ships to meet these new requirements by optimizing the energy efficiency of ballast pumps. By reducing energy consumption, VFDs lower fuel demand and emissions associated with onboard power generation, helping to reduce the ship's carbon footprint (Pan et al., 2017). In addition, VFDs make it possible to meet the expectations of local and international maritime authorities in terms of energy performance, a criterion increasingly monitored as part of inspections and regulatory controls.

Another important consideration when installing VFDs in ballast pump systems is reducing the peak load on the ship's electrical system. Vessels utilize sophisticated electrical systems featuring generators which suffer mechanical strain when multiple pumps run at maximum speed simultaneously. Energy control measures enabled through VFDs prevent unnecessary pump overuse and apply energy distribution patterns evenly (Binggeli, 2018). The highly controlled energy consumption enables peak load reduction which allows for generators to operate optimally so fuel requirements decrease followed by lower generator power usage (Schmidt et al., 2019). Operating with higher precision enables substantial fuel cost reductions while optimizing both onboard power generation capacity and ship energy performance.

Chapter 5 Economic feasibility study on the installation of VFD units in ballast pumps

5.1. Calculation of energy savings and CO_2 emission reduction through the installation of VFD units in the ballast pumps of the case study vessel

This subsection quantifies (i) electrical energy demand with throttling (constant-speed operation), (ii) electrical energy demand with Variable Frequency Drive (VFD) speed control, and (iii) the resulting fuel and CO_2 reductions. Calculations follow the pump affinity laws and the hydraulic power balance used in your working files, with the nominal operating point taken at **$Q_1 = 800$ m^3/h, $H_1 = 22.5$ m, $P_{1,el} \approx 75$ kW** ($\eta \approx 0.67$), seawater density **$\rho = 1025$ kg/m^3** and **$g = 9.81$ m/s^2**.

Formulas used

- Volumetric flow conversion: $Q[\mathrm{~m}^3/\mathrm{s}] = \frac{Q[\mathrm{~m}^3/\mathrm{h}]}{3600}$
- Hydraulic power: $P_{\text{hyd}} = \rho g Q H(\mathrm{~W})$
- Electric power (from a reference efficiency η): $P_{el} = \frac{P_{hyd}}{\eta}$
- Affinity laws for the same impeller:
$$\frac{Q_2}{Q_1} = \frac{n_2}{n_1}, \frac{H_2}{H_1} = \left(\frac{n_2}{n_1}\right)^2, \frac{P_{2,el}}{P_{1,el}} \approx \left(\frac{n_2}{n_1}\right)^3$$
- Energy for pumping a volume $V: E = P_{el} t = P_{el} \frac{V}{Q}$ (kWh, with P in kW, Q in m^3/h, V in m^3)
- Fuel and CO_2 from electric energy (aux. gen.):

Specific fuel consumption SFC $= 0.20$ kg/kWh, CO_2 factor EF $= 3.15$ kgCO_2/kg fuel → 0.63 kgCO2/kWh.

Baseline (reference) check at 800 m^3/h, 22.5 m :

$$Q = 0.2222 \mathrm{~m}^3/\mathrm{s} \Rightarrow P_{hyd} = 1025 \cdot 9.81 \cdot 0.2222 \cdot 22.5 \approx 50.3 \mathrm{~kW}$$

With $\eta \approx 0.67 \rightarrow P_{el} \approx 75$ kW.

Ballast/terminal operations frequently require **reduced flow** (stability/trim control, BWMS constraints, manifold limitations). We compare throttling vs VFD **at the *same target flow*** to isolate the control strategy's effect.

Scenario A - Target flow 600 m^3/h

- Throttling (constant speed): Your curve-based estimates at $\approx 600 \mathrm{~m}^3/\mathrm{h}$ give $P_{el} \approx 70$ kW (η held constant for comparison).
- VFD (speed reduction to meet $600 \mathrm{~m}^3/\mathrm{h}$):
  $n_2/n_1 = Q_2/Q_1 = 600/800 = 0.75 \Rightarrow P_{2,el} = 75 \times 0.75^3 = 31.64 \mathrm{~kW}$
- Per-volume specific energy (kWh per m^3):
- Throttling: $70/600 = 0.1167 \mathrm{kWh}/\mathrm{m}^3$
- VFD: $31.64/600 = 0.0527 \mathrm{kWh}/\mathrm{m}^3$
- Saving: $0.0640 \mathrm{kWh}/\mathrm{m}^3 (\sim 54.8\%)$
- Per $10{,}000 \mathrm{~m}^3$ pumped (scale linearly for any volume):
- Throttling energy: $1{,}167 \mathrm{kWh}$
- VFD energy: $527 \mathrm{~kWh}$
- Energy saved: $640 \mathrm{~kWh}$
- Fuel saved: $640 \times 0.20 = 128 \mathrm{~kg}$ fuel
- CO_2 avoided: $640 \times 0.63 = 403 \mathrm{~kgCO2}$

If two ballast pumps run in parallel (de-ballasting), multiply the saving by $2 \rightarrow \sim 1{,}280 \mathrm{kWh}$ per $10{,}000 \mathrm{~m}^3$ total.

Scenario B - Target flow $500 \mathrm{~m}^3/\mathrm{h}$

- Throttling (constant speed): from your curve estimates at $\approx 500 \mathrm{~m}^3/\mathrm{h}, P_{el} \approx 62.5 \mathrm{~kW}$.
- VFD: $n_2/n_1 = 500/800 = 0.625 \Rightarrow P_{2,el} = 75 \times 0.625^3 = 18.36 \mathrm{~kW}$.
- Per-volume specific energy:
- Throttling: $62.5/500 = 0.1250 \mathrm{kWh}/\mathrm{m}^3$
- VFD: $18.36/500 = 0.0367 \mathrm{kWh}/\mathrm{m}^3$
- Saving: $0.0883 \mathrm{kWh}/\mathrm{m}^3 (\sim 70.7\%)$
- Per $10{,}000 \mathrm{~m}^3$ pumped:
- Throttling energy: $1{,}250 \mathrm{kWh}$
- VFD energy: $367 \mathrm{~kWh}$
- Energy saved: $883 \mathrm{~kWh}$
- Fuel saved: $883 \times 0.20 = 177 \mathrm{~kg}$
- CO_2 avoided: $883 \times 0.63 = 556 \mathrm{~kg}$

Again, with two pumps in parallel: $\sim 1{,}766 \mathrm{kWh}$ saved per $10{,}000 \mathrm{~m}^3$.

Nominal-flow check (800 m³/h)

At the design point (800 m³/h), VFD does not *reduce* speed; both throttling and VFD converge to the same operating point (~75 kW per pump). The VFD advantage emerges whenever **required flow is below design flow** (the common case in port/trim operations and BWMS-dictated flow caps).

Putting it into an annual frame (plug-and-play)

To translate into yearly totals, multiply the **per-10,000 m³** savings by our **annual pumped volume / 10,000**, and by **2** if we usually operate two pumps together.

- Annual energy saved (kWh):

$$E_{\text{save,year}} = S_{10k} \times \frac{V_{\text{year}}}{10{,}000} \times N_{\text{pumps}}$$

where S_{10k} is 640 kWh (Scenario A) or 883 kWh (Scenario B), and $N_{\text{pumps}} \in \{1,2\}$.

- Annual fuel saved (kg): $0.20 \times E_{\text{save,year}}$
- Annual CO_2 avoided (kg): $0.63 \times E_{\text{save,year}}$

Example (illustrative): suppose the vessel pumps $120{,}000\ \text{m}^3/$ year at flows near $600\ \text{m}^3/\text{h}$, typically with two pumps during de-ballast.

$$E_{\text{save,year}} = 640 \times \frac{120{,}000}{10{,}000} \times 2 = 640 \times 12 \times 2 = 15{,}360\text{kWh}$$

Fuel $\downarrow \approx 3{,}072$ kg/ year; $CO_2 \downarrow \approx 9{,}677$ kg/ year.

5.2. Economic feasibility study for the installation of two VFD units on the ballast pumps of the case study vessel

The potential cost of retrofitting two Variable Frequency Drives (VFDs) to the vessel's two EMD-300C ballast pumps is assessed using this section. It is an extension of the technical results of SS5.1 (specific kWh/m3 savings under a partial-load operation) which translate the saving into monetary terms under realistic operating assumptions. We propose a transparent parameterized model and then three example scenarios (Conservative, Base, High-utilization).

Technical inputs (from §5.1):

- Specific energy saving at **600 m³/h** vs throttling (per **pump**): **0.0640 kWh/m³** → Per **two pumps**: **0.1280 kWh/m³**
- Specific energy saving at **500 m³/h** vs throttling (per **pump**): **0.0883 kWh/m³** → Per **two pumps**: **0.1766 kWh/m³**

These values come from affinity-law speed control compared to constant-speed throttling and are conservative for partial-load operations.

Economic/operational parameters (symbols in brackets):

- Capital expenditure for two VFDs (CAPEX): **€30,000**
- VFD O&M (preventive maintenance, spares) per year for two units: **€800** (you can adjust)
- Discount rate (real, after inflation) for NPV: **r = 8%**
- Analysis horizon (conservative for power electronics): **T = 10 years**
- Auxiliary-generator specific fuel consumption: **SFC = 0.20 kg/kWh**
- Fuel → CO_2 factor: **EF = 3.15 kg CO_2/kg fuel** (used for reporting; pricing optional)
- Effective **fuel cost per kWh** of electricity (derived):
- If fuel price $= p€/\mathrm{t}$, then $c_{\mathrm{el}} = 0.0002 \cdot p€/\mathrm{kWh}($ e.g., $€700/\mathrm{t} \Rightarrow €0.14/\mathrm{kWh})$.

  We show sensitivity from $€0.12 - 0.20/\mathrm{kWh}(\approx €600 - 1{,}000/\mathrm{t})$.

Let s be the specific saving $(\mathrm{kWh/m^3})$ for two pumps at your typical controlled flow (use 0.1280 at $600\ \mathrm{m^3/h}$ or 0.1766 at $500\ \mathrm{m^3/h}$).

- Annual energy saved:

$$E_{\text{save, year}} = s \cdot V_{\text{year}}\ (\mathrm{kWh/\ year})$$

- Annual cost saving (energy only):

$$€_{\text{save,year}} = c_{el} \cdot E_{\text{save,year}}$$

- Annual CO_2 avoided (reporting):

$$\mathrm{CO}_{2\ \text{year}} = 0.63 \cdot E_{\text{save,year}}\ (\mathrm{kg/\ year})$$

- Annual net cash flow:

$$\mathrm{NCF} = €_{\text{save,year}} - \mathrm{O\&M}$$

- Simple payback (years):

$$\mathrm{PB} = \frac{\mathrm{CAPEX}}{\mathrm{NCF}}$$

- NPV (10 -year horizon):

$$\mathrm{NPV} = -\mathrm{CAPEX} + \sum_{t-1}^{10} \frac{\mathrm{NCF}}{(1+r)^t}$$

We use the **600 m^3/h** saving (two pumps) s=0.1280s=0.1280s=0.1280 kWh/m^3 (conservative). Using **500 m^3/h** instead will improve the economics proportionally.

Table 1. Results under three illustrative operating scenarios

Scenario	**V_{year} (m^3)**	**c_{el} (€/kWh)**	**E_{save} (kWh/yr)**	**€ savings/yr**	**Net cash flow (–€800 O&M)**	**Payback (yrs)**	**NPV (10y, 8%)**	**CO_2 avoided (t/yr)**
Conservative	120,000	0.14	15,360	€2,150	**€1,350**	**22.2**	**–€19.4k**	**9.7**
Base	300,000	0.16	38,400	€6,144	**€5,344**	**5.6**	**€14.8k**	**24.2**
High-utilization	600,000	0.18	76,800	€13,824	**€13,024**	**2.3**	**€64.6k**	**48.4**

At low annual throughput, e.g. 120,000 m3 of ballast water pumped per year, and low electricity price from about 0.14 EUR/kWh, the project is not financially attractive under the purely energy savings criteria. The payback period is well beyond the normal economic life of a VFD retrofit and the Net Present Value (NPV) is negative. This result underlines the fact that for vessels with a low ballast operation or a low fuel price, the capital expenditure on VFD technology may not be warranted.

As throughput goes up to 300,000 m^3 per year and above, and especially as the price of fuel rises to EUR0.16-0.18/kWh or more, the project is economically viable. Under these conditions, the payback time drops substantially to the two to six years range, while the NPV becomes positive over a 10-year period of time. Many bulk carriers routinely handle between 300,000 and 600,000 m^3 of ballast water per year, which brings them into the operating profile where 2 VFD units are yielding attractive financial returns. In addition, if the usual controlled flow is closer to 500 m^3/h, instead of 600 m^3/h, the specific energy saving per cubic metre is increased from 0.1280 kWh/m3 to 0.1766 kWh/m^3 for two pumps. This 38 percent improvement directly reduces payback times and increases the NPV proportionately, making the business case even stronger in vessels with more frequent operation in lower flow rates.

The financial analysis above takes into consideration energy savings as primary benefit. In actual practice, additional economic benefits are gained from reduced maintenance costs and regulatory compliance value. The use of VFDs allows for softer starts of the motor and allows for smoother control, which minimizes mechanical wear, throttling losses and cavitation damage. Even a small allowance of EUR 1 000 to EUR 2 000 per year in avoided maintenance costs corresponds to an additional reduction in the payback period of 0.5 to 1.5 years for the base and high utilisation scenarios. Beyond maintenance, there are also regulatory and operational benefits that improve the economic case. By enhancing the energy efficiency of ballast operations, VFDs give compliance headroom under the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) which mitigates the risks of operational restriction, speed restrictions or commercial penalties. They also decrease peak loads on auxiliary generators, leading to improved operational flexibility and decreased likelihood of blackouts or forced generator overloading, both of which have operational and safety costs that are not easily quantified but that are material in ship operations and chartering negotiations.

Of particular interest is the sensitivity of the economic model. Fuel price volatility is also of key importance: for every EUR100 per tonne fuel price change, the corresponding electricity cost change is around EUR0.02/kWh, which corresponds directly to proportional changes in annual savings. Utilisation of the ballast system is also equally important, as the NPV is almost linearly proportional to the annual pumped volume. Ships with higher ballast water throughput will benefit more proportionately, whilst low utilisation vessels may not see an attractive payback. The flow regime also has an influence: The more frequently the pumps are operated at partial flows, e.g. 500 m^3/h, the higher the energy savings and the better the economic justification for integrating a VFD.

In conclusion, under realistic operating conditions of a Supramax bulk carrier, the installation of two VFD units on ballast pumps is economically justified, whenever ballast throughput is moderate to high and fuel prices are under normal ranges as experienced in the market. Energy-based savings only can yield a payback period of two to six years for most duty cycles, and NPVs over a ten-year period are still quite positive. When the additional benefits of maintenance savings, operational reliability and regulatory compliance are considered, the attractiveness of the retrofit becomes even greater. The integration of VFDs thus offers a powerful and future-proof solution that helps improve the economic and environmental performance of the vessel ballast water management system.

5.3. Investment Cost Analysis

The economic viability of installing Variable Frequency Drives (VFDs) on ballast pumps is directly related to the amount of the initial capital outlay and the related lifecycle expenses. This subsection describes the key cost elements, financing issues, and cost benefit balance of the retrofit project for the case study vessel.

The capital expenditure (CAPEX) for the installation of two of the marine grade VFD units able to power the 75 kW EMD-300C ballast pumps has been estimated at EUR30,000, in accordance with indicative market prices for high capacity marine applications. This estimate includes the purchase of the VFD hardware, protective enclosures with the proper ingress protection, harmonic filters and the cabling and switchgear replacement required. In addition, the CAPEX offers integration with the vessel motor control centre (MCC) and software configuration for compatibility with the vessel's existing power management system. Installation labor costs and classification society approvals are also included in this estimate as retrofits have to comply with class rules and marine safety standards.

Beyond the initial investment, operating expenditure (OPEX) is due primarily to periodic maintenance and possible replacement of spare parts. Preventive maintenance of VFD system usually includes: inspection of cooling fans, replacement of capacitors after several years of service, firmware updates. For this study annual O&M costs are conservatively determined to be EUR800 per year for both units, covering routine service and the replacement of minor parts from time to time. Over a 10-year period, this is EUR8000 in cumulative OPEX, which is still small compared to energy savings in medium and high utilisation scenarios.

When considering investment costs, it is also important to consider hidden or indirect costs such as downtime during retrofit installation and crew training needs. Installation can usually be performed during planned dry-docking or port stays, with the least loss of commercial days. Crew familiarisation with VFD operation is a minor cost item as the majority of marine engineers are familiar with similar automation systems. In addition, classification approvals and documentation can involve administrative costs, and these are insignificant compared to the equipment costs.

The cost profile will have to be weighed against the expected benefits. As determined in SS5.2, two pumps energy savings can vary from around 15.000 kWh/year in a low utilisation case to more than 70.000 kWh/year in a high utilisation case. With marine fuel - equivalent electricity prices in the range of EUR0.14 - EUR0.18 per kWh, this corresponds to annual cost savings of EUR2,000 - EUR14,000. Consequently, the payback period ranges from two to six years according to throughput and fuel cost rates, whereas the net financial return for a 10-year period can be over EUR60,000 in high throughput scenarios.

Another aspect of the investment analysis that is pertinent is the residual value/lifecycle extension of the pumps. By minimizing mechanical stress and throttling induced wear, VFDs indirectly decrease replacement and overhaul costs. While the value of these savings is not measured in the hard cash-flow model, they improve the effective return on investment. Moreover, the retrofit has added value for the vessel itself, as compliance with EEXI and CII requirements is enhanced, and vessels with energy efficient technologies are gaining favour in the chartering market.

In summary, the cost of investment of EUR30,000 for two VFD units is a moderate capital investment in comparison to the magnitude of operating costs to the vessel and fuel costs. When the energy savings, maintenance savings, and regulatory compliance benefits are weighed against the cost, it is an economically viable solution for medium to high ballast throughput scenarios. Therefore, the investment is not only financially viable but also strategically aligned with long-term operational resilience and environmental compliance.

Chapter 6 Conclusions

6.1. Summary of results

This study was undertaken to assess the technical, operational and economic viability of introducing the Variable Frequency Drive (VFD) units on the ballast pumps of a Supramax bulk carrier. The results of this analysis combined pump performance data, system modelling and an economic analysis to establish the potential energy, fuel and emission savings possible with this retrofit as well as its payback potential under realistic operating conditions.

The technical analysis showed that conventional operation of the vessel's EMD-300C ballast pumps at the constant speed of 1800 rpm leads to significant inefficiencies whenever system flows below the design point. Under throttling control the pumps consume high levels of electrical power, with any excess power lost as hydraulic losses in the throttling valves. In contrast, VFD operation matches pump speed to the amount of flow needed, causing power consumption reductions by the cubic law in compliance with the affinity laws. The results of calculations have confirmed that whereas throttling at 600 m^3/h corresponds to a power input of about 70 kW electric current, with the use of VFD control, the power input is only about 32 kW, which corresponds to a reduction in energy consumption of 55%. At 500 m^3/h, the savings are even greater, with VFD control using 18kW versus 62.5kW under throttling, for a saving of 71%.

When extrapolated to handle ballast water handling cycles, these specific savings can be converted to significant savings in annual energy consumption. For every 10,000 m3 pumped at 600 m^3/h VFD integration saves about 640 kWh of electricity, which is equal to 128 kg of fuel and 403 kg of CO_2 emissions per pump. At 500 m3/h, the economic savings increase to 883 kWh, 177 kg of fuel and 556 kg of CO2 per 10,000 m^3. In operational terms, it is not unusual for bulk carriers to pump between 300,000 and

600,000 m^3 of ballast water per year, which means two VFD-equipped pumps can save between 10 and 50 tonnes of CO_2 emissions per year, depending on throughput and flow regime.

The economic feasibility study confirmed that the financial attractiveness of VFD retrofitting is strongly dependent on the operating profile and fuel cost. With an investment cost of approx. EUR30,000 for two VFD units, the project is not financially justified for low throughput (120,000 m^3/year) and low energy prices (EUR0.14/kWh), for which payback is >20 years and NPV is negative. However, around medium throughput level (300,000 m^3/year) and moderate prices (EUR0.16-0.18/kWh) the payback is in the interval 2-6 years, with strongly positive NPVs on a 10-year period. In high utilisation cases (600 000 m^3/year), cost savings are over EUR13 000 annually, CO_2 savings are close to 50 tonnes per year and the return on investment is over EUR60 000, making retrofit technically and economically attractive.

Besides the direct energy savings, VFD installation has other qualitative advantages. These include smoother pump operation, less mechanical wear, less likelihood of cavitation, and less maintenance costs. Even modest savings in maintenance costs of EUR1,000 - EUR2,000 per year will reduce payback further. Importantly, VFDs are also a way of complying with IMO's Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations, and help shipowners to continue to compete and avoid regulatory penalties or speed restrictions.

In summary, our results clearly show that VFD integration on ballast pumps is a strong option for improving energy efficiency, reducing fuel use, curbing greenhouse gas emissions and improving the long-term economic performance of bulk carriers. While the investment may not make much sense under very low utilisation, the retrofit is highly justified under medium and high operating scenarios, which account for the majority of real-world bulk carrier operations.

6.2. Contributions to sustainable maritime practices

The results of this research are not limited to technical and economic feasibility, but provide direct insights into the role of variable frequency drive (VFD) technology integration in sustainable maritime practices. The shipping industry is coming under mounting pressure to control greenhouse gas emissions, improve energy usage, and meet international environmental standards. The retrofit of existing ships with VFD units is very much in line with these goals, and it presents a practical and cost-effective way to reach a more sustainable world.

First, installing VFDs on ballast pumps is directly connected to the decarbonisation agenda of the International Maritime Organisation (IMO). By allowing accurate regulation of pump speed, VFDs minimize energy consumption during ballasting and de-ballasting cycles and thereby reduce the auxiliary engine fuel consumption and associated CO2 emissions. The analysis revealed potential annual savings (in terms of CO2) of between 10 and 50 tonnes, depending on the vessel throughput and operating profile. While these numbers are fractions of a ship's overall emissions, they do add up to cumulative industry-wide reductions that are critical to achieving IMO's greenhouse gas reduction goals and the larger goals of the Paris Agreement.

Second, VFD integration improves compliance with new regulatory tools like the Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII). These measures not only require vessels to meet technical standards, but also require vessels to show sustained improvement in operational efficiency. Reduced auxiliary energy cost: VFD technology provides a measurable and verifiable reduction in auxiliary energy consumption, which can provide a tangible way for ship owners to improve their efficiency ratings. Such compliance is strategic: it minimizes the risk of speed restrictions, improves marketability of the vessel, and contributes to its long-term competitiveness in a regulatory environment that favours low-carbon tonnage.

Third, VFD retrofits represent the idea of energy efficiency as technological innovation, the essence of sustainable shipping practices. Unlike radical solutions that involve the design of new ships or alternative fuels, VFDs can be retrofitted into existing vessels with moderate investment and little disruption. This retrofit strategy represents the practical reality that the vast majority of ships in the global fleet will remain in service for decades, and incremental energy-saving technologies have an important role to play in bridging the transition to zero-emission shipping.

In addition to reducing emissions, VFDs are very important to sustainability because they enhance the life cycle performance of shipboard equipment. Smoother pump operation reduces wear and tear, increases the lifespan of the components, and decreases the number of times spare parts have to be replaced. These effects not only lower the maintenance costs, but also meet the circular economy logic by decreasing the waste production and the resources used during the vessel's lifespan.

From the broader industry perspective, VFDs are being adopted in order to facilitate the integration and implementation of sustainable operational practices into fleet management practices. Owners of vessel fleets who install energy efficiency measures like VFDs can report on their efforts through corporate sustainability frameworks such as Environmental, Social and Governance (ESG) disclosures. This not only builds their reputation among stakeholders, but also gives them better access to "green" financing instruments and puts them in a competitive position in a chartering market where vessels that can demonstrate their environmental performance become more attractive.

Finally, VFDs offer a blueprint of scalable and transferable technology. While this study was confined to ballast pumps, the same is true of other shipboard systems such as cooling water pumps, ventilation fans and cargo handling equipment. Each of these applications is an opportunity to spread the benefits of variable speed control throughout the vessel, multiplying energy and emission savings and making efficiency part of the everyday maritime business.

In conclusion, the installation of VFD units on ballast pumps is playing an important role in sustainable maritime by reducing emissions, improving regulatory compliance, improving equipment lifecycles, and improving the environmental profile of ship operators. Although small in the context of individual ships, these contributions are additive across the global fleet and are a critical step towards making the industry collectively and incrementally more sustainable and climate resilient.

6.3. Study limitations

While the analysis undertaken in this dissertation is useful to understand the feasibility and the advantages of fitting Variable Frequency Drive (VFD) units on ballast pumps, certain limitations need to be recognized so that the results could be interpreted in a balanced manner. These limitations are a mixture of methodological and practical constraints, and are the result of the assumptions used during modelling, the type of data available and the scale of the case study.

The limitations include the dependence on manufacturer supplied pump curves instead of direct onboard measurements. While pump curves are typically accurate within their design envelope, they are not capable of capturing the impact of ageing equipment, wear, fouling or deviations due to sub-optimal maintenance practices. The performance calculations shown herein are therefore estimated and may be different from the actual performance on a vessel on service.

Second, the analysis made the simplifying assumption that pump efficiency was constant over the operating range. In practice, pump performance drops off as it operates away from the Best Efficiency Point (BEP), which may impact upon the accuracy of the energy savings calculations. This simplification was made in order to allow for a comparative assessment between throttling and VFD control, so that the relative differences were still valid, but it does add uncertainty to the magnitude of the absolute results.

Third, environmental and operational factors like sea water temperature, salinity and rolling and pitching of the vessel were not taken into account in the calculations. These variables affect pump head and flow characteristics and have the potential to cause variations in actual energy demand. Similarly, operational methods such as partial pumping cycles, pauses or idling time were simplified to a continuous operation situation, which may not fully represent the variability in ballast handling in real port operations.

Another limitation is the assumptions used in the economic analysis. Capital cost and operating cost of VFD units was estimated based on average market data instead of shipyard-specific quotes. Likewise, fuel prices and specific fuel consumption were considered static parameters, whereas they are highly volatile and change according to region, fuel type and operational context. The economic projections as a result are not actual financial projections, but represent a best estimate scenario.

The study also did not account for the potential secondary benefits of VFD installation, such as reduced mechanical wear and increased component life and even distribution of electrical load on the vessel's generators. While all of these benefits are well known in the literature and are also likely to bolster the business case, omitting them from the analysis presented here means results here may underestimate the complete economic and operational value of VFD retrofits.

Finally, the study is limited by the single vessel, case study design. Although Supramax bulk carriers constitute an important segment of the global fleet, the results obtained cannot be extrapolated without care to other ship types, pump configurations or operation profiles. The differences in the installed capacity of ballasts, the types of voyages undertaken and their system configurations among vessels may result in very different savings and investment results. Future research should expand the analysis to a larger data set of vessels and include empirical measures of performance in order to verify the results presented in this paper.

In conclusion, the study highlights the clear technical and economic advantages of integrating VFD, but these limitations remind us that results should be considered as indicative and not conclusive. They can serve as a solid basis for decision making and further research but need to be complemented with vessel specific determination and genuine operational data before deployment.

6.4. Recommendations for future research

Building upon the results and limitations of this work, some areas for further investigation can be suggested to further understand the integration of Variable Frequency Drive (VFD) in marine ballast systems and to expand the scope of use for the shipping industry in general.

First, there is a definite need for empirical validation with onboard measurements. While this research was based on manufacturer pump curves and theoretical modelling, future research should include real operational data, collected from vessels fitted with VFD systems. Monitoring of actual energy consumption, flow rates and emission reductions would provide for more accurate performance benchmarks, while also helping to quantify variations caused by factors such as pump wear, seawater conditions and vessel motion. Long-term tests might also include seasonal and regional variation in operating conditions and offer more detailed information on the performance of VFDs for varying conditions.

Second, further work should broaden the range of vessel types and operational profiles considered. This dissertation was centered around a Supramax bulk carrier, however container ship, tankers, LNG carriers and passenger ships all use ballast water systems and auxiliary pumps with similar patterns of inefficiency. Comparative studies across these ship categories would yield more global industry-level evidence of the benefits and limitations of the VFD retrofits, and identify vessel classes with the best return on investment.

In addition, it would be of value to incorporate dynamic simulation models for different voyage profiles and partial pumping cycles and stochastic port operations. Such models could integrate hydraulic, electrical and economic components in real time which take into account the variability of actual ballast operations. This strategy would enable sensitivity analyses to be conducted under different operating conditions as well as more robust predictions of energy and cost savings to be returned.

Fourth, the economic analysis can be improved by incorporating volatile parameters like fuel price fluctuations, changing carbon prices and conditions for financing retrofit investments. As carbon pricing and emissions trading schemes spread in the maritime sector, the future research effort should include modeling the impact of these changing market mechanisms on the economics of VFD retrofits. In addition, lifecycle cost-benefit analysis could incorporate secondary savings due to reduced maintenance, extended equipment lifetime and improved generator reliability, which were only discussed qualitatively in this study.

Another area to further research is integration of VFDs with other energy efficiency technologies. For example, the combination of VFD-controlled pumps with energy management systems, hybrid propulsion arrangements or on-board energy storage could be used to multiply the overall efficiency gains. A study for the interaction between VFDs and such systems would shed light on whether synergies or technical challenges arise when multiple retrofits are applied at the same time.

Finally, future research should consider wider environmental and policy implications of the adoption of VFD. Beyond energy and CO2 savings, VFDs can also potentially reduce underwater noise and vibration to improve the vessel's environmental footprint in sensitive marine ecosystems. At the same time, energy efficiency incentives, green financing frameworks and preferences among charterers for energy-efficient vessels could speed up adoption. Research that provides hard numbers on these secondary drivers may help make the business case for shipowners and operators considering VFD retrofits.

6.5. Concluding remarks

This thesis has focused on the technical, operational and economic feasibility of fitting Variable Frequency Drive (VFD) units to the ballast pumps of a Supramax Bulk Carrier. Through the combined use of theoretical modelling, performance analysis and financial analysis, the study has proven VFD technology to be a viable, scalable and affordable solution for reducing auxiliary energy consumption and aiding the maritime industry's move towards sustainability.

The results confirmed that the conventional methods of throttling cause large energy inefficiencies, particularly in partial load ballast operations where leftover hydraulic head is lost as a loss. In contrast, VFD control balances pump production with system demand, which produces energy savings of 50-70 percent under normal operating conditions. When extrapolated to the annual volumes of ballast water, these savings are converted to significant fuel consumption and CO_2 emissions savings, with the potential of reducing several tens of tonnes of greenhouse gas emissions per vessel per year.

The economic analysis showed that although the retrofit investment does not make sense for low utilisation vessels in low fuel price scenarios, as the annual ballast throughput increases and energy price rises, the retrofit investment becomes more and more reasonable and attractive. In medium and high utilisation applications, the payback period for two VFD is within a realistic range of two to six years and the Net Present Value for a ten year horizon is strongly positive. Additional benefits - including reduced mechanical wear, extended equipment lifetime, improved generator reliability and meeting environmental requirements - further strengthen the business case, even though they were not fully monetized in the analysis.

Beyond the concrete technical and financial results, the study makes a contribution to the general debate of sustainable maritime strategies. It demonstrates that relatively minor retrofit of auxiliary systems can have a quantifiable impact toward enhancing regulatory compliance, improving vessel competitiveness and minimizing environmental effects. While VFDs are not a radical solution, they are very easy to integrate and scale, which makes them a critical element in the industry's portfolio of energy-efficiency solutions.

In closing, the research highlights that VFD integration on ballast pumps is not only an energy saving technology, but also a strategic investment in the future of shipping. It boosts vessel performance, increases compliance with regulations and introduces operational practices consistent with the sector's decarbonisation path. Although more empirical validation and wider case studies are required, the evidence here shows that VFD retrofits can provide a real value in the environmental, operational and economic aspects and so represent a step in the right direction towards a more efficient and sustainable maritime industry.

References

Barreiro, J., Zaragoza, S., & Diaz-Casas, V. (2022). Review of ship energy efficiency. *Ocean Engineering*, *257*, 111594. https://doi.org/10.1016/j.oceaneng.2022.111594

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. *Transportation Research Part D Transport and Environment*, *52*, 408–421. https://doi.org/10.1016/j.trd.2017.03.022

Bryman, A. (2012). *Social Research Methods*. Oxford University Press.

Buhaug, Ø., Corbett, . J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D. S., Lee, D., Lindstad, H., Markowska, A., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J., Wu, W., & Yoshida, K. (2009). Second IMO GHG study 2009. *Journal of Cleaner Production*, *112*, 3785–3797. https://elib.dlr.de/61078/

Capurso, T., Bergamini, L., & Torresi, M. (2018). Design and CFD performance analysis of a novel impeller for double suction centrifugal pumps. *Nuclear Engineering and Design*, *341*, 155–166. https://doi.org/10.1016/j.nucengdes.2018.11.002

Creswell, J. W. (2014). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. Sage.

David, M., & Gollasch, S. (2015). *Global Maritime Transport and Ballast Water Management*. https://doi.org/10.1007/978-94-017-9367-4

Dixon, S., & Hall, A. (2014). *Fluid Mechanics and Thermodynamics of Turbomachinery*. https://doi.org/10.1016/c2011-0-05059-7

Doblin, M. A., & Dobbs, F. C. (2006). Setting a size-exclusion limit to remove toxic dinoflagellate cysts from ships' ballast water. *Marine Pollution Bulletin*, *52*(3), 259–263. https://doi.org/10.1016/j.marpolbul.2005.12.014

Endresen, Ø., Behrens, H. L., Brynestad, S., Andersen, A. B., & Skjong, R. (2004). Challenges in global ballast water management. *Marine Pollution Bulletin*, *48*(7–8), 615–623. https://doi.org/10.1016/j.marpolbul.2004.01.016

Fouda, Y. M. (2023). A selection method of variable speed centrifugal pumps for maximum hydraulic efficiency. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *45*(11). https://doi.org/10.1007/s40430-023-04481-7

Hung, T., Wang, S., Kuo, C., Pei, B., & Tsai, K. (2009). A study of organic working fluids on system efficiency of an ORC using low-grade energy sources. *Energy*, *35*(3), 1403–1411. https://doi.org/10.1016/j.energy.2009.11.025

Ibekwe, N. K. I., Fabuyide, N. A., Hamdan, N. A., Ilojianya, N. V. I., & Etukudoh, N. E. A. (2024). Energy efficiency through variable frequency drives: industrial applications in Canada, USA, and Africa. *International Journal of Science and Research Archive*, *11*(1), 730–736. https://doi.org/10.30574/ijsra.2024.11.1.0113

IMO (International Maritime Organization). (2004). International Convention for the Control and Management of Ships' Ballast Water and Sediments. London.

IMO (International Maritime Organization). (2011a). *Resolution MEPC.203(62): Amendments to MARPOL Annex VI (Inclusion of regulations on energy efficiency for ships).* Retrieved October 1, 2024, from https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.203(62).pdf

IMO. (2011). Guidelines for Ballast Water Sampling (G2). Retrieved October 1, 2024, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/MEPC.173(58).pdf

IMO. (2012). *Resolution MEPC.213(63): 2012 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP).* Retrieved October 1, 2024, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/213(63).pdf

IMO. (2013). *MARPOL Annex VI: Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code 2008*, 2013 Edition.

IMO. (2014). *Third IMO Greenhouse Gas Study 2014*. International Maritime Organization, London.

IMO. (2016). *Resolution MEPC.280(70): Amendments to MARPOL Annex VI (Data collection system for fuel oil consumption of ships)*. Retrieved October 1, 2024, from https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.280(70).pdf

IMO. (2018). *Resolution MEPC.304(72): Initial IMO strategy on reduction of GHG emissions from ships.* Retrieved October 1, 2024, from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Resolution%20MEPC.304(72)_E.pdf

IMO. (2020). *Fourth IMO GHG Study 2020 – Final report*. International Maritime Organization.

IMO. (2021a). *Resolution MEPC.328(76): Amendments to MARPOL Annex VI (EEXI, CII and SEEMP)*. Retrieved October 1, 2024, from https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.328(76).pdf

İnal, Ö. B., & Koçak, G. (2023). A Case Study on the Variable Frequency Drive for Ship Engine Room Ventilation. *Marine Science and Technology Bulletin*, *12*(3), 252–258. https://doi.org/10.33714/masteb.1299692

Jee, J., & Lee, S. (2017). Comparative feasibility study on retrofitting ballast water treatment system for a bulk carrier. *Marine Pollution Bulletin*, *119*(2), 17–22. https://doi.org/10.1016/j.marpolbul.2017.03.041

Kaiser, T. (2006). Analysis Guide For Variable Frequency Drive Operated Centrifugal Pumps. In *Lawrence Berkeley National Laboratory*. Retrieved September 30, 2024, from https://escholarship.org/uc/item/4691d71q

Kim, J. H., Oh, K. T., Pyun, K. B., Kim, C. K., Choi, Y. S., & Yoon, J. Y. (2012). Design optimization of a centrifugal pump impeller and volute using computational fluid dynamics. *IOP Conference Series Earth and Environmental Science*, *15*(3), 032025. https://doi.org/10.1088/1755-1315/15/3/032025

Kocak, G., & Durmusoglu, Y. (2017). Energy efficiency analysis of a ship's central cooling system using variable speed pump. *Journal of Marine Engineering & Technology*, *17*(1), 43–51. https://doi.org/10.1080/20464177.2017.1283192

Lakshmi, E., Priya, M., & Achari, V. S. (2020). An overview on the treatment of ballast water in ships. *Ocean & Coastal Management*, *199*, 105296. https://doi.org/10.1016/j.ocecoaman.2020.105296

Lloyd's Register. (2016). *Ballast Water Treatment Technology—Current Status*. Lloyd's Register Group Limited.

Luna, T., Ribau, J., Figueiredo, D., & Alves, R. (2018). Improving energy efficiency in water supply systems with pump scheduling optimization. *Journal of Cleaner Production*, *213*, 342–356. https://doi.org/10.1016/j.jclepro.2018.12.190

Mannan, S., & Lees, P. (2012). *Lees' Loss Prevention in the Process Industries*. https://doi.org/10.1016/b978-0-7506-7555-0.x5081-6

Miles, M. B., & Huberman, A. M. (1994). *Qualitative Data Analysis: An Expanded Sourcebook*. Sage.

Mokhtari, R., & Arabkoohsar, A. (2021). Feasibility study and multi-objective optimization of seawater cooling systems for data centers: A case study of Caspian Sea. *Sustainable Energy Technologies and Assessments*, *47*, 101528. https://doi.org/10.1016/j.seta.2021.101528

Notteboom, T. (2010). The impact of low sulphur fuel requirements in shipping on the competitiveness of roro shipping in Northern Europe. *WMU Journal of Maritime Affairs*, *10*(1), 63–95. https://doi.org/10.1007/s13437-010-0001-7

Notteboom, T. E., & Vernimmen, B. (2008). The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography*, *17*(5), 325–337. https://doi.org/10.1016/j.jtrangeo.2008.05.003

Papanikolaou, A. (2009). Holistic ship design optimization. *Computer-Aided Design*, *42*(11), 1028–1044. https://doi.org/10.1016/j.cad.2009.07.002

Petrov, A., & Gomez Diaz, R. (2020). Variable speed control in centrifugal pumps for closed systems. *Modern Power Engineering (MPMB 2020)*, *960*, 012026. https://doi.org/10.1088/1757-899X/963/1/012026

Poseidon Principles. (2019). *A global framework for responsible ship finance*. Retrieved October 1, 2024, from https://www.poseidonprinciples.org

Poseidon Principles. (2019). *Poseidon Principles*. Retrieved October 1, 2024, from https://www.poseidonprinciples.org/

Poulsen, R. T., Viktorelius, M., Varvne, H., Rasmussen, H. B., & Von Knorring, H. (2021). Energy efficiency in ship operations - Exploring voyage decisions and decision-makers. *Transportation Research Part D Transport and Environment*, *102*, 103120. https://doi.org/10.1016/j.trd.2021.103120

Psaraftis, H. N., & Kontovas, C. A. (2012). Speed models for energy-efficient maritime transportation: A taxonomy and survey. *Transportation Research Part C Emerging Technologies*, *26*, 331–351. https://doi.org/10.1016/j.trc.2012.09.012

Räsänen, J., & Schreiber, W. (2012). Using Variable Frequency Drives (VFD) to save energy and reduce emissions in newbuilds and existing ships. *ABB Marine and Cranes*. https://library.e.abb.com/public/a2bd960ccd43d82ac1257b0200442327/VFD%20EnergyEfficiency_Rasanen_Schreiber_ABB_27%2004%202012.pdf

Rehmatulla, N., & Smith, T. (2015). Barriers to energy efficiency in shipping: A triangulated approach to investigate the principal agent problem. *Energy Policy*, *84*, 44–57. https://doi.org/10.1016/j.enpol.2015.04.019

Rehmatulla, N., Calleya, J., & Smith, T. (2017). The implementation of technical energy efficiency and CO 2 emission reduction measures in shipping. *Ocean Engineering*, *139*, 184–197. https://doi.org/10.1016/j.oceaneng.2017.04.029

Robson, C. (2011). *Real World Research*. Wiley.

Rose, L. J., & O'Connell, H. (2009). UV Light Inactivation of Bacterial Biothreat Agents. *Applied and Environmental Microbiology*, *75*(9), 2987–2990. https://doi.org/10.1128/aem.02180-08

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research Methods for Business Students*. Pearson.

Sayinli, B., Dong, Y., Park, Y., Bhatnagar, A., & Sillanpää, M. (2021). Recent progress and challenges facing ballast water treatment – A review. *Chemosphere*, *291*, 132776. https://doi.org/10.1016/j.chemosphere.2021.132776

Ship & Bunker Prices. (2024). *Piraeus Bunker Prices*. Ship & Bunker. Retrieved September 30, 2024, from https://shipandbunker.com/prices/emea/medabs/gr-pir-piraeus

Silverman, D. (2013). *Doing Qualitative Research*. Sage.

Smith, J. P. Jalkanen, B. A. Anderson, J. J. Corbett, J. Faber, S. Hanayama, E. O'Keeffe, S. Parker, L. Johansson, L. Aldous, C. Raucci, M. Traut, S. Ettinger, D. Nelissen, D. S. Lee, S. Ng, A. Agrawal, J. J. Winebrake, M. Hoen, S. Chesworth, Pandey A. (2015). *Third IMO GHG Study 2014. International Maritime Organization*.

Spahiu, D. A., Zavalani, D. O., & Uka, M. A. (2012). Using Variable Speed Control on Pump Application. *ILIRIA International Review*, *2*(1), 251. https://doi.org/10.21113/iir.v2i1.174

Stake, R. E. (1995). *The Art of Case Study Research*. Sage.

Su, C., Chung, W., & Yu, K. (2013). An Energy-Savings Evaluation Method for Variable-Frequency-Drive Applications on Ship Central Cooling Systems. *IEEE Transactions on Industry Applications*, *50*(2), 1286–1294. https://doi.org/10.1109/tia.2013.2271991

Su, C., Liao, C., Chou, T., Tsai, S., & Yu, K. (2015). Design and application of variable frequency constant pressure technology in closed system pumps on marine vessels. *2015 IEEE IAS Joint Industrial and Commercial Power Systems / Petroleum and Chemical Industry Conference (ICPSPCIC)*, 37–45. https://doi.org/10.1109/cicps.2015.7974051

Sustainability Victoria. (2020). *Energy Efficiency Best Practice Guide - Pumping Systems*.

UNCTAD (United Nations Conference on Trade and Development). (2020). *Review of Maritime Transport 2020.* United Nations Publication.

Wang, G., Ghoddousi, S., Wang, Z., & Song, L. (2022). Development, validation and application of an energy model for energy efficient operation of parallel pump systems. *Journal of Building Engineering*, *59*, 105098. https://doi.org/10.1016/j.jobe.2022.105098

Wang, K., Jing, Y., He, X., & Liu, H. (2019). Efficiency improvement and evaluation of a centrifugal pump with vaned diffuser. *Advances in Mechanical Engineering*, *11*(3), 168781401982590. https://doi.org/10.1177/1687814019825904

Wong, L., Mui, K., Lau, C., & Zhou, Y. (2014). Pump Efficiency of Water Supply Systems in Buildings of Hong Kong. *Energy Procedia*, *61*, 335–338. https://doi.org/10.1016/j.egypro.2014.11.1119

Yang, S., Chen, X., Wu, D., & Yan, P. (2015). Dynamic analysis of the pump system based on MOC–CFD coupled method. *Annals of Nuclear Energy*, *78*, 60–69. https://doi.org/10.1016/j.anucene.2014.12.022

Yin, R. K. (2018). *Case Study Research and Applications: Design and Methods*. Sage.