ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ
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ΣΧΟΛΗ ΝΑΥΤΙΚΩΝ ΔΟΚΙΜΩΝ
ΤΜΗΜΑ ΝΑΥΤΙΚΩΝ ΕΠΙΣΤΗΜΩΝ

ΔΠΜΣ

Διοίκηση στη Ναυτική Επιστήμη και Τεχνολογία

Διπλωματική Εργασία

“Multi-criteria analysis of ship energy efficiency measures for LNG carriers of various ages and economic implications”

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Μάρτιος 2024

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"I would like to express my deepest gratitude to all those who made the completion of this thesis possible. First and foremost, my sincere thanks go to my advisors, for their invaluable guidance, patience, and support throughout this journey. Their expertise and insightful feedback have been instrumental in shaping both the direction and the outcome of this work.

I owe a great deal of thanks to my colleague and friend Mouka Vasileio, who provided encouragement, insightful discussions, and a supportive environment that motivated me to persevere through the challenges of this research.

Special thanks to my family who have been my constant source of encouragement, and support.

This thesis stands as a testament to the collective effort and kindness of all those mentioned above, and many others who, in one way or another, contributed to its completion. Thank you."

Abstract

This Master's thesis conducts a multi-criteria analysis of ship energy efficiency measures, and especially for Steam Turbine Liquefied Natural Gas (LNG) carriers, focusing on both technical and environmental implications. By evaluating a range of energy efficiency measures, including technological innovations and operational strategies, the study aims to identify the most cost-effective approaches to reduce greenhouse gas emissions and enhance operational efficiency. The research employs a multi-criteria decision-making framework to balance environmental benefits with economic feasibility, considering the unique characteristics of LNG carriers of various ages. Findings reveal that certain energy efficiency measures offer significant advantages in reducing environmental impact and operational costs, though their effectiveness varies by ship size and design. The thesis emphasizes the need for a tailored approach in implementing energy efficiency solutions, highlighting the importance of industry-wide collaboration to achieve sustainability goals in the maritime sector.

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1. LNG Carrier Industry in Global Energy Trade

The LNG carrier industry occupies a pivotal role in the global energy trade, facilitating the efficient transport of natural gas from production hubs to regions of high demand. Natural gas stands as a cleaner and cost-effective substitute for coal and oil in power generation, industrial applications, and it extends its utility to residential and commercial sectors. However, global natural gas resources are not uniformly distributed, leading to situations where certain regions exhibit surplus supply while others grapple with insufficient availability. This divergence underscores the imperative for a dependable and effective means of conveying natural gas across vast distances, even traversing the expansive oceans. LNG carriers represent the vanguard of vessels purpose-built to undertake the bulk transportation of liquefied natural gas (LNG).

The transformation of natural gas into LNG involves chilling it to a frigid -162°C, resulting in reduction in volume by a factor of 600. This process renders LNG both more manageable and safer for storage and transportation. The specialized containment systems within LNG carriers play a pivotal role in preserving LNG in its liquid state, assiduously guarding against leakage or evaporation. Various types of containment systems exist, including membrane tanks, spherical tanks, and prismatic tanks, each possessing its own distinct merits and drawbacks.

The utility of LNG carriers extends to addressing the energy needs of countries lacking adequate domestic production or pipeline infrastructure. Furthermore, LNG carriers serve as vital conduits for the transportation of natural gas originating from remote, economically unviable, or offshore reservoirs. Additionally, LNG carriers offer a unique versatility as floating storage and regasification units (FSRUs). These FSRUs can receive, store, and convert LNG back into its gaseous form offshore, subsequently delivering it to the mainland via pipelines or other means.

The ascendancy of LNG carriers as the preferred mode of natural gas transportation is underpinned by a multitude of advantages spanning environmental, economic, and operational dimensions. LNG carriers make notable contributions to reducing greenhouse gas emissions and curtailing air pollution by employing LNG as a cleaner-burning fuel, juxtaposed with heavy fuel oil or marine diesel oil. Simultaneously, they wield the ability to curtail fuel-related expenditures and enhance operational adaptability by accessing the global natural gas marketplace. The adoption of LNG carriers also augments safety and security measures, mitigating the risk of fire, explosions, or sabotage incidents.

According to the available data, as of January 2020, a total of 251 LNG vessels were in active operation, excluding the 600 LNG carriers engaged in the transportation of LNG between export and import terminals. Predominantly constituting containerships, this fleet diversifies further to encompass other vessel categories such as crude oil and chemical tankers, bulk carriers, car carriers, and even cruise ships that have embraced LNG as their preferred fuel. Furthermore, the industry demonstrates substantial growth, with over 200 LNG vessels on order, with an estimated 10% to 20% of the new order book dedicated to LNG-fueled vessels. [1-2]

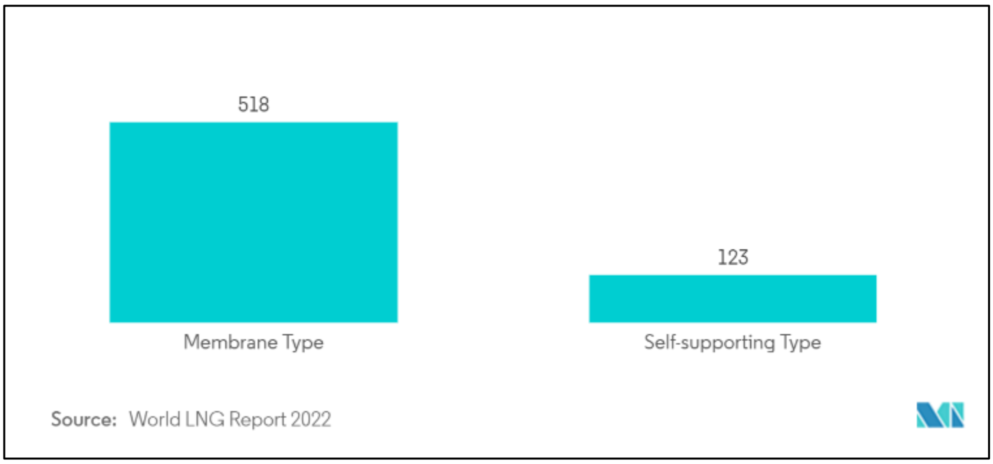

Figure 1: LNG Carrier Market for 2021 [3]

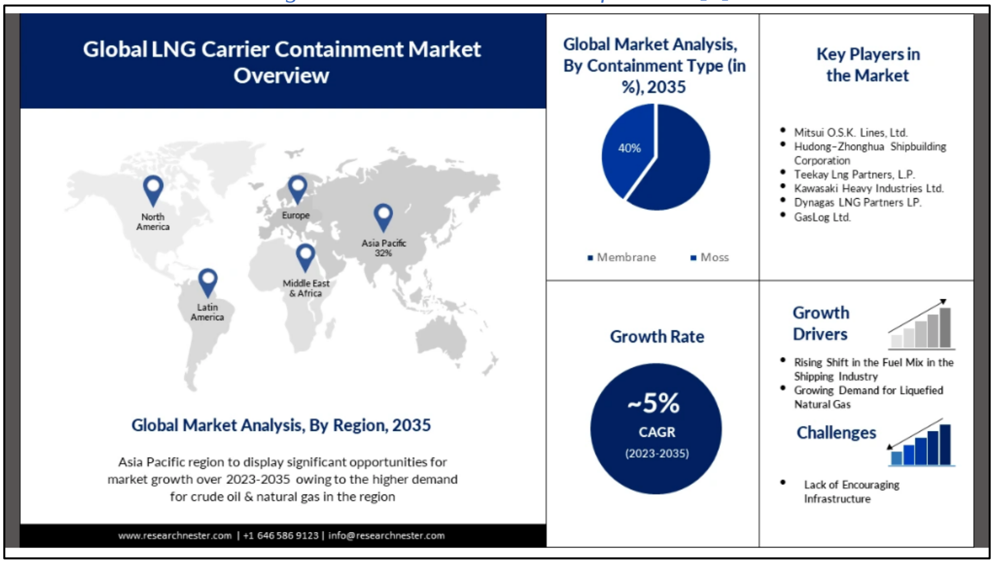

Figure 2: Global LNG Market Overview [4]

2. Introduction Of Energy Efficiency Measures In The Context Of Environmental Concerns And Economic Considerations.

Energy efficiency measures constitute a set of deliberate actions designed to curtail the energy consumption required to deliver equivalent levels of service or output. They encompass a diverse array of strategies, ranging from optimizing building design and operations to enhancing the efficiency of appliances, vehicles, and industrial processes. Additionally, these measures involve the incorporation of renewable energy sources and the deployment of smart grid technologies to maximize energy conservation.

The impulse to adopt energy efficiency measures arises from the fusion of environmental concerns and economic imperatives. On one front, they serve as forceful tools to mitigate the adverse effects of climate change and air pollution by reducing emissions of greenhouse gases and other noxious substances stemming from the combustion of fossil fuels. The International Energy Agency (IEA) underscores the centric role of energy efficiency measures by projecting that they could contribute more than 40% of the emissions reductions required to meet the goals stipulated in the Paris Agreement by 2040. Simultaneously, these measures offer a means to generate substantial savings and foster economic competitiveness by diminishing energy expenditures and augmenting overall productivity. According to the IEA, energy efficiency measures hold the potential to accrue annual savings exceeding $500 billion for households and businesses by 2040.

As a result, the integration of energy efficiency measures emerges as an indispensable lever for steering humanity and the environment toward a sustainable and prosperous future. These measures simultaneously yield a plethora of advantages, encompassing improved health, enhanced comfort, security, and the promotion of social equity. Nevertheless, it is vital to acknowledge that energy efficiency measures face a variety of challenges and barriers, including issues related to awareness, information deficits, financial constraints, policy inadequacies, and technological impediments. Hence, it becomes clear that a compelling need exists for more resolute, harmonized, and collective endeavors, uniting governments, businesses, civil society, and individuals, to advocate for and implement energy efficiency measures across all sectors and geographical domains. [5-9]

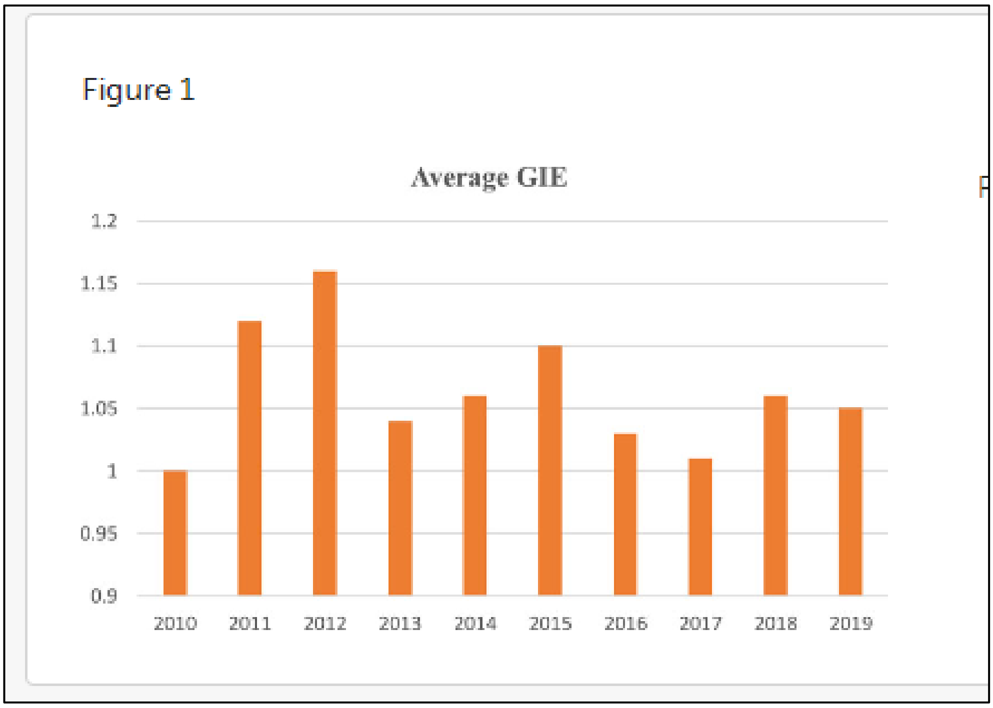

Figure 3: Average green innovation efficiency [10]

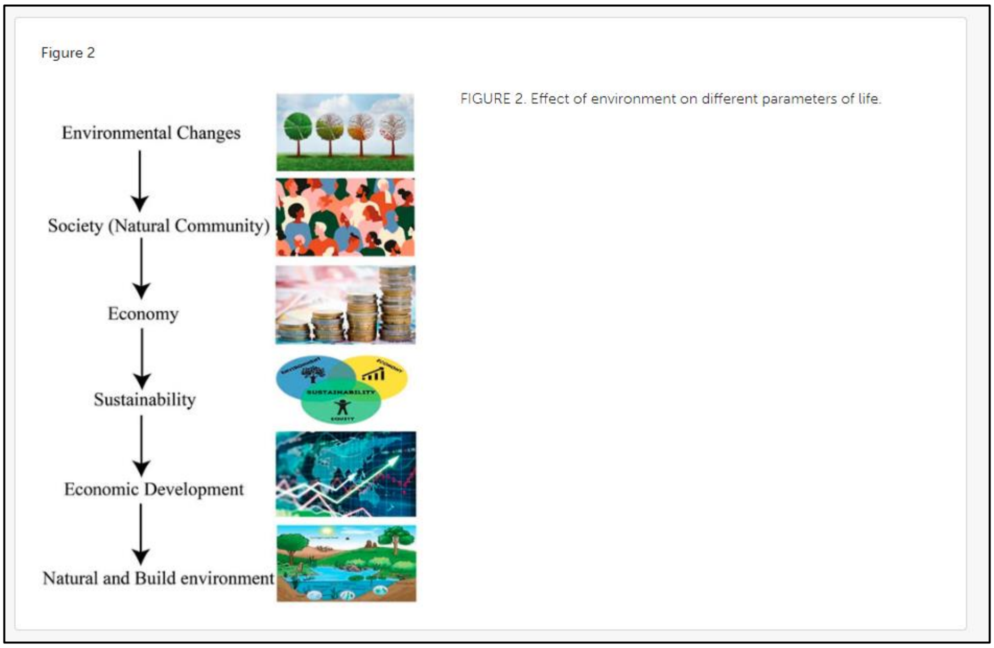

Figure 4: Effect of environment on various sections [11]

2.1 Improving Efficiency of Vessels

Improving the efficiency of vessels is a key concern for the maritime industry, especially with the International Maritime Organization (IMO) setting ambitious targets for the reduction of carbon emissions. The Energy Efficiency Design Index (EEDI) for new ships has been in place since 2013, promoting energy-efficient designs with a phased approach that intensifies every five years. As part of this initiative, the EEDI has demanded increasingly higher levels of energy efficiency for various ship types, such as containerships and gas carriers, with Phase 3 calling for a minimum of 30% reduction in carbon intensity for all vessels, and up to 50% for some ship types.

For existing ships, the IMO introduced the Energy Efficiency Existing Ship Index (EEXI), which became mandatory on January 1, 2023. This index applies to in-service vessels over 400 GT and requires ship operators to assess and adjust their ships' energy consumption and CO2 emissions to meet specific energy efficiency benchmarks for each vessel type.

Alongside EEXI, the Carbon Intensity Indicator (CII) has been established for ships over 5,000 GT to quantify and report carbon emissions from their operations. The CII sets a required reduction factor for CO2 emissions that must be achieved annually, ensuring continuous improvement in line with regulations. This indicator forms a part of the Ship Energy Efficiency Management Plan (SEEMP), which is a mandatory document for ship operators that outlines plans for improving a vessel's energy efficiency in a cost-effective manner.

As the maritime industry moves towards cleaner seas, these regulations play a crucial role in steering ships towards meeting the IMO's targets of a 40% reduction in carbon emissions by 2030, and a 70% reduction by 2050, compared to 2008 levels. The ultimate aim is to achieve a 50% cut in overall greenhouse gas emissions across the sector by 2050.

To comply with these new standards, shipowners and operators are exploring various strategies, such as using advanced ship designs that include more efficient hulls, propellers, and rudders, as well as implementing energy-saving devices (ESDs), and optimizing voyage planning with advanced software. Additionally, the integration of digital technologies for better data management and operational efficiency measures, exploration of alternative fuels, and crew training for energy-efficient practices are all part of the comprehensive approach towards improved vessel efficiency and reduced environmental impact. [12-14]

2.2 Energy Saving Devices: A Key Strategy for Enhanced Vessel Efficiency and Reduced Environmental Impact

Energy Saving Devices (ESDs) are a critical component of a comprehensive approach to improving vessel efficiency and reducing environmental impact. ESDs can help to reduce drag, improve engine efficiency, and optimize energy consumption. These devices range from simple modifications to ship hulls to complex systems that integrate with the vessel's propulsion and power generation systems.

The implementation of ESDs can lead to significant fuel savings and emissions reductions. For example, hull fairings can reduce drag by up to 10%, while rudder optimization systems can improve hydrodynamic performance by up to 5%. Exhaust gas recirculation systems can also help to reduce fuel consumption by up to 10% by increasing the efficiency of the combustion process.

The use of ESDs is becoming increasingly important as the shipping industry faces stricter environmental regulations. The IMO's Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) mandate that new and existing vessels meet increasingly stringent energy efficiency standards.

In addition to regulatory requirements, the adoption of ESDs can also provide economic benefits for ship owners. Fuel savings can lead to reduced operating costs, and improved efficiency can extend the lifespan of a vessel's propulsion and power generation systems.

The three main ESD categories will be analyzed are machinery, propulsion, and steam turbine.

Machinery Energy Saving Devices:

Essential components in modern shipping industry. These devices are designed to optimize the energy consumption of various types of machinery and equipment, ultimately leading to reduced energy costs and a smaller environmental footprint. They come in a wide range of forms, from advanced control systems and sensors to efficient motors and variable frequency drives. By monitoring, adjusting, and regulating energy usage, these devices enable businesses to improve their overall energy efficiency and sustainability while simultaneously enhancing productivity and reducing operational expenses.

Propulsion Energy Saving Devices:

These devices encompass a variety of technologies and systems that enhance the efficiency of propulsion systems in ships. The primary goal of propulsion energy-saving devices is to optimize the conversion of energy into propulsive force, ultimately leading to substantial reductions in fuel consumption and a consequential decrease in operational expenditures for shipping companies.

Steam Turbine Energy Saving Devices:

Steam turbine energy saving devices are a crucial part of enhancing the efficiency and reducing environmental impact of marine vessels. These devices focus on optimizing steam consumption, improving thermal efficiency, and enhancing the overall power generation system. By implementing steam turbine energy saving devices, shipowners can achieve substantial reductions in fuel consumption, emissions, and operating costs. These measures contribute to a more sustainable and environmentally friendly maritime industry while enhancing economic competitiveness.

3. Portfolio of Energy Saving Devices Applicable to Steam Turbine LNG Carriers

In that section presented a comprehensive compilation of innovative solutions aimed at enhancing the energy efficiency of steam turbine-powered Liquefied Natural Gas (LNG) carriers. A collection of devices and technologies that have been identified through extensive bibliographic research as potential catalysts for reducing energy consumption and, consequently, operational costs in the maritime transport of LNG are presented below.

Each solution included in this portfolio has been evaluated for its relevance and applicability to the specific context of steam turbine LNG carriers, considering factors such as energy savings potential, implementation feasibility, and compatibility with existing systems. The presentation of these energy-saving devices is structured to provide a clear understanding of their operational principles, anticipated benefits, and practical considerations for integration aboard LNG carriers.

It is important to note that while this section offers a foundational overview of promising energy-saving solutions, the information presented is based on available literature and may not reflect the most current advancements in technology. Stakeholders, ship owners, and engineers interested in exploring these solutions further are encouraged to contact the manufacturers or developers directly. Such direct engagement will facilitate access to the most accurate and up-to-date information, including technical specifications, commercial availability, and support services, thereby ensuring informed decision-making in the pursuit of enhanced energy efficiency aboard steam turbine LNG carriers.

3.1 Evaluation of Machinery Energy-Saving Devices

3.1.1 Onboard Carbon Capture and Storage (OCCS)

OCCS is an emerging technology in the maritime industry aimed at significantly reducing carbon dioxide emissions from ships. This technology involves the installation of carbon capture systems on vessels, integrating them with the vessel's fuel systems. OCCS can be implemented using either pre-combustion or post-combustion methods. Pre-combustion involves converting ship fuel into gas and capturing CO2 before it is combusted, while post-combustion captures CO2 directly from the ship's exhaust. This technology has the potential to reduce tank-to-wake emissions — those resulting from burning fuel in a vessel's tank — by 75-80%. [16-18]

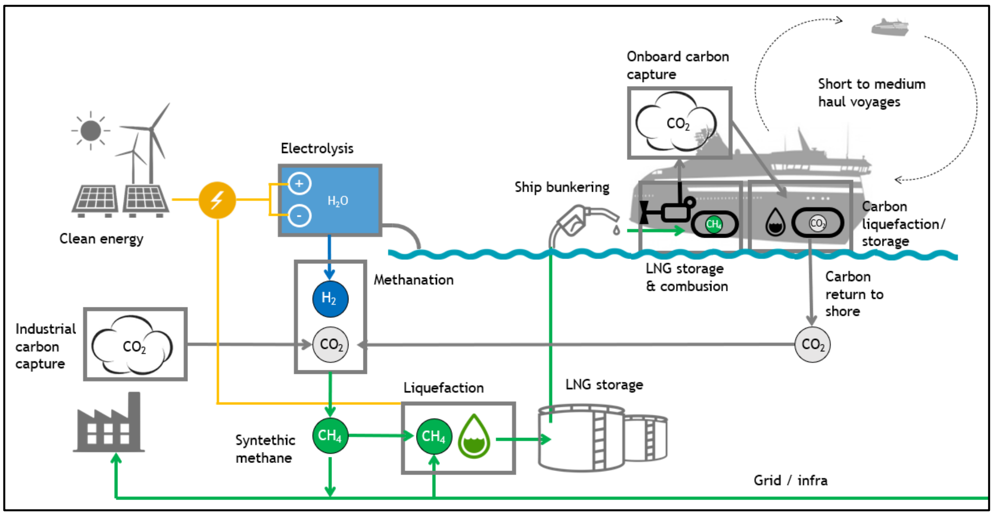

Figure 5: Carbon Capture System working Principle [17]

Advantages:

Significant Emission Reduction: OCCS has the potential to drastically lower CO2 emissions, contributing to global environmental sustainability efforts.

Versatility in Methods: The option of pre-combustion or post-combustion capture methods offers flexibility based on different ship designs and operational requirements.

Alignment with Regulatory Pressures: OCCS supports the shipping industry in meeting increasing regulatory demands for lower emissions.

Enhanced Environmental Compliance: Helps shipping companies comply with international standards and avoid potential penalties.

Future-Proofing: Positions the maritime industry towards a more sustainable future by adopting advanced emission reduction technologies.

Disadvantages:

High Installation and Operational Costs: The installation and maintenance of OCCS systems can be expensive.

Space and Weight Considerations: OCCS equipment requires significant space and adds weight, potentially affecting cargo capacity and ship stability.

Technological Complexity: OCCS involves complex technology that requires specialized knowledge and training for operation and maintenance.

Dependence on Technology Development: The effectiveness and efficiency of OCCS are contingent on the ongoing development and improvement of carbon capture technologies.

Disposal and Storage Challenges: Captured carbon needs to be safely stored or disposed of, presenting additional logistical challenges.

3.1.2 Waste Heat Recovery Systems (WHRUs)

WHRU are innovative devices designed to capture the residual heat energy from engine or boiler exhaust gases and convert it into valuable forms of energy, including electricity, steam, or cooling. Their application is pivotal in enhancing the efficiency and mitigating emissions in various vessels by harnessing heat that would otherwise go to waste. To illustrate the potential benefits, WHRUs can be strategically integrated into LNG steam turbine vessels to address their inherently low thermal efficiency. By doing so, these systems effectively recover the heat from the steam turbine's exhaust gases, subsequently generating supplementary power or steam for onboard utilization.

For instance, a WHRU is proficient at producing electricity through the operation of a power turbine or generator. Simultaneously, it has the capacity to generate steam by heating water within a Heat Recovery Steam Generator (HRSG). The resultant electricity and steam can be channeled towards serving various auxiliary loads on the vessel, such as powering lighting, heating, cooling, and pumping systems. This integrated approach not only enhances the overall energy efficiency of the vessel but also contributes to environmental sustainability by reducing emissions.

Various types of WHRUs can be effectively applied on LNG steam turbine vessels, with their selection dependent on the specific ship's design and configuration. Some of them are the following:

- Combined Cycle WHRU System: This system integrates a WHRU with a power turbine and a generator to harness the energy from the steam turbine's exhaust gas for the production of electricity. The design of the power turbine can vary, offering options for a single-stage or a multi-stage turbine. The choice depends on factors such as the pressure and temperature of the exhaust gas. The electricity generated by the power turbine can be seamlessly directed either to the main switchboard for ship-wide distribution or to an electric motor responsible for propeller shaft propulsion. Remarkably, this integrated system has the potential to boost the vessel's overall efficiency by as much as 10%.

- A cogeneration system that uses a WHRU with an HRSG to produce steam from the exhaust gas of the steam turbine. The steam can be used for various purposes on board, such as heating, cooling, desalination, or propulsion. The cogeneration system can also include a back-pressure turbine that extracts some of the steam from the HRSG and drives a generator to produce electricity. This system can reduce the fuel consumption and emissions of the vessel by up to 15%

- A combined heat and power (CHP) system that uses a WHRU with both a power turbine and an HRSG to produce electricity and steam from the exhaust gas of the steam turbine. The power turbine and the HRSG can be arranged in series or in parallel, depending on the desired output and quality of the electricity and steam. The CHP system can provide both power and heat for the ship's systems, improving the energy utilization and reducing the environmental impact of the vessel. [19-23]

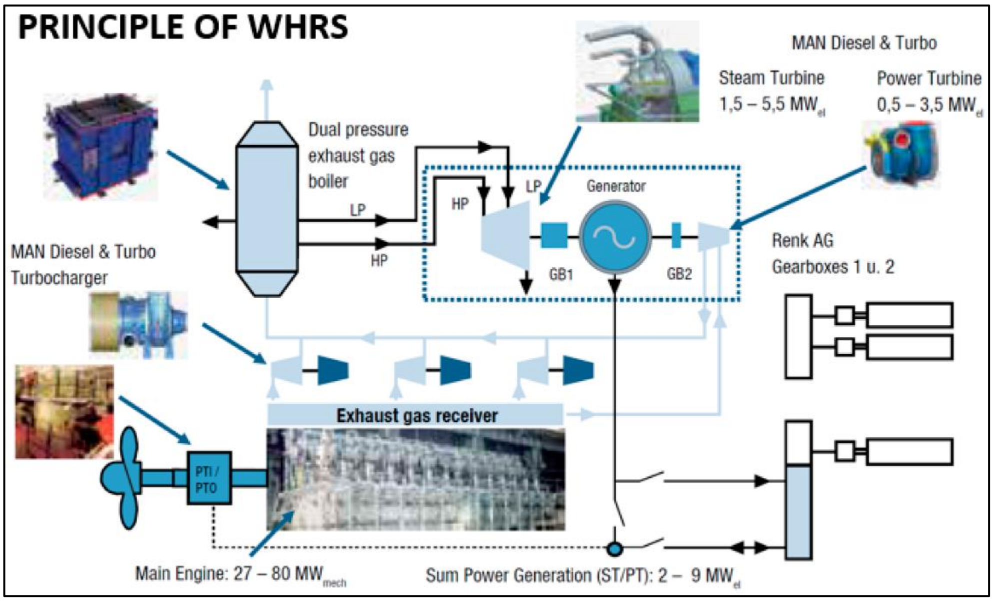

Figure 6: The construction principle of a WHRS [21]

Advantages:

Reduced fuel consumption: WHR systems can reduce fuel consumption by up to 10%. This can save shipowners significant money on fuel costs.

Reduced emissions: WHR systems can reduce emissions of greenhouse gases and air pollutants such as NOx and CO2. This can help to improve air quality and reduce the ship's environmental impact.

Increased power efficiency: WHR systems can increase the efficiency of steam turbine power plants by up to 40%. This can lead to higher power output and reduced fuel consumption.

Reduced maintenance costs: WHR systems can also help to reduce maintenance costs by reducing the wear and tear on steam turbines and other shipboard equipment.

Disadvantages:

High Installation and Operational Costs: The installation and maintenance of OCCS systems can be expensive.

Space and Weight Considerations: OCCS equipment requires significant space and adds weight, potentially affecting cargo capacity and ship stability.

Technological Complexity: OCCS involves complex technology that requires specialized knowledge and training for operation and maintenance.

Dependence on Technology Development: The effectiveness and efficiency of OCCS are contingent on the ongoing development and improvement of carbon capture technologies.

Disposal and Storage Challenges: Captured carbon needs to be safely stored or disposed of, presenting additional logistical challenges.

3.1.3 Wind-Assisted Propulsion Systems (WASP)

WASP, are a collection of technologies in the maritime industry that utilize wind power to aid in propelling a vessel. These systems serve as an auxiliary to the main engine, harnessing natural wind energy to move the ship forward. Incorporating various technologies such as rigid or soft wing sails, Flettner rotors, ventilated foils, and kites, these systems are increasingly equipped with intelligent control and automation, minimizing the need for additional crew and ensuring safe operation. [30-31]

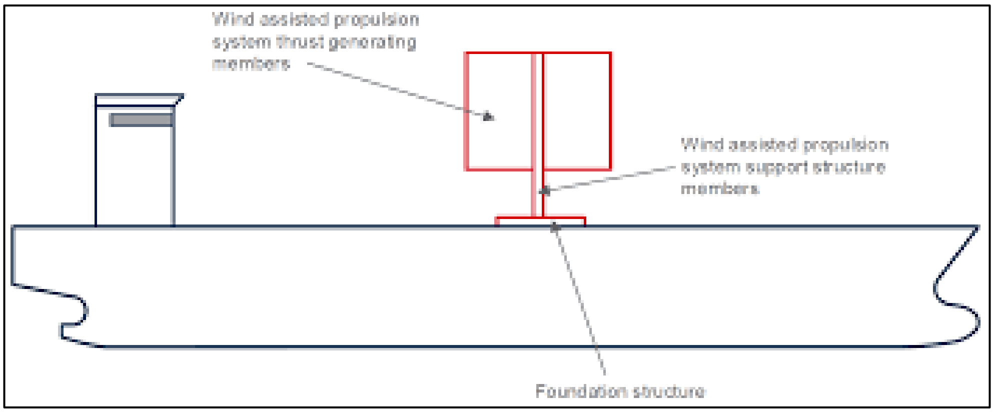

Figure 7: Wind assisted Propulsion System Schematic [31]

Advantages:

Fuel Efficiency: These systems significantly reduce fuel consumption by harnessing wind power, leading to lower operational costs.

Emission Reduction: By relying on wind energy, they contribute to a decrease in greenhouse gas emissions, aligning with environmental sustainability goals.

Potential for Significant Savings: Studies, including those by DNV, show that fuel savings can range from 4.5% to 9%, with the potential to reach up to 25% in retrofit installations.

Enhanced for Modern Shipping: Modern wind-assisted systems are designed for safe operation with minimal crew intervention due to advanced control and automation systems.

Adaptable to New Builds and Retrofits: They offer higher efficiency margins in ships specifically designed to incorporate these systems.

Disadvantages:

Variable Performance: The efficiency of these systems heavily depends on wind conditions, which can be unpredictable and variable.

Initial Investment Costs: The installation of wind-assisted propulsion systems can be capital-intensive, particularly for retrofitting existing vessels.

Space and Design Considerations: These systems require significant space on the deck and can influence the vessel's design and aerodynamics.

Operational Complexity: Managing these systems requires a balance between wind propulsion and traditional engine power, adding complexity to ship operations.

Maintenance Requirements: Additional components like sails or rotors necessitate maintenance, adding to the operational workload.

3.1.4 Solar Panels

On vessels represent an emerging technology designed to generate onboard power using solar energy. These panels can be integrated into the ship's structure to provide electricity for systems such as lighting, navigation, communication, and auxiliary equipment. While not very common in current maritime operations, there has been a gradual increase in installations in recent years. The applicability of solar panels on ships is particularly suited to vessels where deck space is not critical. [32-34]

Advantages:

Renewable Energy Source: Solar panels provide a clean, renewable source of energy, reducing reliance on traditional fossil fuels.

Decreasing Costs of Technology: The cost of solar modules has been dropping, making this technology more accessible and affordable.

Disadvantages:

Space Requirements: The need for a large installation area limits their applicability, especially on vessels where deck space is at a premium.

Limited Efficiency Gains: Current projections suggest that solar panels may not become significantly more efficient or less space-consuming in the near future.

Weather Dependent: Solar panel efficiency is contingent on weather conditions, with reduced effectiveness during cloudy or overcast periods.

3.1.5 Shore Power Connection

Shore power connection also known as "cold ironing," is a system that allows ships to access electrical power from shore-based sources while docked at a port. This system enables the shutdown of the ship's main and auxiliary engines during port stays, which is a significant step towards reducing emissions and noise pollution. It's an integral part of the maritime industry's move towards sustainable operations. Companies like ABB Marine & Ports are at the forefront of providing shore connection solutions suitable for various vessel types, playing a key role in supporting the industry's decarbonization efforts. [35-36]

Advantages:

Emission Reduction: By switching to shore-based power, ships can significantly reduce emissions of CO2, NOx, and other pollutants while in port.

Noise Pollution Reduction: The shutdown of engines while docked leads to a substantial decrease in noise pollution, benefiting both port workers and nearby communities.

Operational Cost Savings: Reduced fuel consumption while in port can lead to notable cost savings for ship operators.

Disadvantages:

Infrastructure Requirements: The implementation of shore power connections requires significant infrastructure development at ports.

Compatibility Challenges: Not all ships are equipped to connect to shore power, and retrofitting can be costly.

Upfront Investment Costs: The initial cost of installing shore power systems can be high for both ports and shipping companies.

Limited Availability: Shore power facilities are not universally available at all ports, limiting its use to specific locations.

Dependence on Local Power Grid: The effectiveness and environmental benefit of shore power depend on the green credentials of the local power grid.

3.1.6 Energy Efficient Lighting (EEL)

EEL is a technology designed to reduce energy consumption and emissions on ships. It encompasses the use of LED lamps, dimming controls, occupancy sensors, and daylight harvesting systems. This technology optimizes lighting levels and quality according to the needs of the crew and passengers. [37-39]

Advantages:

Reduced Energy Consumption: EEL can decrease lighting power demand by up to 80%, contributing significantly to the overall energy efficiency of the vessel.

Extended Lamp Life: LED lamps used in EEL have a lifespan up to 10 times longer than conventional incandescent or fluorescent lamps.

Environmental Benefits: By reducing electrical load and heat generation, EEL can save up to 5% of fuel and similarly reduce CO_2 emissions.

Improved Comfort and Safety: Better lighting quality and visibility enhance the comfort and safety of crew and passengers.

Disadvantages:

Higher Initial Cost: The installation of EEL systems, particularly in luxury or passenger vessels, can be more expensive compared to traditional lighting systems.

Technical Requirements: Implementing EEL requires meeting specific technical and quality requirements, such as color rendering index values and light homogeneity, which can be challenging.

3.1.7 Air Lubrication Systems (ALS)

ALS enhance ship efficiency by reducing drag resistance between the ship's hull and seawater. This is achieved through injecting air bubbles or creating an air layer on the hull surface. The technology is particularly effective for low-speed, large-displacement ships like gas carriers, bulk carriers, and tankers. [40-41]

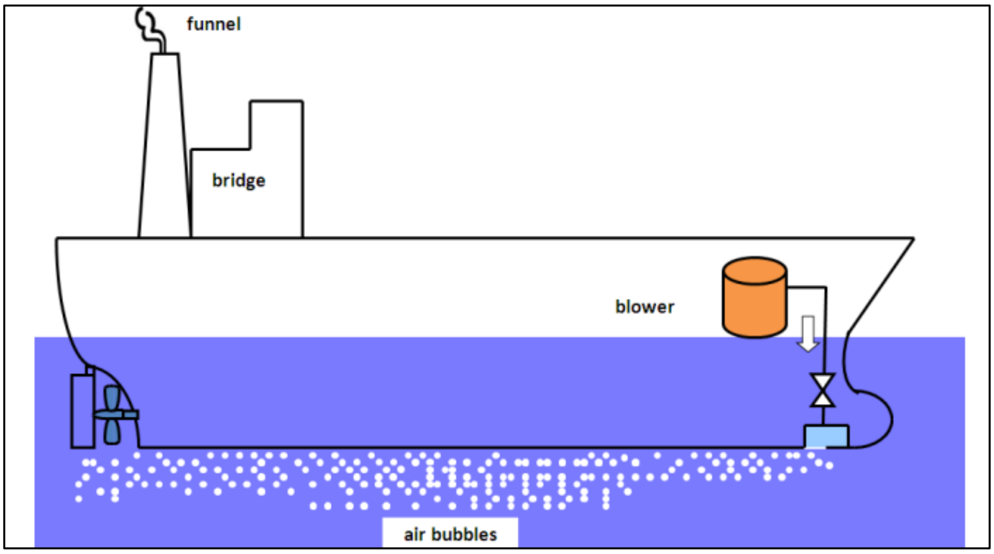

Figure 8: Air Lubrication system Schem [40]

Advantages:

Fuel Consumption and Emission Reduction: ALS can significantly reduce fuel consumption and CO2 emissions, with potential savings up to 15%.

Increased Efficiency: The reduction in frictional drag leads to improved ship efficiency.

Enhanced Maneuverability and Stability: ALS modifies the flow around the hull, potentially improving the ship's maneuverability and stability.

Disadvantages:

Limited Applicability: The effectiveness of ALS is more pronounced in certain types of ships, particularly those with large displacements and low speeds.

Complex Installation: The installation of ALS can be complex, requiring modifications to the hull and the installation of additional equipment like pumps and piping.

3.1.8 Shaft generator system

Shaft generator is an innovative electrical power generation solution used on ships. It capitalizes on the ship's main engine to generate electrical power for onboard requirements. This system diverges from the traditional use of auxiliary engines for electricity generation, integrating power production with the primary propulsion system. It is particularly beneficial in maritime operations where efficient power management and environmental considerations are paramount. [42-44]

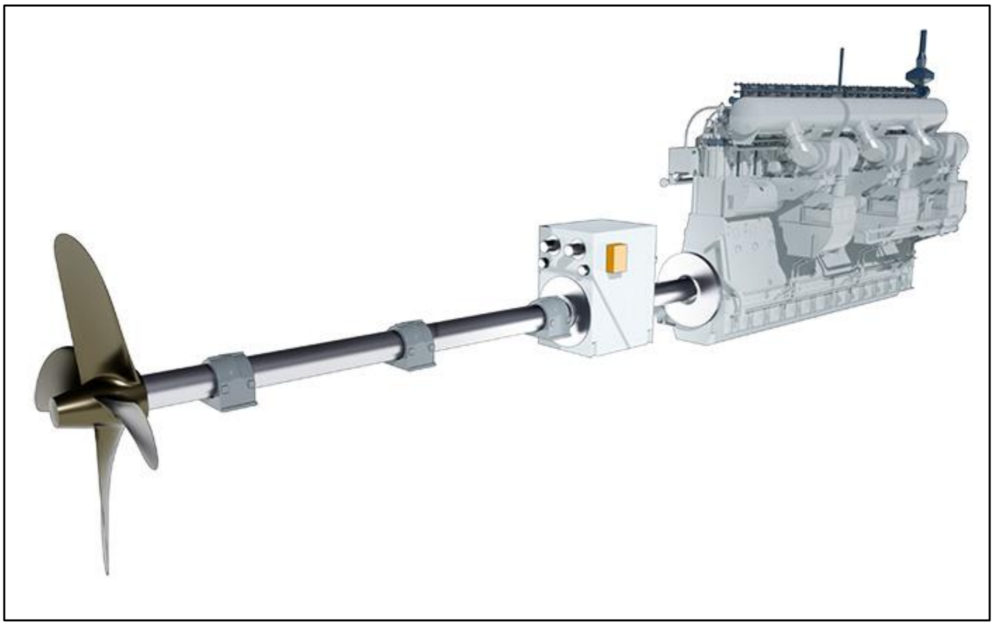

Figure 9: Shaft generator in concept design [42]

Advantages:

Fuel Efficiency: By utilizing the main engine for electricity generation, it significantly reduces the need for fuel consumption compared to auxiliary engines.

Noise Reduction: It offers a quieter operation compared to the use of auxiliary engines, enhancing the onboard environment.

Disadvantages:

Complex Control Systems: Requires sophisticated control systems to manage power generation effectively, which might need specialized maintenance and operational expertise.

Limited Operational Flexibility: In situations where the main engine is not running, such as during docking, an alternative power source is needed.

Potential for Increased Wear and Tear: The additional load on the main engine might lead to increased maintenance requirements over time.

3.2 Evaluation of Hull and Propulsion Improvement Devices

3.2.1 Pre-swirl fins and stators

Pre-swirl fins and stators are energy-saving devices that enhance the propulsive efficiency of ships. They generate a favorable pre-swirl flow at the propeller plane, reducing rotational losses and increasing propeller thrust. These devices can be passive, like fixed hydrofoils, or active, involving rotating blades or jets. [45-47]

Advantages:

Improved Propulsive Efficiency: By optimizing the flow at the propeller plane, these devices enhance propeller performance, leading to more efficient propulsion.

Fuel Consumption and Emission Reduction: Pre-swirl fins and stators can contribute to up to 10% savings in fuel consumption and a corresponding reduction in CO_2 emissions.

Enhanced Maneuverability and Stability: The alteration in flow around the hull improves the ship's maneuverability and stability.

Disadvantages:

Specific Applicability: Their effectiveness is more pronounced in ships with large propeller diameters and certain design characteristics.

Installation Complexity: Especially for active devices, installation may require significant modifications to the ship's existing systems.

3.2.2 Mitsui Integrated Ducted Propeller (MIDP)

MIDP is an innovative energy-saving device designed to enhance propulsive efficiency in ships. This technology modifies the conventional ducted propeller design by moving the duct forward and making it non-symmetrical. This adaptation better aligns with the stern flow and reduces cavitation erosion on the duct's inner surface. [48-49]

Advantages:

Improved Propulsive Efficiency: MIDP optimizes propeller performance, leading to better propulsion efficiency.

Fuel Consumption and Emission Reduction: The device can save up to 10% of fuel and reduce CO_2 emissions by a similar margin.

Enhanced Propeller Reliability and Safety: By avoiding low-load operation and reducing wear and tear, MIDP improves the reliability and safety of the propeller system.

Disadvantages:

Specific Ship Compatibility: MIDP is particularly suitable for ships with large propeller diameters and specific design characteristics, which may limit its applicability to certain vessel types.

Complexity in Design and Implementation: The non-symmetrical and advanced design of the MIDP may pose challenges in terms of integration and installation on existing vessels.

3.2.3 Hitachi Zosen Nozzle (HZN)

HNZ is an advanced energy-saving device designed to enhance propulsive efficiency. This innovation involves modifying the traditional nozzle propeller design by incorporating a non-symmetrical nozzle shape and a skewed propeller. These modifications are intended to better adapt to the stern flow, thereby reducing cavitation and vibration. [50]

Advantages:

Improved Propulsive Efficiency: By optimizing the flow at the propeller plane, HZN leads to better propulsion efficiency.

Reduced Fuel Consumption and Emissions: The device can save up to 15% of fuel and similarly reduce CO2 emissions.

Enhanced Propeller Reliability and Safety: HZN contributes to propeller reliability by avoiding low-load operation and reducing wear and tear.

Disadvantages:

Specific Ship Compatibility: HZN is particularly suitable for ships with large propeller diameters and specific design characteristics, limiting its applicability to certain vessel types.

Design and Installation Complexity: The non-standard design of the HZN may pose integration and installation challenges in existing vessels.

3.2.4 The Sumitomo Integrated Lammertsen Duct

Sumitomo Integrated Lammersten Duct is a cutting-edge energy-saving device that enhances propulsive efficiency in ships. It modifies the conventional Lammertsen duct design by incorporating a non-symmetrical duct shape and a skewed propeller. This design adaptation is aimed at optimizing stern flow, thereby reducing cavitation and vibration. [51-52]

Advantages:

Enhanced Propulsive Efficiency: SILD optimizes the propeller performance, leading to more efficient propulsion.

Reduced Fuel Consumption and Emissions: The device can contribute to up to 15% savings in fuel consumption and a corresponding reduction in CO_2 emissions.

Improved Propeller Reliability and Safety: By avoiding low-load operation and reducing wear and tear, SILD enhances the reliability and safety of the propeller system.

Disadvantages:

Design Specificity: The effectiveness of SILD is contingent on the ship's design, particularly its propeller diameter and block coefficients.

Integration Challenges: The non-standard design may pose integration and installation challenges, especially in existing vessels.

3.2.5 Becker Mewis Duct (BMD)

BMD device designed to improve propulsive efficiency in ships. It functions by generating a favorable pre-swirl flow at the propeller plane, reducing rotational losses and increasing propeller thrust. This technology is particularly effective for vessels with large propeller diameters, low propeller loading coefficients, and high block coefficients. [53-55]

Advantages:

Enhanced Propulsive Efficiency: BMD optimizes propeller performance, leading to increased efficiency.

Reduced Fuel Consumption and Emissions: It can save up to 8% of fuel and reduce CO_2 emissions by the same margin.

Improved Maneuverability and Stability: The modification of flow around the hull enhances the ship's maneuverability and stability.

Disadvantages:

Design Specificity: The effectiveness of BMD depends on the ship's design, making it more suitable for certain vessel types.

Potential Retrofitting Challenges: Integrating BMD into existing vessels, particularly older models, may pose challenges.

3.2.6 Rudder Thruster Fins (RTF)

RTF designed to enhance the propulsive efficiency of ships, particularly beneficial for steam turbine gas carriers. RTF works by generating additional thrust from the interaction between the rudder and the propeller's wake flow. This system not only improves propulsion but also enhances maneuverability and stability by offering better steering and yaw control. [56-57]

Advantages:

Improved Propulsive Efficiency and Fuel Savings: RTF can lead to up to 15% savings in fuel consumption, primarily by optimizing propeller performance and wake field.

Emission Reduction: Corresponding to fuel savings, RTF can also reduce CO_2 emissions by up to 15%.

Enhanced Maneuverability and Stability: By providing effective steering and yaw control, RTF improves the ship's handling capabilities.

Increased Propeller Reliability and Safety: RTF helps in avoiding low-load operations, reducing wear and tear on the propeller, thereby enhancing its reliability and safety.

Disadvantages:

Design Compatibility: The effectiveness of RTF is more pronounced in ships with specific design features, such as large propeller diameters and high block coefficients.

Installation Complexity: Integrating RTF into existing systems may pose challenges, especially in older vessels.

3.2.7 Post Swirl Stators (PSS)

PSS designed to improve the propulsive efficiency of ships, particularly suitable for steam turbine gas carriers. PSS works by creating a favorable post-swirl flow at the propeller plane, which, while increasing rotational losses and decreasing thrust, reduces the torque and power required by the engine. This unique approach to propulsion efficiency offers a balance between thrust generation and energy consumption. [58-60]

Advantages:

Reduced Fuel Consumption and Emissions: PSS can lead to up to 5% savings in fuel and a similar reduction in CO2 emissions by optimizing propeller performance and wake field.

Enhanced Maneuverability and Stability: The altered flow around the hull due to PSS improves the ship's handling capabilities.

Efficiency in Large Vessels: PSS is particularly effective for ships with large propeller diameters and high block coefficients, such as tankers, bulk carriers, and container ships.

Disadvantages:

Trade-off in Propeller Thrust: The increase in rotational losses and decrease in thrust might not suit all operational scenarios.

Complexity in Design and Integration: Implementing PSS requires careful design and integration, particularly in older or uniquely designed vessels.

3.2.8 Asymmetric rudders

Asymmetric rudders are innovative energy-saving devices designed to enhance the propulsive efficiency of steam turbine gas carriers. They diverge from conventional rudder designs by utilizing an asymmetric leading edge. This design effectively diverts the rotational effects of the propeller wake, enhancing the flow along the rudder, thereby reducing drag and increasing thrust. [61-62]

Advantages:

Improved Propulsive Efficiency and Fuel Savings: Asymmetric rudders can lead to up to 10% fuel savings, optimizing propeller performance and wake field.

Emission Reduction: Corresponding to the fuel savings, these rudders can also reduce CO_2 emissions by up to 10%.

Enhanced Maneuverability and Stability: Providing better steering and yaw control, these rudders improve a vessel's handling capabilities.

<u>**Disadvantages:**</u>

Design Compatibility: Their effectiveness is more pronounced in ships with specific design features, particularly those with large propeller diameters.

Complex Integration in Existing Vessels: Retrofitting asymmetric rudders into older vessels might be challenging due to design and space constraints.

3.2.9 <u>Rudder (Costa) bulb</u>

Rudder (Costa) bulb designed to enhance the propulsive efficiency of ships, including steam turbine gas carriers. This device modifies the conventional rudder design by incorporating a bulb-shaped appendage at the leading edge. The primary function of this design is to reduce hub vortex losses and increase the propeller's thrust. [63-64]

<u>**Advantages:**</u>

Improved Propulsive Efficiency and Fuel Savings: The rudder (Costa) bulb can lead to up to 5% savings in fuel consumption by optimizing propeller performance and wake field.

Emission Reduction: Corresponding to the reduction in fuel consumption, CO_2 emissions are also reduced by up to 5%.

Enhanced Maneuverability and Stability: The device improves the ship's steering and yaw control, contributing to better maneuverability and stability.

<u>**Disadvantages:**</u>

Design Specificity: The effectiveness of the rudder (Costa) bulb depends on the ship's design, notably beneficial for ships with large propeller diameters and specific design features.

Potential Retrofitting Complexity: Integrating this system into existing vessels, especially older ones, might present challenges.

3.2.10 Propeller Boss Cap Fit (PBCF)

PBCF developed to enhance propulsive efficiency in ships, including steam turbine gas carriers. It modifies the conventional propeller boss cap design to reduce hub vortex losses and increase propeller thrust by altering the flow near the propeller boss cap. [65-67]

Advantages:

Enhanced Propulsive Efficiency and Fuel Economy: PBCF can save up to 5% of fuel by optimizing propeller performance and the wake field of the ship.

Emission Reduction: Corresponding to fuel savings, PBCF can also reduce CO2 emissions by up to 5%.

Improved Propeller Reliability and Safety: PBCF contributes to the propeller's reliability by reducing wear and tear and avoiding low-load operation.

Disadvantages:

Specific Ship Compatibility: The effectiveness of PBCF is more pronounced in ships with large propeller diameters and specific design characteristics.

Integration Challenges: Retrofitting PBCF into existing vessels, especially older models, might present challenges due to design compatibility.

3.2.11 Divergent Propeller Caps (DPC)

DPC designed to enhance the propulsive efficiency of ships, including steam turbine gas carriers. DPC modifies the conventional propeller cap design by adopting a divergent shape to increase pressure recovery and decrease hub vortex losses of the propeller. [68-70]

Advantages:

Fuel Efficiency and Emission Reduction: DPC can lead to up to 4% savings in fuel consumption, thereby reducing CO2 emissions by a similar margin.

Optimized Propeller Performance: By improving the propeller performance and wake field, DPC enhances the overall propulsion efficiency.

Increased Propeller Reliability and Safety: The device helps avoid low-load operation, reducing wear and tear on the propeller.

Disadvantages:

Design Suitability: The effectiveness of DPC is more significant in ships with large propeller diameters and specific design features, limiting its applicability to some vessel types.

Retrofitting Challenges: Integrating DPC into existing ships, particularly older models, may require substantial modifications.

3.2.12 <u>Grim Vane Wheel (GVW)</u>

GWV is an innovative energy-saving device designed to improve the propulsive efficiency of maritime vessels, including steam turbine gas carriers. It functions by generating additional thrust from the propeller slipstream. The device, installed on the propeller shaft behind the propeller, has a larger diameter than the propeller itself and operates partly as a turbine (inner part) and partly as a propeller (outer part). [71-72]

<u>Advantages:</u>

Enhanced Propulsive Efficiency and Fuel Savings: GVW can lead to up to 10% savings in fuel consumption by optimizing propeller performance and wake field.

Reduction in Emissions: Corresponding to fuel savings, GVW can also reduce CO2 emissions by up to 10%.

Improved Propeller Reliability and Safety: By avoiding low-load operation and reducing wear and tear, GVW enhances propeller reliability.

<u>Disadvantages:</u>

Design Suitability: GVW is more effective in ships with specific design characteristics, such as large propeller diameters and high block coefficients.

Retrofitting and Integration Challenges: The installation of GVW in existing ships, especially older models, might be complex due to its size and operational dynamics.

3.3 Evaluation of Energy-Saving Devices for STaGE

3.3.1 Boil-Off Gas (BOG) compressors

Boil-off gas compressors are critical devices in maintaining the tank pressure of liquefied gas vessels, such as steam turbine gas carriers. They extract BOG generated due to heat ingress in the tank. The extracted BOG can either be re-liquefied and returned to the tank or compressed for use as fuel gas. [73-75]

Advantages:

Fuel Savings and Emission Reduction: Utilizing BOG as a fuel source or re-liquefying it minimizes gas flaring, leading to fuel savings and emission reductions.

Enhanced Reliability and Safety: By maintaining optimal tank pressure, BOG compressors prevent overpressure and potential leakage, enhancing vessel safety.

Energy Efficiency: The use of BOG as an energy source improves the overall energy efficiency of the vessel.

Disadvantages:

Complexity in Design and Operation: The design and operation of BOG compressors depend on various factors like the type and amount of BOG, tank conditions, and regulatory requirements, making them complex systems.

Maintenance Requirements: Due to their critical nature and operational complexity, BOG compressors may require regular maintenance and monitoring.

3.3.2 LNG reliquefaction plants

Reliquefaction plants on steam turbine gas carriers are systems designed to manage boil-off gas (BOG) by re-liquefying it, thus maintaining the cargo's temperature and pressure. These systems typically utilize various thermodynamic cycles, like the Brayton or Claude cycles, to efficiently reliquefy the BOG. [76-78]

Advantages:

Fuel Savings and Efficiency: LNG reliquefaction plants contribute to significant fuel savings by utilizing BOG as an additional energy source, enhancing overall vessel efficiency.

Emission Reduction: These systems reduce the need for gas flaring, thereby lowering emissions.

Improved Cargo Management: By reliquefying BOG, the cargo's pressure and temperature are maintained, ensuring the quality and quantity of the LNG cargo.

Versatility in Technology: Various technological options like the mixed refrigerant cycle and reverse Brayton cycle provide flexibility in choosing the most suitable system based on specific vessel needs.

Disadvantages:

Complexity and Maintenance: These systems are complex and require regular maintenance and skilled operation.

Initial Investment Cost: The installation of LNG reliquefaction plants involves a significant initial investment.

Space Requirements: These systems require considerable space, which may be a constraint on some vessels.

3.3.3 Deaerators and feedwater heaters

Deaerators and feedwater heaters play a vital role in removing dissolved gases, particularly oxygen and carbon dioxide, from the feedwater and improving the thermodynamics of the steam cycle. By preheating the boiler feedwater, these systems significantly enhance the efficiency of the steam cycle in maritime vessels. [79-80]

Advantages:

Improved Efficiency: By preheating the feedwater, these systems reduce the fuel consumption required for heating, thereby improving the overall efficiency of the steam cycle.

Extended Equipment Life: Deaerators help in removing corrosive gases from the feedwater, which reduces corrosion and extends the life of the steam system components.

Increased Thermal Performance: Feedwater heaters optimize the extraction fraction and cycle efficiency, leading to better thermal performance of the steam cycle.

Disadvantages:

Maintenance Requirements: Both deaerators and feedwater heaters require regular maintenance and monitoring to ensure efficient operation.

Complexity: The integration and operation of these systems add complexity to the steam cycle management in gas carriers.

3.3.4 Condensate recovery system

Condensate recovery system designed to collect and reuse condensate water from the steam distribution system. This system typically includes components like a condensate pump, a flash tank, a heat exchanger, and a deaerator. The primary purpose is to enhance energy efficiency, reduce water consumption, and lower operating costs. [81-83]

Advantages:

Enhanced Energy Efficiency: By recovering and reusing condensate water, the system reduces the need for additional heating, improving energy efficiency.

Reduced Water Consumption: The reuse of condensate water minimizes the requirement for fresh water in the boiler system.

Lower Operating Costs: With improved efficiency and reduced water usage, the system helps in lowering overall operational costs.

Environmental Benefits: Efficient use of resources and reduction in emissions contribute to environmental sustainability.

Disadvantages:

Complex System Management: The operation of such a system can be complex, requiring careful monitoring and control.

Maintenance Requirements: Regular maintenance is necessary to ensure optimal functioning and to prevent system failures.

Installation Space: The system may require significant space for installation, which can be a constraint in some vessels.

3.3.5 Variable Inlet Guide Vanes

Variable Inlet Guide Vanes are utilized in integrally geared centrifugal compressors to optimize performance. They adjust the flow of gas into the compressor, enhancing efficiency and operational stability. [84-85]

Advantages:

Increased Power Output and Fuel Efficiency: VIGV can significantly boost power output and improve fuel efficiency.

Enhanced Compressor Stability: Helps maintain a constant compressor pressure ratio, even in varying conditions, thus enhancing diffuser stability and overall compressor efficiency.

Disadvantages:

Complexity in Management: Requires precise control and management to ensure optimal performance.

Potential for Increased Wear: Continuous adjustments can lead to increased wear and maintenance requirements.

3.3.6 Full-arc Steam Control Valves (FACSVs)

FACSVs modulate steam flow in high-pressure and high-temperature steam systems on vessels, including main propulsion boilers, auxiliary boilers, and steam turbines. [86]

Advantages:

High Controllability and Accuracy: Their full-arc design ensures a linear relationship between valve lift and flow rate.

Low Noise and Vibration: Suitable for sensitive applications where noise reduction is crucial.

Versatility: Applicable for a wide range of steam applications due to their adaptable design.

Disadvantages:

Complexity: May require more sophisticated control systems for operation.

Maintenance Requirements: Regular maintenance needed to ensure optimal performance.

3.3.7 Condenser optimization systems

Condenser optimization systems focus on enhancing the performance and efficiency of condensers. These systems can involve various aspects such as design, heat transfer, fluid flow, control strategies, and system integration. [87-88]

Advantages:

Improved Efficiency: Optimized condensers lead to better performance of the steam cycle.

Enhanced Heat Transfer: Better heat transfer and fluid flow characteristics can be achieved.

Effective System Integration: Optimization ensures better integration with the vessel's energy system.

Disadvantages:

Complexity: Optimization can add complexity to condenser operations.

Maintenance Requirements: Advanced systems may require more frequent maintenance.

3.3.8 Steam Plant Operation Improvement

Optimizing steam plant operation involves procedural updates, new sensors, minor retrofits, crew training, and maintenance improvements to enhance efficiency in maritime boiler operations. This approach aims at reducing steam consumption and improving steam production efficiency, potentially lowering boiler fuel oil consumption by 10% to 30%. The estimated cost of implementation is about $20,000 annually per ship. [89]

Advantages:

Fuel reduction: Significant reduction in fuel consumption.

Operational efficiency: Enhanced operational efficiency through crew training and maintenance.

Disadvantages:

Maintenance costs: Initial cost of implementation and ongoing maintenance expenses.

Training requirements: Requires investment in training and technology upgrades.

4. Presentation of Energy Optimization Measures for Maritime Vessel Efficiency

The data presented in the table below, outline a spectrum of energy-saving interventions applicable to maritime vessels. These interventions are meticulously classified into either technical modifications or operational adjustments. Each measure is quantified in terms of its potential to reduce fuel consumption—a pivotal factor in both economic and environmental dimensions of maritime operations. The scope of implementation for each measure is assessed, ranging from those suitable for retrofitting existing fleets to those requiring more substantial capital investments. The table outlines the potential cost savings alongside the initial and maintenance costs, providing a holistic view of the economic impact of each energy-saving strategy.

Expanding upon the complexity of vessel energy optimization, the table offers a detailed prognosis on the longevity and efficacy of the measures, indicated by the estimated payback periods. This analytical view allows for a critical assessment of the measures' performance, contrast with their financial and operational feasibility. The measures are further investigated for their compatibility with different vessel sizes and types, as well as for the requisite operational changes they may necessitate—such as dry dock maintenance or complete redesigns.

The data in the below table are obtained from various sources and it is important to note that the actual fuel savings achieved by applying those energy saving measures can vary depending on a variety of factors, including the size and design of the vessel, the operating conditions, and the maker of each system . Additionally, the actual cost of installing those measures should also be further investigated each time according to the market condition.

Measures	Measure type (Technical or Operational)	Savings	Savings to be applied to	Applicability on existing ships	CAPEX	Cost per size of vessel	Maintenance costs/ OPEX	Applicability	System Consumption
Waste Heat Recovery Systems	T	3-8%	Boiler fuel cons.	No	$5,000,000 to $9,500,000	N/A	$20,000 per year	All vessels with engines above 10 MW	No
Variuable Frequency Drives	T	2-10%	Boiler fuel cons.	Yes	$100 to $200 per kW installed auxiliary engine power	N/A	$3,000 per year	All	No
Wind Assisted Propulsion Systems (incl. rotors, kites, suctions wings, etc.)	T	Up to 35%	Boiler fuel cons.	Yes	Up to $ 3,000,000, Figure 10	Figure 10	Yes	All	maybe (mainly rotors and suction wings)
Solar Panels	T	Up to 2%	Boiler fuel cons.	Yes	1,400,000 m // $420,000 to $450,000	From $2.8 to $3.4 (USD) per watt	N/A	All	N/A
Shore Power Connection	T	50-100%	Boiler fuel cons.	Yes	$50,000 to $750,000 (figure 11)	Figure 11	N/A	Smaller vessels and in ports with developed solutions for larger vessels	N/A
Energy Efficiency Lighting	T	Up to 5% , cruise & passenger ships >10%	Boiler fuel cons.	Yes	$100,000 to 200,000 // 1,000,000 for passenger & cruise ships	N/A	N/A	All	No

Air Lubrication Systems	T	3-10%	Boiler fuel cons	Yes	2-3% of New Build Cost $130,000 to $3,380,000	Silverstream 800, 000 euros for a smaller vessel (products tanker or smaller ro-ro ship), or up to 2 million euros for a larger vessel (e.g. VLOC)	Yes	Most vessels in deep sea trade	Yes
Shaft Generator	T	2-5%	Boiler fuel cons	No	$240,000 to $600,000	Initial cost estimated $400/kW	No	All vessels in need of a larger amount of power for heating or cooling, and sailing long transits.	Speed power deteriorates
Propulsion Improving Devices (PIDs)	T	2-5%	Boiler fuel cons	Yes	$100,000 to $700,000	Cost is independent of ship size	No	All	No
Propeller Retrofitting	T	2-5%	Boiler fuel cons	Yes	$400,000 to $500,000	n/a	No	All (mainly slow steaming, especially container and large vessel series)	No

Hull Form Optimization	T	4-8%	Boiler fuel cons	Yes	$150,000 to $500,000	Cost is independent of ship size	No	All	No
Hull Retrofit (bulbous bow can be combined with the hull shape optimization)	T	3-5%	Boiler fuel cons	Yes	$250,000 to $700,000	Cost is independent of ship size	N/A	Applicable for tanker, LNG carrier, bulk, container vessels operating in off-design conditions	No
Hull Coating	T	1-4%	Boiler fuel cons	Yes	$30,000 to $500,000	N/A	Needs to be renewed often	All	No
Steam System Efficiency (Improve operations and maintenance of steam plant system saving fuel on oil fired boiler)	O	10-30%	Boiler fuel cons	Yes	N/A	N/A	$20,000 per ship per year	Mainly LNG carriers, Crude oil and product tankers	No

Table 1: Types of Energy Saving Technologies and data for implementation onboard [90-97]

	WASP	Rotor sail		Suction wing		Hard sail		Kite	
	Costs (EUR 1,000)	min	max	min	max	min	max	min	max
CAPEX	Asset costs	560	1,050	200	900	438	876	340	2,345
	Installation costs (newbuild)	84	158	30	135	66	130	51	351
	Installation costs (retrofit)	140	263	50	225	109	219	85	586
One-off costs	Training	10	10	10	10	10	10	10	10
OPEX	Annual maintenance & repair	12	22	4	18	8	18	17	117
	Annual energy consumption WAPS	26	79	26	53	No data available			

* The per unit installation costs are assumed to amount to a certain percentage of the asset costs, with this percentage being lower for the largest units.

Figure 10: Costs analysis for Wind Assisted Propulsion Systems [94]

Investment cost for vessel (USD)	1000 – 4999 GT	5000 – 9999 GT	10000 – 24999 GT	25000 – 49999 GT	50000 – 99999 GT	>= 100000 GT
Crude tankers	$50 000 – $350 000	$100 000 – $400 000	$100 000 – $400 000	$100 000 – $400 000	$300 000 – $750 000	$300 000 – $750 000
Chemical / product tankers	$50 000 – $350 000	$100 000 – $400 000	$300 000 – $750 000	$300 000 – $750 000		
Gas tankers	$50 000 – $350 000	$300 000 – $750 000	$300 000 – $750 000	$300 000 – $750 000	$300 000 – $750 000	$300 000 – $750 000
Bulk carriers	$50 000 – $350 000	$50 000 – $350 000	0,5 – 3 Mill	0,5 – 3 Mill	$100 000 – $400 000	
General cargo	$50 000 – $350 000	$50 000 – $350 000	0,5 – 3 Mill	$100 000 – $400 000		
Container vessels	$50 000 – $350 000	$50 000 – $350 000	$100 000 – $400 000	$300 000 – $750 000	$300 000 – $750 000	$300 000 – $750 000
Ro Ro vessels	$50 000 – $350 000	$50 000 – $350 000	$100 000 – $400 000	$100 000 – $400 000	$300 000 – $750 000	
Reefer	$50 000 – $350 000	$50 000 – $350 000	$100 000 – $400 000			
Passenger ship	$50 000 – $350 000	$50 000 – $350 000	$100 000 – $400 000	$300 000 – $750 000	$300 000 – $750 000	$300 000 – $750 000
Offshore supply ship	$50 000 – $350 000	$100 000 – $400 000				
Other offshore service ships	$50 000 – $ 350 000	$100 000 – $400 000	$100 000 – $400 000	$100 000 – $400 000	$100 000 – $400 000	$100 000 – $400 000
Other activities	$50 000 – $ 350 000	$100 000 – $400 000	$300 000 – $750 000	$300 000 – $750 000	$300 000 – $750 000	$300 000 – $750 000
Fishing vessels	$50 000 – $ 350 000	$100 000 – $400 000				

Figure 11: Costs analysis for Shore power connection implementation [93]

5.Life Cycle Cost Analysis Tool for Energy-Saving Devices

The development of a comprehensive Life Cycle Cost Analysis (LCCA) tool serves as a pivotal component of this thesis, aimed at evaluating the cost-effectiveness of various energy-saving measures within maritime operations. The Excel-based tool is structured across three main sheets: Inputs, Measures, and LCCA, each serving a unique function in the analytical process.

Inputs Sheet: This foundational sheet captures the following critical operational and financial parameters.

Operational parameters:

- (MCR) of Steam Turbine or turbogenerator: This parameter represents the maximum continuous rating of a Steam turbine or the Turbogenerator.
- Average Load: Defined as the ratio of the actual load to the maximum possible load over a given period. This parameter reflects the operational intensity and efficiency of the equipment being analyzed.
- Operating Hours per Year: This quantifies the total operational duration of the equipment annually, providing a basis for calculating annual energy consumption and savings.
- Specific Fuel Oil Consumption (SFOC): Measured in grams per kWh, SFOC is a key efficiency indicator, representing the fuel required to generate a unit of electricity. It directly impacts the operational cost and environmental footprint of the operation.
- Consumption per Hour (MT/h) and Annual Fuel Consumption (MT): These figures elaborate on the fuel efficiency and overall fuel demand of the operations, essential for assessing the potential savings from energy efficiency measures.

Financial Parameters:

- Capital Expenditure (CAPEX): Reflects the initial investment required to implement the energy-saving measure, including purchase, installation, and commissioning costs.

- Savings Percentage: This indicates the expected reduction in operational costs as a percentage, attributable to the energy-saving measure.
- Operational Expenditure (OPEX) per year: Represents ongoing costs associated with the operation of the energy-saving measure, including maintenance, repair, and operational costs.
- Technology Lifespan: The expected operational life of the energy-saving technology, crucial for calculating the total benefits and cost savings over time.
- Discount Rate: Used to discount future savings and costs to their present value, reflecting the time value of money and investment risk.

This detailed input collection facilitates a nuanced analysis, enabling the tool to model the financial and operational impacts of energy-saving measures with high precision.

LCCA Sheet: The culmination of the analysis is presented in this sheet, where the financial outcomes of the energy-saving measures are synthesized. Key outputs include annual savings and total savings over the technology's lifespan, providing a clear financial perspective on the benefits of implementing the selected energy-saving measures.

- Annual Savings ($): Calculated by applying the savings percentage to the annual operational costs, this metric quantifies the direct annual financial benefit of implementing the energy-saving measure.
- Total Savings Over Lifespan: By aggregating the annual savings across the technology's lifespan, this figure offers a long-term view of the financial returns, providing a compelling case for investment in energy efficiency.
- Net Present Value (NPV): This key indicator assesses the total value of future savings, discounted back to the present day, to compare against the initial investment (CAPEX). A positive NPV indicates a profitable investment.
- Return of Investment (ROI): The ROI provides insight into the efficiency of the investment, representing the profitability of it.
- Payback Period: This metric estimates the time required for the savings generated by the energy-saving measure to cover its initial costs, offering a straightforward assessment of investment recovery time.

This tool helps to analyze in the life cycle cost analysis of energy-saving devices, offering a guidance for decision-making. By evaluating the financial implications of various energy-saving measures, stakeholders can make informed decisions that not only contribute to operational efficiency but also align with environmental sustainability goals.

6. Case Study

This study outlines the potential outcomes of applying different energy saving measures, as detailed in Table 1 above, to a STaGe LNG Carrier. Due to confidentiality concerns, the ship is referred to as Ship A, and its particulars are displayed in Table 2 below.

Particulars	Ship A
Ship Type	**LNG Carrier**
Shipbuilder	Daewoo Shipbuilding & Marine Engineering Co., Ltd
Year of Delivery	2006
LOA (m)	279.8
LBP (m)	268.8
B (m)	43.3
D (m)	26.0
Design Draft (m)	11.5
Scantling Draft (m)	12.5
LWT (tons)	30,105.9
DWT Scantling (tons)	74,893.6
Propulsion System	Marine Steam Turbine
Steam Turbine MCR (kW)	23,830.0
No. of the installed A/Es	2
A/E MCR (kW)	1,800.0

Table 2: Main Particulars of Ship A

All calculations were performed using the LCCA Excel tool, which was developed specifically for this master thesis, and the outcome presented in the diagram below A detailed guide on how to use this tool is provided in Appendix A. The lifespan of each measure has been determined to be 7 years, with the exception of hull coating, which have a designated duration of 5 years. This exception accounts for the period leading up to the vessel's forthcoming dry-dock and repainting session.

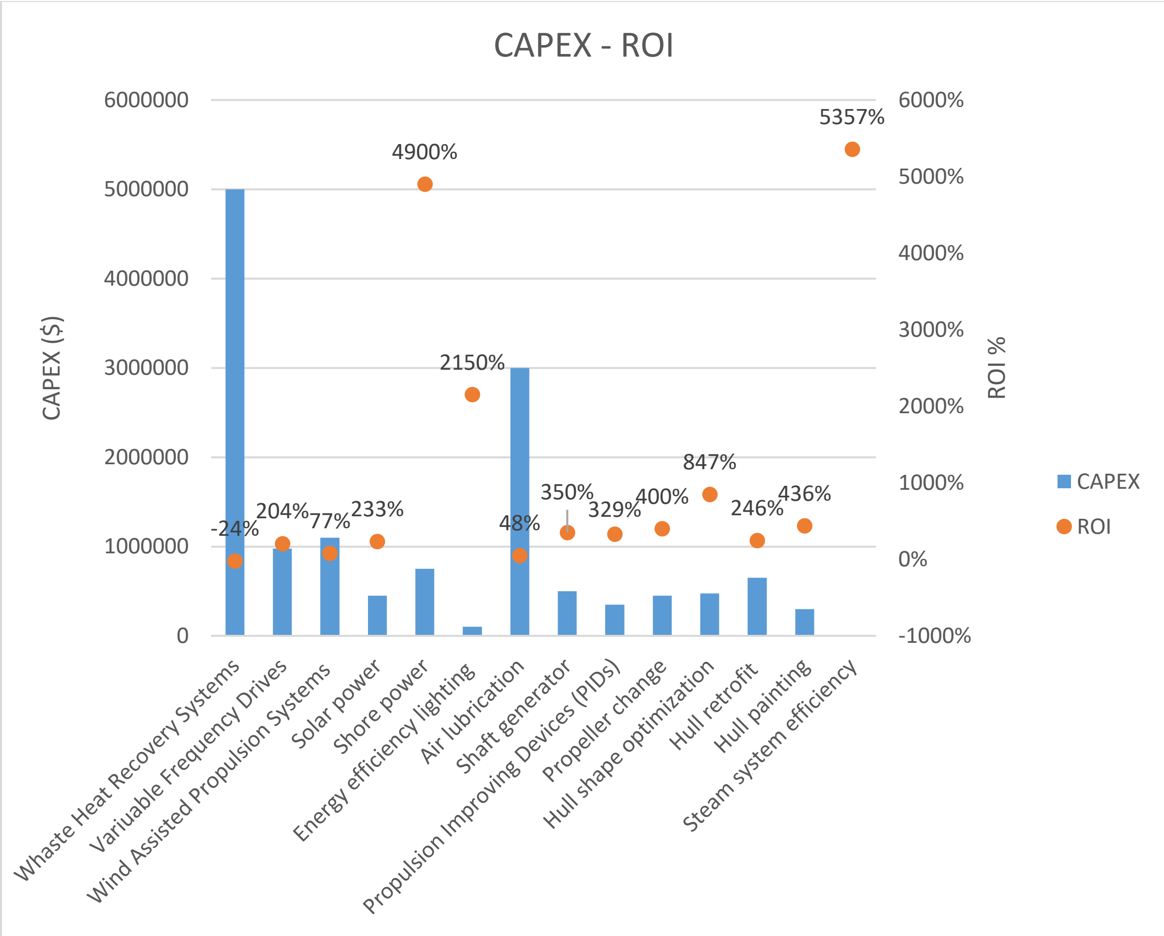

Figure 12: CAPEX and ROI diagram

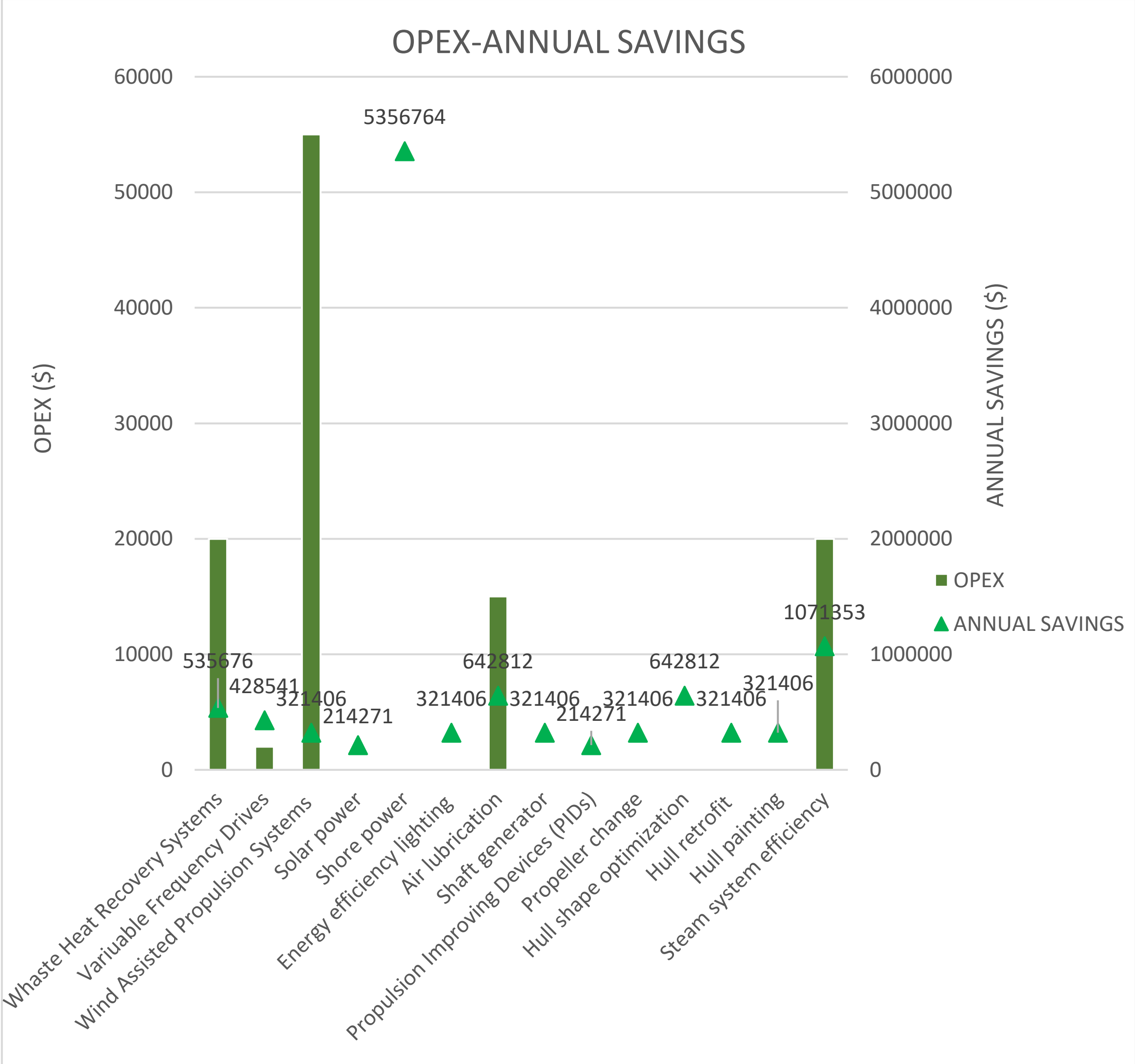

Figure 13: OPEX and Annual Savings diagram

The figures 12 and 13 above exhibit a comparative analysis of various energy efficiency measures with respect to their capital and operational expenditures, as well as their return on investment (ROI) and annual savings.

Capital Expenditure (CAPEX): The data indicate a variance in CAPEX across measures, with Steam System Efficiency requiring the lowest investment, thereby suggesting its cost-effectiveness in implementation. Conversely, Waste Heat Recovery Systems and Wind-Assisted Propulsion System are shown to demand higher initial capital, reflecting their complex technology and installation requirements.

Operational Expenditure (OPEX) & Annual Savings: Operational costs are highest for the Wind Assisted Propulsion System. Measures such as Propulsion Improving Devices (PIDs) and Hull Modifications demonstrate lower operational expenses and moderate annual savings, emphasizing their operational cost-efficiency.

Return on Investment (ROI): The ROI analysis underscores the long-term financial benefits, with Air Lubrication and Steam System Efficiency illustrating ROIs surpassing 5000%, which may indicate significant fuel savings or other operational efficiencies. In contrast, the negative ROI associated with Waste Heat Recovery Systems raises concerns over its economic viability with the current data.

This analysis aids in assessing the financial feasibility and potential benefits of implementing specific energy-saving measures on maritime vessels, considering both short-term costs and long-term gains.

Significant observations on the implemented measures:

Among the evaluated measures, the integration of solar power and wind-assisted propulsion systems appears impractical for LNG carriers, primarily due to the specific design constraints imposed by the cargo tanks located on the deck. As a result, the most convenient solution seems to be installation of Kite instead of any other technologies. The findings presented herein derive from an extensive review of bibliographic sources, focusing on fuel savings percentages as well as operational and capital expenditure estimates. It is imperative to conduct further investigations, taking into account the unique characteristics of each vessel and their operational profiles, to ensure the accuracy and applicability of these measures to specific LNG carriers within the broader context of this study.

6.1 Conclusions

While some energy efficiency measures might require substantial upfront investments, their long-term benefits can be substantial. The strikingly high ROIs for some of them imply that these technologies, once implemented, could offer significant cost savings, making them potentially attractive options for reducing long-term operational costs.

The negative ROIs associated with certain measures could be a reflection of various factors such as technology immaturity, inappropriate application for this specific type of vessel, or a mismatch between the technology and the operational profile of the ship. It is also possible that these technologies may offer other types of value, such as environmental benefits, which are not captured solely by financial ROI.

The disparity between CAPEX and OPEX across different measures suggests a complex decision-making landscape for ship operators. It is imperative to consider not only the financial outlay but also the operational context, the anticipated lifespan of the ship, and the expected evolution of fuel and maintenance costs.

In conclusion, the analysis underscores the necessity of a holistic approach when evaluating energy efficiency measures for STaGe LNG Carriers. Decisions should be informed by a comprehensive understanding of both the immediate financial implications and the long-term financial and environmental benefits.

LNG carrier industry stands at the forefront of integrating energy efficiency, vessel performance enhancements, and the deployment of innovative technologies targeting sustainability in maritime transport. A deep dive into the sector reveals its pivotal role in the global energy trade, marked by significant advancements in vessel design and operational efficiencies that not only meet but often exceed environmental regulations. These strides represent a broader commitment to innovation and sustainability, transcending mere compliance to embody a proactive approach to environmental stewardship.

Evidence points to a resolute dedication towards innovation, particularly through the integration of energy-saving devices (ESDs). These innovations highlight the industry's effort to reduce fuel consumption and emissions, signaling a shift towards aligning economic and environmental objectives. Such endeavors reflect an industry-wide move towards sustainability, marrying profitability with ecological responsibility.

The industry's agile response to environmental regulations, featuring technologies ranging from Waste Heat Recovery Systems to Steam system efficiency, showcases its capacity to not only comply with but also anticipate future regulatory changes. This forward-thinking stance ensures the LNG carrier sector remains a beacon of environmental innovation, well-equipped to face the dynamic challenges and opportunities that lie ahead.

Discussions on the economic impact of these technological advancements advocate for a strategy that maintains environmental integrity without compromising financial performance. This calls for a continued strategic alliance among stakeholders—shipowners, operators, industry bodies, and policymakers—to foster sustainable innovation. Such collaboration is essential for promoting sustainability within the industry.

The future calls for ongoing investment in sustainable technologies and collaborative efforts to steer the maritime industry towards a more efficient and environmentally friendly direction. Collective action is crucial for the LNG carrier industry to continue its essential role in the global energy trade, balancing economic efficiency with environmental stewardship.

In summary, the developments within the LNG carrier industry underscore the importance of continued innovation and collaboration in achieving a sustainable maritime transport sector. This sector is capable of supporting the global energy trade's demands while conserving our environmental legacy for future generations. The focus on sustainability and innovation sets a clear path for future research and initiatives, aiming to enhance the maritime industry's contribution to a sustainable future.

Appendix A: Introducing the Calculator: An Excel Based Tool

This section provides the fundamental guide for utilizing the Excel-Based Tool created for conducting Life Cycle Cost Analysis of various energy-saving measures.

The initial tab, labeled "Inputs" for straightforward recognition, is where all the input values should be entered. The columns should be completed from the user are highlighted with yellow color. The following subsections detail this process:

MCR (boiler)	27066
Average Load	50,00%
Operating hours per year	3960
SFOC gr/KWh	302,90
Cons/h (MT/h)	4,10
Total fuel consumption per year (MT)	**16233**

Figure 14: LNG Carrier operational data inputs

Boiler		
Load	Power	SFOC
100%	27066	275
90%	24359	273,5
80%	21653	276,4
50%	13533	302,9

Figure 15: LNG Carrier operational data inputs

All values marked for input within red rectangles can be found in the vessel's Steam Heat Balance and Flow Diagram.

Energy Saving Technology	Steam system efficiency
CAPEX ($)	0
Savings (%)	10%
OPEX ($/year)	20000
Lifespan (years)	7
Discount Rate (%)	3%
Current fuel price ($/MT)	660

Figure 16: Energy Measure data Inputs

The values referenced above are initially provided in Table 1 of this thesis. However, users have the flexibility to update these values to reflect the current market conditions.

Once all the cells are populated with the necessary values, the results will be displayed in the LCCA tab, within the subsequent table.

Life cycle cost analysis		Description
Annual Savings ($)	**1071353**	*Amount of savings per year*
Total Savings Over Lifespan	**7499469**	*Total savings over the device's lifespan*
Total OPEX Over Lifespan	**140000**	*Total operational expenses over the device's lifespan*
Net Savings Over Lifespan	**7359469**	*Net savings over the device's lifespan*
Net Present Value (NPV)	**220784**	*Present value of net savings, considering the discount rate*
Payback Period (years)	**0,0**	*Time required to recoup the initial investment from savings*
Total Cost of Ownership (TCO)	**140000**	*Sum of CAPEX and total OPEX over lifespan*
Net Profit	**7499469**	*Total savings minus CAPEX*
Return on Investment (ROI)	**5357%**	*Profitability of the investment as a percentage*

Figure 17: LCCA results presentation.

Appendix B: Sample of Steam Heat Balance and Flow Diagram

This Appendix lists the essential documents needed from the vessel for reference.

- **Steam Heat Balance and Flow Diagram**

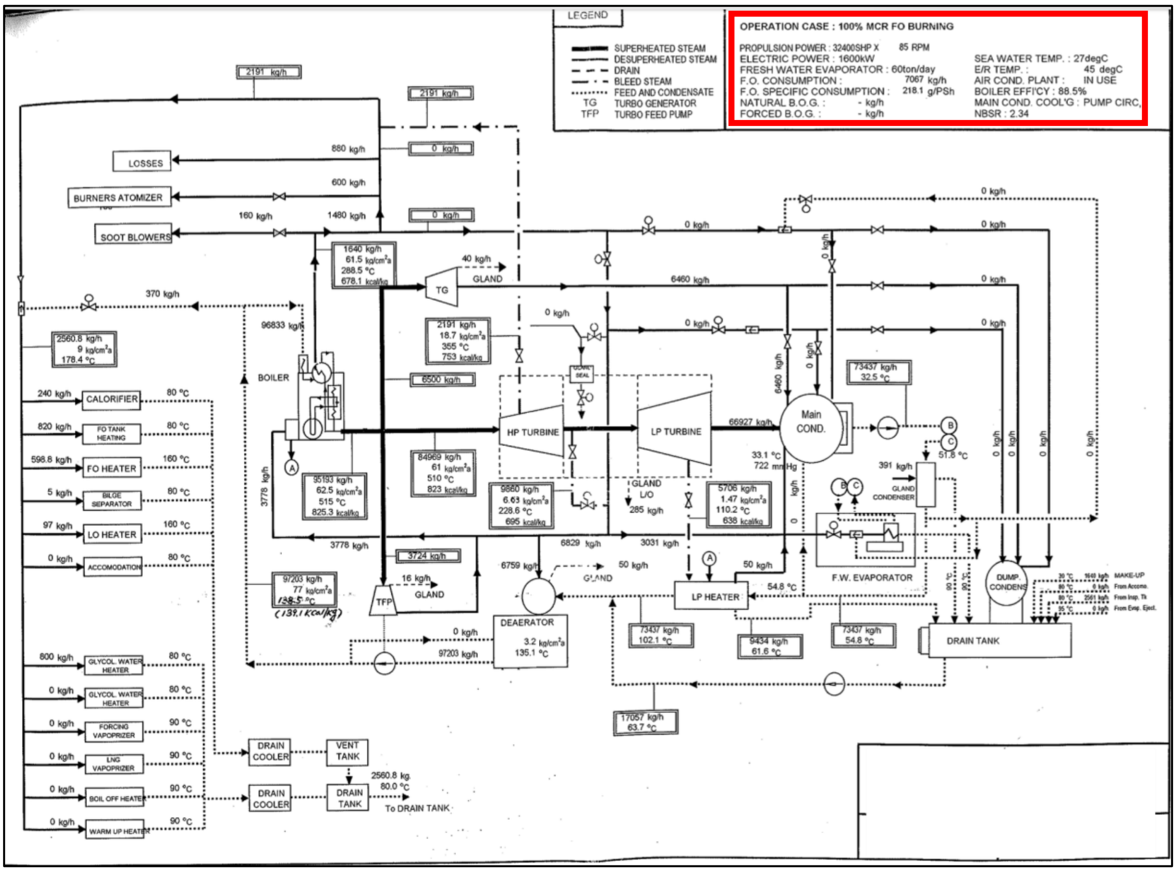

Figure 18: Indicative Steam Heat Balance and Flow Diagram at 100% MCR

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