



Renewable Energy to Auxiliary Power & Propulsion Boost on a Bulk Carrier

MBA THESIS



Student: Cpt. Andrianos Ioannis Vlachakis

Supervisor: Dr. Iraklis Lazakis

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Abbreviations

AC – Alternating Current

BESS – Battery Energy Storage System

CAPEX – Capital Expenditure

CFD – Computational Fluid Dynamics

dB – Decibel

DC – Direct Current

ECA – Emission Control Area

EMS - Energy Management System

ESS – Energy Storage System

ETS - Emission Trading System

EU – European Union

EUA – EU Carbon Emission Allowance

EU ETS - European Union Emissions Trading System

GHG – Greenhouse gases

HAWTs - Horizontal axis wind turbines

HF – High Frequency

Hz – Hertz

FO – Fuel Oil

GWP – Global Warming Potential

ICAP - International Carbon Action Partnership

IMO - International Maritime Organization

JAMDA - Japan Marine Machinery Development Association

kN – Kilonewton

kW – Kilowatt

LCV – Lower Calorific Value

Li-ion – Lithium-ion

LSFO – Low Sulphur Fuel Oil

MCR – Maximum Continuous Rating

MGO – Marine Gas Oil

MF – Medium Frequency

MHD – Magnetohydrodynamic

MW – Megawatt

μ W – Microwatt

nm – Nautical mile

OCIMF - Oil Companies International Marine Forum

OPEX – Operating Expenditure

PTI – Power Take In

PTO – Power Take Off

PV – Photovoltaic

RF – Radiofrequency

ROI – Return Of Investment

RPM – Revolutions Per Minute

SECA – Sulphur Emission Control Area

TRC – Trade Route Cycle

UHF – Ultra High Frequency

ULCC - Ultra large crude carrier

US – United States

VAWTs – Vertical axis wind turbines

VHF – Very High Frequency

3D – Three Dimensional

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Words Count

15995

Abstract

The purpose of this study is to review existing and potentially applicable maritime renewable energy technologies which can be also commercially viable. Through literature review, hybrid research methodology and sorting of reviewed systems, a joint technologies' concept has been developed. A brief technical study, separately on each element of the full concept, which consists of photovoltaic panels, wind turbines, piezo acoustic panels, a magnetic shaft generator and an energy storage system, being retrofitted on a Kamsarmax bulk carrier, has been conducted. Finally, a scenario-based environmental and economic analysis of the joint technologies concept, applied on the case study vessel trading between EU and US, along with deployment variations of the included components, has been carried out. The ten different comprised scenarios are the full concept application at maximum capacity, then independently, photovoltaic panels options at 100% and 50% hatch coverage panels, helical savonius wind turbines at collapsible and aerodynamic non-collapsible configurations, the piezoacoustic energy harvesting panels, the magnetic shaft generator under 3 operating modes and finally an optimum combination of the two most cost efficient technologies.

The scenarios which included photovoltaics or magnetic shaft generators, resulted in considerable environmental benefit and commercially viable outcomes. A full concept's application may reduce emissions up to 6.5% at open sea with optimum operation of all systems and up to 12.8% at port, solely from photovoltaics' usage. Full concept's required initial investment of approximately 8 million euros would require 12.5 years for amortization. The reviewed vertical axis wind turbines, without taking into account any possible aerodynamic deployment benefit, and piezoacoustic panels options are considered non-efficient due to very high installation costs, relatively low power production and non viable return of investment periods. On the contrary, even if independently installed, the solar panels and magnetic shaft generator options can provide viable return of investment periods between 9 and 16 years. The return of investment for the most efficient configuration, which consists of photovoltaic panels at full hatch coverage and the magnetic shaft generator under optimum usage, has been calculated at 10.5 years period, while providing up to 6.1% total average reduction of emissions and the flexibility of zero usage of vessel's diesel generators, while at open sea. The existing renewable energy technologies can provide both actual environmental and economic benefits, though more bold steps within the shipping industry are necessary in order vessels being able to sail and operate more efficiently, environmentally wise.

Chapter 1 – Introduction, Aim, Scope and Objectives

1.1 Introduction

Since the creation of the first man-made canoes and sail boats, the humankind has developed various types of boats and ships through an unstoppable race on enhancing vessels' speed, carrying capacity, efficiency and maneuverability by exploiting all available energy and thrust resources.

The end to the glorious era of sailing merchant ships (Knick, 2015) was only brought during the late 19th century, by the invention of steam ships and iron hulls (Goodwin, 1998), in conjunction with augmented carrying capacities and more rapid, stricter delivery timetables. The evolution of vessels' engines along with enhanced propulsion types, hull designs and increased sizes continued at great pace with various remarkable shipbuilding projects, such as the internal combustion engine or azipod propulsion systems (Samoilescu et al., 2018), which had been installed on breathtaking enormous vessels like the 458m long, 650 thousand tons tanker 'Seawise Giant'¹ or the 365m long, 250 thousand tons cruise ship 'Icon of the Seas' (Notteboom et al., 2025).

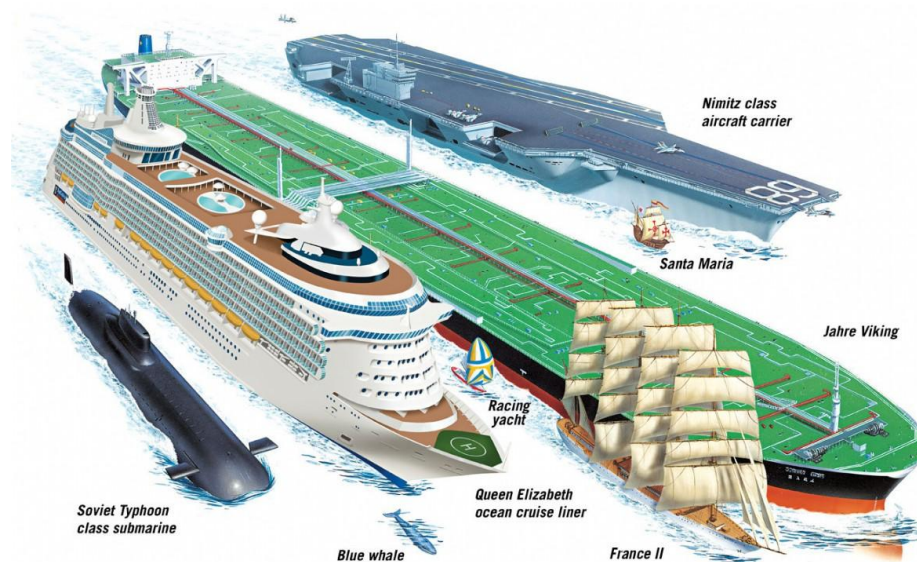


Figure 1 – Pictorial scale comparison of "Seawise Giant" (later "Jahre Viking") with smaller ships. (Octabeck, 2016).

¹ 'Seawise Giant', later Happy Giant, Jahre Viking, Knock Nevis, Oppama, and finally Mont, was a ULCC supertanker and the longest self-propelled ship ever built.

However, the unstoppable uptrend line of vessel sizes and maximum speeds presumably reached a peak after 1980s at some of the maritime transportation sectors such as crude oil (Thuong and Elvey, 1985) and containers (Wu, 2020), as insurmountable barriers appeared. These limiting barriers were not solely orientated from technical or structural perspective, as may have been expected. On the contrary, mostly economical and environmental factors suppressed the insatiable human predisposition for continuous evolution and development; at least temporarily. In example, no charterer of that period was comfortable having 4 million barrels of crude oil travelling around the world on a single tanker, as it was automatically creating a tremendous liability in a possible collision or oil spill scenario similar to the ‘Torrey Canyon’ in the 1960s (Wells, 2017). Regarding the reduction of the optimum cruising speed, particularly in the case of container ships with high cruising speeds well over 20 knots that have been reduced to below 20knots, it has occurred as a result of the volatile bunker prices especially after 2006 along with the imposed regulatory compliance for fuel efficiency and GHG emissions.

Especially after the recent enforcement of EU ETS (Mao et al., 2024) and other similar developed systems from various countries, but also through the International Carbon Action Partnership (ICAP, 2025)², the correlation between fuel consumption, emissions and costs has been made even more significant among many parties of the shipping industry and trading markets. The shipping evolution race now seems to have shifted lane; from aiming increased speed and capacity towards energy efficiency and lower carbon footprints. Perhaps the pragmatic transformation of carbon emissions to real money has been the necessary catalyst for people, companies and governments thus commencing to really comprehend the cost of environmental damage.

Consequently, various energy efficiency, optimization and emission reduction technologies, including green energy exploitation, have been introduced within the maritime industry with the ultimate goal of both reducing carbon emissions and simultaneously achieving a cost-benefit gain for the implementing organizations.

In this study, I am going to initially review some of the latest technological achievements of energy harvesting, optimization and emission reduction systems that have already been or could be installed on board vessels. Thereafter, a concept of combined green energy harvesting

² ICAP is an open forum comprised of public authorities and governments that have established or are actively pursuing Emissions Trading Schemes (ETS).

technologies with an electromagnetic propulsion boosting system will be reviewed and illustrated on a bulk carrier possible retrofit scenario. Ultimately, scenario based environmental and economic analysis of the concept's application will be conducted.

1.2 Aim

The aim of this project is to explore the potential application of existing energy harvesting technologies on board, which could then be cumulatively transformed into propulsion boosting thrust through a retrofit electromagnet on existing propulsion systems, thus further improving efficiency, minimizing carbon emissions and inspiring the maritime industry to seek for zero emission operations.

Considering that renewable energies' supply can be unlimited, the Net Zero target (IMO, 2025) should not be our ultimate goal. Emitting and recapturing carbon emissions is also an energy demanding process but as Rudolf Clausius had initially explained with the first thermodynamic law, energy cannot be created or destroyed, but only converted between different forms (Clausius, 1879). Consequently, the arising question is “Why do not we solely use renewable energy sources as our primary energy source, especially now that the technologies are available?” An answer on that could be the necessary infrastructure costs in conjunction with other commercial reasons when compared to fossil fuels (Gejguš et al., 2016), as well as the absence of readily available redundancy. For instance, since the ancient years the use of wind energy through sails has been undoubtedly a very environmentally friendly option, nevertheless had been proven commercially inadequate in regards to viable carrying capacities, speeds and guaranteed timetables.

Imagine nowadays, a Chinese container's planned delivery time to US being solely related to the prevailing wind conditions, while its actual delivery time being continuously varying. Even with contemporary observation means and technologies the weather forecasts' accuracy still significantly reduces especially after the 3 days range (Zhu and Pi, 2014) and therefore a 40-day accurate wind prognosis is currently considered fiction. Therefore, such a scenario even though it could be considered viable, it creates enormous commercial and logistic issues. Unfortunately, within most modern societies the priority of commercial satisfaction still overwhelms the urgency for environmental health, despite considerable efforts pursuing to mitigate this imbalance.

Through this project, hoping to inspire achieving one more step towards that direction where maritime trade and transportation are aligned with environmental health and synchronized with its forces. In spite of confronting the commercial satisfaction, would not it better to allure it towards environmental sustainability?

1.3 Scope

The scope of the study is to review established maritime renewable energy technologies and also explore technologies with maritime potentiality, along with supporting energy storage and power management. Magnetic propulsion technologies reviewed as ultimate power consumers of the harvested renewable energies, in conjunction with vessel's auxiliary power demands. From the various described technologies and options only a specific combination has been selected after assessment and sorting, comprising a joint technologies concept.

A brief technical study and model illustration, for possible retrofitting on a case study bulk carrier, was conducted, individually for each component and solely for illustrational and academic purposes, without guaranteeing direct possible installation of technologies on a vessel. A more thorough technical study may be needed prior an actual installation.

Due to limited available real marine operational, historic and economic data on some of the proposed technologies, the operational capabilities, as well as costs' estimation have been carried out basis both commercially shareable data, discussions with other maritime experts and data from similar installations or studies. Installation and maintenance costs' variations of some elements are simulated and included by approximation due to absence of shareable data.

For the sake of clarification, the demonstrated components should not be considered as market's preferable, most optimum or cost efficient options, however chosen basis technical data availability for academic reference only and not commercial or marketing purposes. Relevant costs are indicative and have been simulated for academic purposes only.

Specific scenario-based environmental and economic analysis carried out on the full concept, basis case study vessel, including deployment variations of the included components.

1.4 Objectives

The objectives of this project are:

- ❖ Thorough literature and critical review of existing renewable energy harvesting, storing and distribution technologies which have already been applied on maritime industry, while also identifying other potentially applicable options for merchant vessels.
- ❖ Demonstrate a wholistic concept of renewable energy accumulation and transformation of the harvested energy to electricity, which can be then directly delivered as auxiliary and electromagnetic propulsion boosting power or stored in batteries for future use.
- ❖ Review and analyze the applicability of the concepts' elements including regulatory, structural and other restrictions for retrofit possibilities on a bulk carrier case.
- ❖ Analyze the consumption and emissions of the case study vessel, sailing on a major trade route.
- ❖ Conduct scenario based environmental and economic analysis on different variations of the concept.
- ❖ Identify the optimum configuration with highest environmental and economic efficiency.

Chapter 2 – Literature Review, Renewable Energy & Propulsion Systems in Shipping

2.1 Chapter 2 Introduction

The main focus of the literature review in this research was to elaborate on the various developed renewable energy power generation and storage systems, while simultaneously identifying the ones which have the best potential of being interconnected towards auxiliary power supply and magnetic propulsion boosting on board a vessel. The here below illustrated systems may have already had maritime applications, while others are still under development with potentiality of future use. Installation and maintenance costs factors, though being referred, are excluded from the systems identified and selected as optimum, with efficiency and practicability being the main contributing factors for initially choosing the optimum combination of technologies.

The power demands of a Bulk Carrier will also be reviewed, as part of the case technical study. Sources will be mainly scientific and reputable maritime systems manufactures, as well author's trusted maritime experts' review and feedback.

2.2 Established renewable energy systems with Maritime application

2.2.1 – Solar Energy – Integration of Photovoltaics

Solar Panels' technology, a long established and tested renewable energy solution since the 1950s (Goetzberger et al., 2002), has experienced great development with various applications in the recent years, especially on shore installations and infrastructure. In the maritime industry however, the evolution and range of applications is not following a similar pace, despite several studies and projects, mostly due to the required initial investment's capital costs.

Nevertheless, few maritime vessel projects have already been materialized providing absolutely necessary feedback for further progress. In example, the NYK's solar-assisted car carrier 'Auriga Leader' has been an impressive green shipping pioneer since 2008, with more than 300 installed solar panels (Pan *et al.*, 2021). The stand-alone 40KW PV panel system was providing the 1% of vessel's electricity demand and 0.1% of propulsion power demand. The annual benefit was calculated at 13 tons of fuel saving.



Figure 2 - Car Carrier “Auriga Leader” (JASNAOE, 2025)

Similarly, in 2011, COSCO’s “Tengfei” ocean-going car carrier was equipped with 540 installed PV panels of 143KW rated power and 750 KW capacity Li-ion batteries. With “Tengfei” also being part of a later research, Yuan et al. (2018) calculated that the fuel consumption reduction could reach 4% per year, while the yearly CO₂ emissions could be lowered by 8.5%, during normal sailing periods and under 22.7% ratio of solar power’s grid integration of ship’s load. The vessel’s power system has been a hybrid combination of solar/diesel generator and battery power as illustrated in Figure 3.

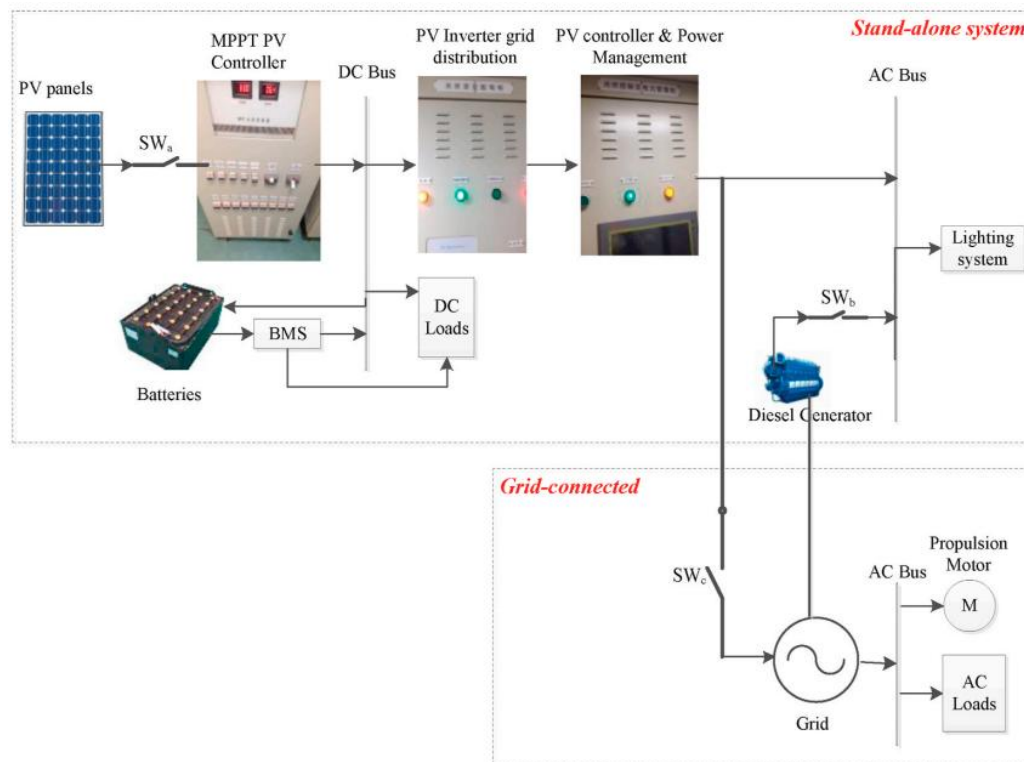


Figure 3 - Ro-Ro “Tengfei” hybrid power system (Pan et al., 2021)

The complete system initially consists of the photovoltaic panels connected with a maximum power point tracker (MPPT) controller which ensures maximum efficiency. Thereafter, the generated DC is going through vessel’s DC Bus, super capacitors and DC/DC converters towards storage batteries, matching the voltages and determining the real output power of the system. An installed battery management system (BMS), compensates for any possible power shortages caused by power fluctuations by switching battery banks from charging to discharging mode, or vice versa. In addition, DC/AC converters allow the generated power to connect to the AC grid of the vessel, supplementing the diesel generators on the AC Bus.

The PV generation system could operate in stand-alone mode, adequately supplying vessel’s lighting system on main grid, on days with sufficient sunlight. Other environmental factors, such as ambient temperature, can also greatly influence the performance of the system and generated output power. That has also been the case for PV panels being estimated by Golroodbari and Sark (2020) as up to 13% more efficient in average at sea rather than at shore, also due to the cooling breeze generated while panels operate at sea.

2.2.2 – Wind Energy – Sails, Rotors, Kites and Wind Turbines

2.2.2.1 – Sails

In the 1980s rigid sails started reappearing as an accountable force of thrust on board commercial ships, mainly due to the tremendous spike of oil prices globally (Atkinson *et al.*, 2018). Few ships, like the sail-assisted tanker ‘Shin Aitoku Maru’ (Figure 4), had installed the Japan Marine Machinery Development Association (JAMDA) rigid sails. The actual gathered data from such vessels of that period, has provided solid evidence, that fuel reduction could even reach at 30% or more, similarly to the performance of ‘‘Usuki Pioneer’’³ during her first voyage in the winter 1984 (Marine Engineers Review, 1985). However, later wide spread installation on the global fleet was not the case due to engineering or other operational challenges and of course as a result of the ultimately reduction of fuel prices, which tendered installation and maintenance costs again uneconomical for shipowners.



Figure 4 - Tanker ‘‘Shin-Aitoku Maru’’fitted with wingsails (Ariffin et al., 2020).

Lately, sails and their environmentally friendly variations started reappearing as economically tempting and emission controlling solutions. A combined wind and solar energy sails’ concept has been demonstrated by Greg Atkinson and Eco Marine Power (Ecomarinepower, 2014). The idea is to install solar PV panels on rigid sails arrays which can be automatically positioned via

³ The 26,000-dwt bulk/log carrier Usuki Pioneer during her first voyage, in winter 1984-85, from Japan to Seattle and return, with an average speed of 12 knots reported of having achieved over 30% fuel savings with the use of JAMDA type sails.

a computer controlled system, thus using renewable energy thus reducing fuel consumption for auxiliary power, while simultaneously providing sail-assisted propulsion.

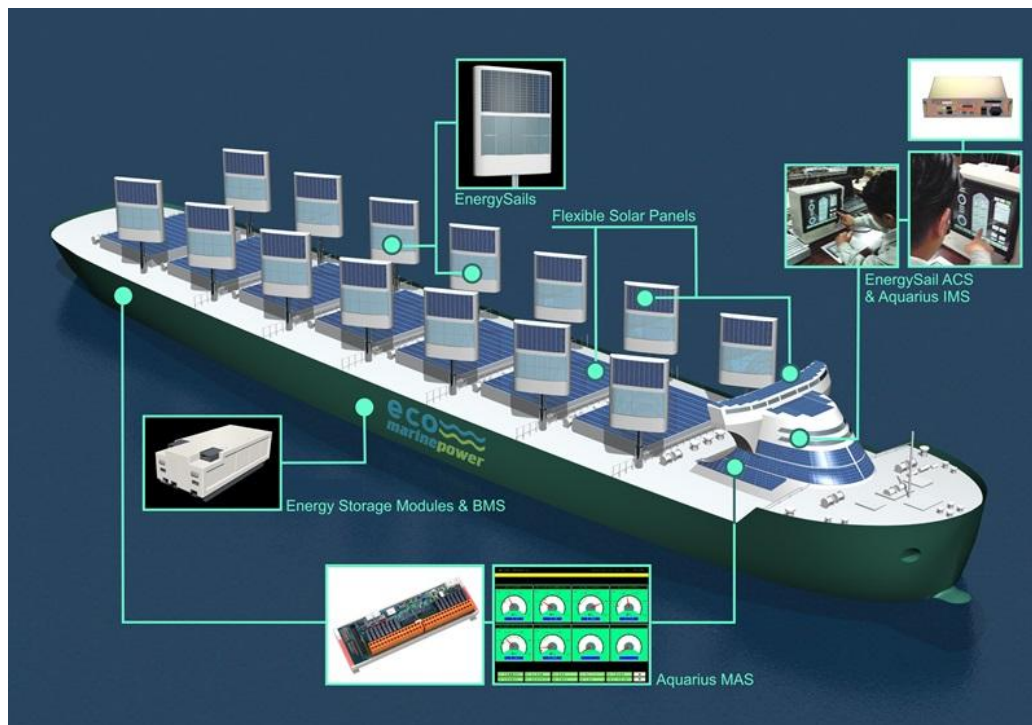


Figure 5 - Aquarius MRE ship design (Ecomarinepower, 2025)

2.2.2.2 – Rotor Sails

In 1925 Anton Flettner, invented the Flettner Rotors system, in which rotating cylindrical structures could provide wind-assisted propulsion via the Magnus Effect principle (Yilmaz et al., 2025). The concept of system's operation and how the aerodynamic lift is created by wind is briefly demonstrated in Figure 6. The top discs of the system which have added substantial additional force, where patented by Alexander Thom, 10 years later (Thom, 1934).

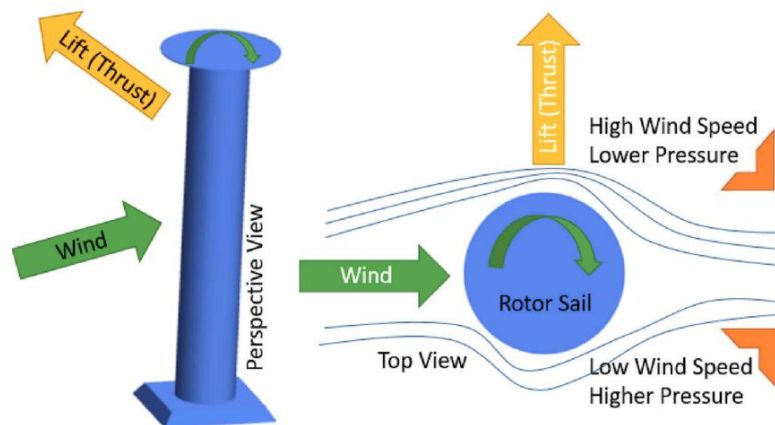


Figure 6. Magnus effect principle on a flettner rotor (Yilmaz et al., 2025)

The system has been initially installed on board the ‘‘Buckau’’ ship in 1925, while the next installation took place on a cargo vessel named ‘‘E-Ship 1’’ (Figure 7.) in 2010, amazingly 85 years later as a green initiative by Enercon company, claiming to having achieved 15% reduction in fuel consumption, or even more in peak conditions, as per the technical report presented by Enercon Wind Company (2013) during the 4th conference on ship efficiency in Hamburg, with rotors serving as auxiliary power to the main diesel engine (Titahelu et al., 2021). It was also mentioned that the vessel could sail up to 12 knots by using only her Flettner rotors under favorable wind conditions. A similar project, the K-Sail, of integrated sail management system which incorporates various vessel automations and route optimization, has also been development by the Norwegian maritime technology company Kongsberg Maritime (Kongsberg, 2026). The system utilizes advanced data analytics in order to optimize and integrate propeller, steering and wind-assisted propulsion.



Figure 7. Cargo vessel ‘‘E-Ship 1’’ (Hilly B., 2026)

2.2.2.3 – Kites

Using kites as propulsion means has been put under test since the early 2000s by the pioneer company Skysails (SkySails Marine, 2026). The main idea was to exploit the strong and constant winds at high altitudes (up to 400m) in order to produce advantageous thrust for the vessel through the towing kite’s automated dynamic maneuvers, which are constantly computer controlled and flying under figure-eight pattern. Actual installation of the kite system took place on a small fleet of pilot customer vessels like the research vessel ‘‘Beaufort’’ and the cargo vessel ‘‘Michael A.’’ It was designed to offer an effective thrust up to 190 kN or 2000KW engine power equivalent, under optimum wind conditions (Schmehl et al., 2013).

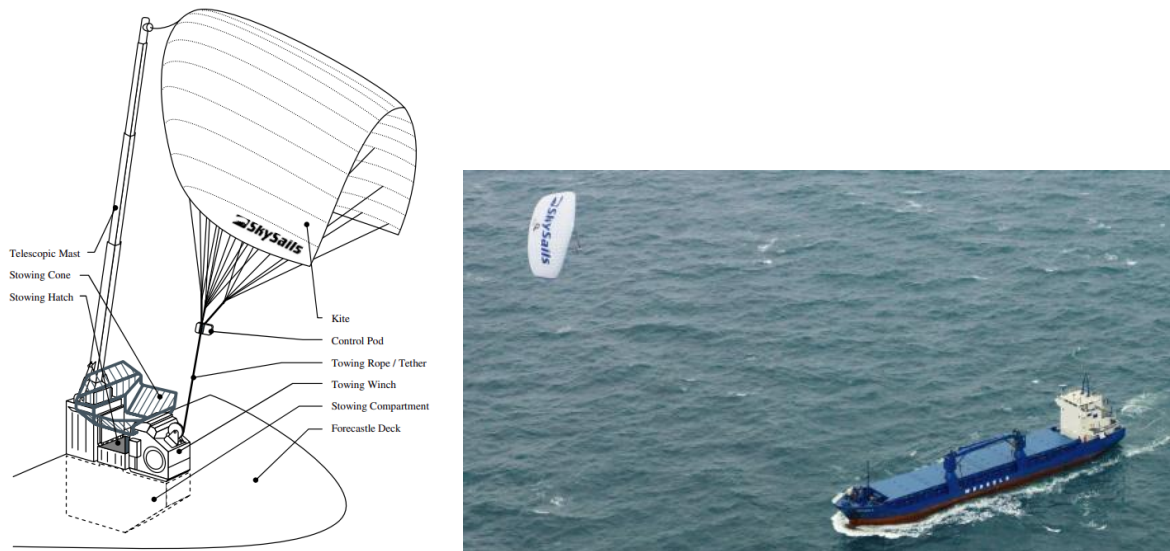


Figure 8. SkySails' Kite system on board cargo vessel "Michael A." (Schmehl et al., 2013)

The further evolution and marketing of the system has however been currently set on hold, as the company decided to focus mainly on the wind energy production sector through Kite systems (SkySails Power, 2026).

2.2.2.4 – Wind Turbines

The use of wind turbines for electric power production, both on shore and off shore, has been one of the major green energy transition contributors in the recent years. In EU wind power alone, as renewable energy source, accounted for the 18% of the gross electricity consumption of 2024 (Eurostat, 2026). Harnessing the endless wind forces around earth and transforming them to electricity seems just ideal. However, despite wind and especially head winds being probably the biggest negative counter force to propulsion thrust, installing and using wind turbines on board moving vessels has not been so popular yet, mostly due structural, risk and safety limitations. Installing a wind turbine on a rolling, pitching and yawning⁴ car carrier for example could create stability issues, as an efficient for a ship's needs wind turbine would be quite enormous. A study by Bockmann and Steen from the Norwegian University of Science and Technology demonstrated that by installing a 600KW Vestas V39/600 wind turbine for auxiliary power generation, on a 150m long tanker trading between Peterhead and Bremerhaven, could save up to 24.4% of the total fuel (Bockmann and Steen, 2011). The proposed wind's turbine diameter would be 39 m wide.

⁴ Rolling, pitching, and yawing. The three primary rotational movements of a vessel at sea.

Furthermore, a major affecting factor for wind turbines on board sailing vessels is the relative wind's force and direction, which would be constantly changing at extremely faster and more unpredictable pace when compared to a fixed shore installation. Therefore, it is vital for any installed maritime wind turbine to be agile, multidirectional and robust thus being able to provide maximum efficiency.



Figure 9. Illustration of a Vestas V39/600 wind turbine onboard a 150m tanker (Bockmann and Steen, 2011) and model tanker "Airmax" (Carlson and Nilsson, 2015).

Real sea measurements have been performed on Stena's 1:12 scale model tanker "Airmax", as part of a similar project by Carlson and Nilsson with also the support of the start-up company PROPit AB, Swedish Energy Agency among also supporters (Carlson and Nilsson, 2015).

Future optimization of wind turbines' design, orientated for maritime applications, could assist mitigating any safety or efficiency concerns. Improved large Vertical axis wind turbines (VAWTs) can be considered as most optimum due to their multidirectional function, despite their up to 25% lower efficiency when compared to the widely used big Horizontal axis wind turbines (HAWTs), (Al-Rawajfeh and Gomaa, 2023). Pioneer concepts of VAWTs (i.e. Hybrid Savonius-Darrieus or Super Turbine) with maritime application potentially, will also be reviewed during next section. For the integrated Green energy concept of this study the vertical axis wind turbine is chosen and analyzed in Chapter 4.

2.3 Renewable energy systems with potentiality for Maritime application

In order to identify additional renewable energy sources with possible practical maritime application, this study focuses on initially harvesting forms of energy which are encountered on board vessels yet remain unexploited. Subsequently, also being able to be transformed into electricity, which can be either stored or directly integrated into the main power grid, similarly to the previously mentioned established renewable energy systems.

Here below, I will review and refer to two of yet unexploited forms of renewable energy, available onboard vessels.

2.3.1 – Noise & Acoustic Energy Harvesting

Harvesting sound energy has been a very promising green energy exploitation concept with various possible applications both at shore and off shore. The idea of collecting the relentless ambient sound waves, later amplifying them through resonators or acoustic metamaterial and finally converting them to electric energy through piezoelectric, electromagnetic or even triboelectric methods (Choi, Jung and Kang, 2019) and finally storing or even directly using it as usable electric energy, is without doubt tempting.

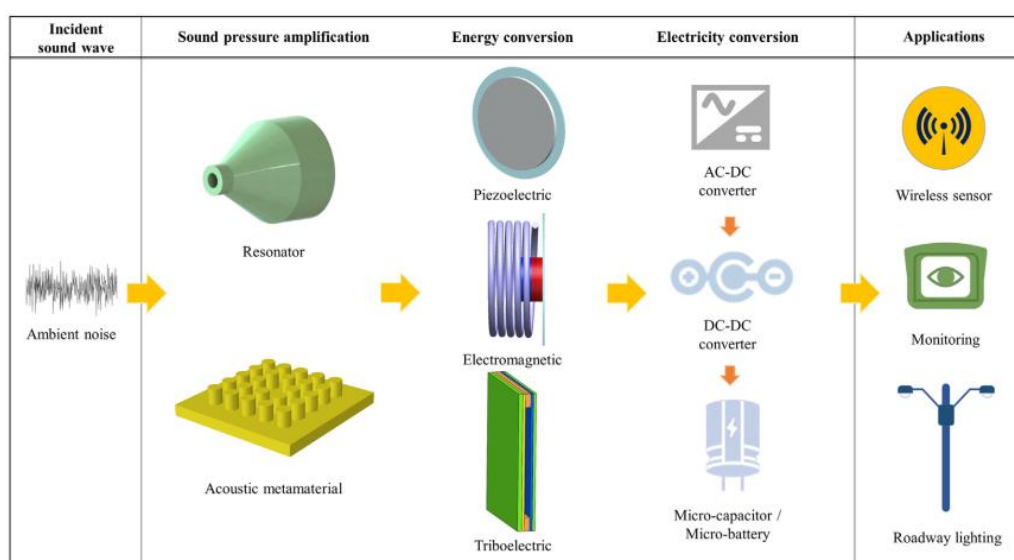


Figure 10. Schematic of sound energy harvesting (Choi, Jung and Kang, 2019)

Especially in an environment such as the engine room of a vessel, where the generated noise levels are elevated in a wide spectrum of frequencies between 31.5Hz and 8000Hz, while also exceeding the 100 dB range (Bocanegra et al., 2023), the amount of unharvested wasted energy

can be considerable. Since there are various types of sound energy harvesters, such as the piezoelectric beams on top of Helmholtz resonator type which can give a power output between 137~1430 μW at 100 dB, resonating in the range of 170-206 Hz with a single 4liter approx. size device at (Yang et al., 2014) or an electromagnetic based harvester which can deliver up to 1960 μW , at 125 dB of 143 Hz resonant frequency (Khan and Izhar, 2013), a vessel specific acoustic study of engine room, would be absolutely necessary prior any installation, in order to identify the most dominant resonating frequencies during the various rpms of the engines. Thereafter, stress and endurance study has also to be conducted, ensuring longevity and maintenance needs of the system. Due to the low levels of produced power, considering a bulk carrier's direct power needs, storage of the accumulated electric power for later use is not to be considered.

2.3.2 – Maritime Radio Frequencies' Energy Harvesting

Radio frequency (RF) energy harvesting is also a promising renewable energy source for the maritime industry, as vessels are sailing, emitting and receiving almost continuously, vast amounts of radio waves with extended band range. From MF/HF, VHF or UHF communication systems to 9GHz maritime radars and satellite systems, the vessels are continuously bombarded by various radio waves' energy. Some of that energy is of course absorbed though vessels' antennas for the navigational and communicational purposes, however most of that emitted energy is just reflected on vessels' steel.

A common maritime X-Band radar has peak power output of 12, 25 or 50kW with up to 96nm range (Furuno, 2018), nevertheless the received and possibly exploitable power would be significantly less, due to the pulses' short emission and always reducing at higher range. The Radar Equation (Probert-Jones, 1962), can give us an approximate of radar's reflected power on a target (Li, 2005). In example, from a 25kW X-Band maritime radar only approximately $5.82\text{E}-17$ Watts of energy could reach an one square meter receiver at a distance of 12 nm, without interference from other environmental criteria. Yes, the power is insignificant, nevertheless if multiplied with the approximate 10 million hourly repetitive pulses (Ramanamahefa et al., n.d.) of 30 or more unceasingly emitting naval sources in an area of high marine traffic density, then a considerable accumulative amount of free energy can emerge.

A RF harvesting system mainly comprises of the signal reception antenna, which can be of variable type (single-band, multi-band, single-port, multi-port, etc.), an impedance and power

rectification unit which can convert the electromagnetic energy to DC power and the energy storage units such as capacitors or batteries, incorporated into an energy management which regulates and stabilizes the output voltage and current to the grid (Kallumottakkal et al., 2025).

A schematic illustration of the system together with experimental performance data of RF energy harvesting systems are illustrated in the figures below.

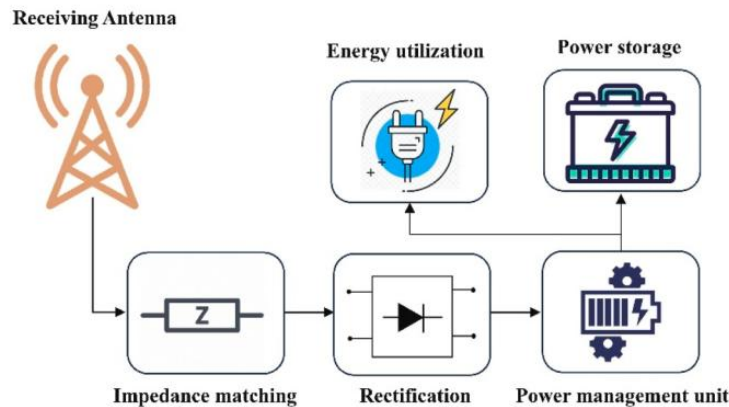


Figure 11. Schematic block diagram of radio frequency (RF) energy harvesting system (Kallumottakkal et al., 2025)

Frequency (MHz)	Distance (m)	Transmitted Power (W)	Harvested Power (μ W)
674–680	4100	4	60
902–928	15	1.78	5.5
868	25	1.78	2.3
868	27	3	2
915	5	3	189
915	11	960,000	1

Figure 12. Experimental performance data of various Radio frequency (RF) energy harvesting systems (Kallumottakkal et al., 2025)

For possible onboard installation multi-band antennas are recommended due to the extended range of radiofrequencies being used in the maritime industry. Optimization of such a system basis most dominant and efficient frequencies should take place after an experimental on board installation. Furthermore, the location of the installed antenna/s, as well as other system's components have to be carefully installed and assessed, thus not interfering with own vessel's navigational and communicational transmitting/receiving signals.

2.4 Energy Management System – Power Rectification, Storage and Distribution

2.4.1 – Energy Management System (EMS)

A main obstacle for implementing renewable energy as a power source on board has been the delivery of the harvested power to the same current form as delivered by the vessel's main power switchboards to grid or stored in battery packs for later use . On most large shipping vessels, the main power switchboards are of 440V AC, 3- phase and 60Hz frequency (Abu Bakar et al., 2023). On the other hand, the output of the produced renewable energy significantly varies in form. As previously mentioned, PV panels for instance, may produce DC of varying output according to sunlight, panels' temperature, etc. Fuel cells (EMSA, 2017) also deliver DC and are mainly used for stable loads, while the generators of most conventional vessels produce

Therefore, the direct integration of the renewable energy into vessel's already installed switchboard and power grid is not always practical or even possible. Some grid arrangements may be able to directly integrate small additions, however for higher power exploitation, additional converters, dedicated switchboards, battery packs, capacitors and a hybrid energy management system (EMS) is necessary, which of course will also need to be approved by vessel's specific classification society (ABS, 2024).

The EMS together with sophisticated software, tailor-made for each vessel, will be dictating whether batteries and capacitors should be charging or discharging, whether fuel cells should supply a steady share of the load and of course when the conventional ship's generators need to step in according to the power demand status.

A simple diagram of such hybrid ship power system with EMS is illustrated in following figure.

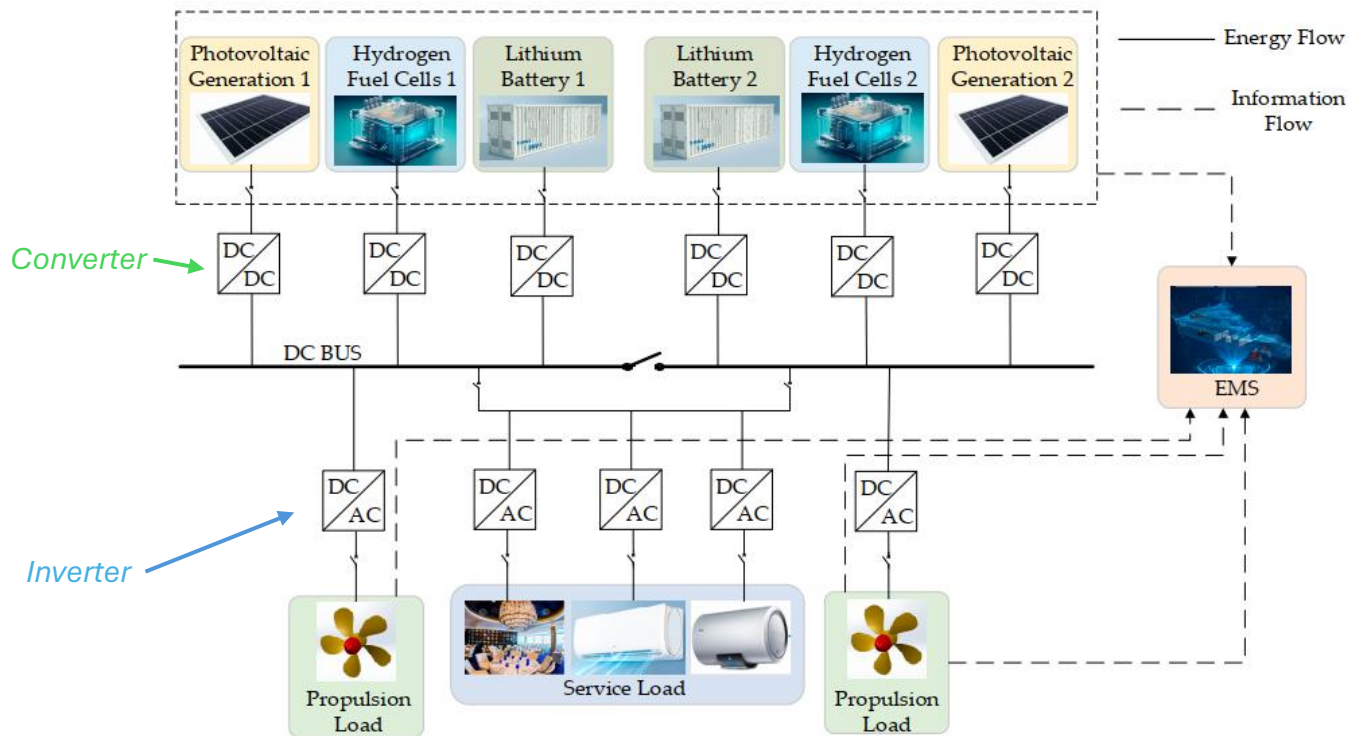


Figure 13. Diagram of a hybrid ship power system (Source: Zhao et al., 2025)

2.4.2 – Power Rectification and Distribution – Converters, Inverters, Switchboard arrangement in Hybrid Systems

The vital rectification process of the harvested energy is occurring through AC/DC (i.e. wind turbine systems) and DC/DC (i.e. PV or RF systems) converters, thus stabilizing the produced voltage towards the storage batteries or another DC/AC inverter for direct use through the main power distribution grid (Di Piazza et.al, 2025).

In a conventional AC vessel where the main generators are the dominant power source the electrical behavior is quite steady and predictable. In a hybrid power system though, the need for separate switchboards with additional converters and inverters is the most optimum and safest solution. The arrangement of the power management system may vary according to vessel's specific needs and capabilities. For example, in many cases the main generators may have a separate AC switchboard and bus or being also integrated into the DC bus of renewable energies through converters (Luo et al., 2024). This also depends on the percentage of the desired dependency on each power source, conventional or renewable.

Redundancy of the power system and main switchboard is mandatory. Especially when the main source of electrical power is necessary for propulsion of the vessel, the main bus must be subdivided into at least two sections, which are normally connected by circuit breakers. If the main switchboard is divided into separate sections which are interconnected by cable, then the cable must also be protected at each end against faults. Additionally, wherever electrical power is vital for propulsion restoration, the capacity is to be sufficient to restore propulsion in conjunction with other necessary machinery from a dead ship condition within thirty minutes (ABS, 2024).

According to vessel's specific arrangement and operating mode a relevant notation will be given by classification society. Following sample table indicates few Hybrid Operation mode notations from ABS.

	<i>Operating Mode</i>	<i>Functionalities / Arrangements</i>	<i>Notation</i>
1	Low Exhaust Emission	1. Electrical power supplies the ship's consumers and main propulsion system by ESS and/or FC-PS 2. Engine driven gensets are off (e.g., at Port) 3. Boilers and incinerators operating on liquid fuel are to be off (e.g., at Port) 4. Specific time limit (vessel operating on ESS) is to be specified.	HYBRID [LEE]
2	Power Management	1. Typical schedule strategies: 1.1 Peak Shaving 1.2 Load Leveling/load smoothing 2. Load sharing control 3. Load shedding/preferential trips 4. Blackout prevention 5. The PMS is to be able to bring online all available generating sources (or ETS) after a blackout and to connect them to the electrical network.	HYBRID [PMT]
3	Power Backup	1. The ESS is to be readily available to the ship's electrical system during a contingency (e.g., loss of a conventional generator). 2. The ESS is to be connected to the main bus or distribution system in a specified time (e.g., in the order of seconds) that maintains the systems' stability . 3. The ESS is capable to provide power backup during certain time (e.g., during failures of the conventional power generation system). The power backup mode is also known as spinning reserve mode.	HYBRID [PBU]
4	PTO/PTI ⁽²⁾	1. Power Take Off (PTO): Operating mode where a shaft generator provides electrical power flow to the ship's electrical network. 2. Power Take In (PTI): Operating mode where a shaft generator operates as a motor to boost the main propulsion engine power.	HYBRID [PTO/PTI]

	<i>Operating Mode</i>	<i>Functionalities / Arrangements</i>	<i>Notation</i>
5	Shore Connection ⁽³⁾	1. When the vessel is provided with a shore connection installation in accordance with Part 6 Chapter 4 of the Marine Vessel Rules. 2. The modes of operation related to the shore connection and hybrid is: <i>i)</i> The shore connection is arranged for charging the on board ESS while providing power to the vessel's electrical consumers, And/or <i>ii)</i> The on board ESS is arranged to provide power to some of the vessel's electrical consumers, while the shore connection provides electrical power to other electrical consumers on the vessel (configuration of electrical distribution system is to be monitored, with alarms, to prevent hidden failure when shore power is disconnected). 3. Operation of the vessel while connected to shore power by reducing onboard power generation, emissions, and local noise. (e.g., all combustion engines/gensets not operating).	HYBRID [SCN]
6	Offshore Charging Connection	1. When the vessel is provided with facilities to enable connection to an offshore charging station in accordance with Part 4, Chapter 5 of <i>ABS Rules for Building and Classing Single Point Moorings</i> and 3/35.3 and 3/35.5 of this document. 2. The modes of operation related to an offshore connection and hybrid is: <i>i)</i> The offshore connection is arranged for charging the vessel's onboard ESS while the vessel is connected to an offshore charging station in accordance with <i>ABS Rules for Building and Classing Single Point Moorings</i>. <i>ii)</i> Operation of the vessel is to be possible while connected to an offshore charging station by an energy source that is not being charged during this operation.	HYBRID [OCC]
7	Electric Mode	1. Electrical power supplies the ship's consumers and main propulsion system by ESS and/or FC-PS and/or any other non-conventional power source. 2. Specific time minimum requirement: <i>i)</i> a minimum of 1 hour for non-SOLAS vessels <i>ii)</i> a minimum of 3 hours for SOLAS vessels while operating on ESS and/or FC-PS and/or any other non-conventional power source is to be specified. <i>Commentary: Alternate times to the minimum specific time limit stated above may be considered with supporting documentation based on the type and operation of the vessel. The actual time for EM operation is to be indicated in the CONOPS document</i>	HYBRID [EM]

Figure 14. Vessel's Hybrid Operating Modes Notations (Source: ABS, 2024).

2.4.3 – Power Storage - Battery Packs, Supercapacitors and Fuels Cells

The power storage of green energy serves multiple purposes. Lithium-ion (Li-ion) batteries and supercapacitors are commonly used (ABS, 2024), thus the extra produced energy which could not be directly consumed by vessel's need can be stored for future use. For example, when a vessel stays idle at anchorage. Additionally, the stored energy can also be initially accumulated for rapid utilization from heavy consumers, such as the propulsion system rather than directly being consumed as auxiliary power (i.e. fans, lighting).

Batteries are also serving as voltage and frequency compensators in the system, thus ensuring stability and reliability of the vessel's power system which can be vulnerable to pulsed power loads⁵ (Hosseinzadehtaher et.al, 2021) or starts of heavy consuming equipment and other destabilizing factors such as swift changes of the environmental conditions. Nevertheless, boundaries seem to have appeared on the future expansion of Li-on batteries maritime usage, due to operating limitations such as temperature and voltage which require complex battery monitoring and fire protection systems; as well as their relatively low power density considering shipboard high energy demands. Another promising alternative could be the still under research and development metal-air batteries, which are very similar to Li-on, however differing on the use of air as cathode and metals like lithium, zinc or aluminum as anodes. Lithium air batteries for instance, have an almost 10 times higher theoretical specific energy compared to the Li-on batteries (ABS, 2021). On the other hand, issues like dendrite formation and practical rechargeability issues need to be solved prior such technologies could have wide maritime application. Other developing batteries technologies such as the Vanadium Redox or Ammonia flow batteries could also have great prospects for maritime implication, after also countering their respective disadvantages such as costs or lifespan.

⁵ Pulsed power loads are electrical systems or apparatuses that may demand extremely high power for very short, frequent bursts—often in milliseconds or nanoseconds—rather than a continuous load.

Below tables present comparison data between different battery technologies.

Battery Type		Voltage (V)	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Cycle Life	Power Density (mW/cm ²)
Lithium Ion		3.7	265	670	High	**
Metal-Air Batteries	Lithium-Air Batteries	2.96	3,463*	2,004*	Low	**
	Zinc-Air Batteries	1.65	1,085*	1,670*	Low	479
	Aluminum-Air Batteries	2.71	2,791*	**	Low	**
Redox Flow Batteries	Vanadium Redox Flow Batteries	1.25	20	15-25	High	**
	Iron-Chromium Flow Batteries	0.94	**	**	High	70-100
Ammonia Batteries	Thermally Regenerative Ammonia Batteries	**	**	1.03	Very Low	3.7
	Ammonia Flow Batteries	**	**	**	Very Low	2.80 at 55 °C
Solid State Batteries		2.6	350	**	Medium	**

* indicates theoretical value

** indicates no established value

Battery Type	Lithium Ion	Metal-Air	Redox Flow	Ammonia	Solid State
Rate of Charge	Fast	*	Medium**	Slow	Fast

*Current metal-air batteries are recharged mechanically by replacing the anodes and electrolyte

**Redox flow batteries can also be recharged mechanically by replacing the electrolytes in addition to standard charging methods

Figure 15. Batteries' Technologies comparison (ABS, 2021).

Supercapacitors or ultracapacitors are mainly chosen for high-frequency power demand applications but they cannot solely stand as main energy storage units, unlike the lithium batteries, due their low energy density. Therefore, they need to be combined with other energy storage technologies. Furthermore, supercapacitors' advantages are their high efficiency, load variations' compensation capabilities, low environmental and extremely high cycle life which can be up to 10 times longer than other energy storage means (Nuchturee et al., 2020). In most hybrid ultracapacitor/Li-on battery arrangements, as expected the high frequency power is bore by the supercapacitors while the low frequency by the latter (Du et.al, 2023).

Fuel cells are also one of the most popular and promising technologies which can assist the maritime industry to reduce its environmental impact towards the ultimate goal of zero emissions. Especially the low temperature hydrogen type, solid oxide fuel cell system is considered a viable solution for onboard application, despite its greater space demand which can be up to five times higher compared to other high temperature or energy denser fuel cell systems (Van Biert et al., 2016). Natural gas-fueled cells another possibly viable alternative, due to the already established natural gas infrastructure, lower cost than hydrogen and relatively low emissions.

Aziz et al. suggested that polymer electrolyte membrane fuel cells are more suitable for shipping application due to their low operating temperature in the range of 60°C and 80°C and their higher reaction rates (Aziz et al., 2025).

Fuel cells' power is mainly used for auxiliary power supply due to their restricted output, while accompanied by battery stacks through a hybrid energy storage system. Below fact sheet from US Department of Energy (DOE, 2015) briefly illustrates the comparison among different fuel cells technologies.

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	<120°C	<1 kW - 100 kW	60% direct H ₂ ⁱ 40% reformed fuel ⁱⁱ	- Backup power - Portable power - Distributed generation - Transportation - Specialty vehicles	- Solid electrolyte reduces corrosion & electrolyte management problems - Low temperature - Quick start-up and load following	- Expensive catalysts - Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60% ⁱⁱⁱ	- Military - Space - Backup power - Transportation	- Wider range of stable materials allows lower cost components - Low temperature - Quick start-up	- Sensitive to CO₂ in fuel and air - Electrolyte management (aqueous) - Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40% ^{iv}	Distributed generation	- Suitable for CHP - Increased tolerance to fuel impurities	- Expensive catalysts - Long start-up time - Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50% ^v	- Electric utility - Distributed generation	- High efficiency - Fuel flexibility - Suitable for CHP - Hybrid/gas turbine cycle	- High temperature corrosion and breakdown of cell components - Long start-up time - Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60% ^{vi}	- Auxiliary power - Electric utility - Distributed generation	- High efficiency - Fuel flexibility - Solid electrolyte - Suitable for CHP - Hybrid/gas turbine cycle	- High temperature corrosion and breakdown of cell components - Long start-up time - Limited number of shutdowns

Figure 16. Comparison of Fuel Cell Technologies (Source: DOE, 2015)

Nonetheless, not all fuel cell technologies can have directly application. Specific design, construction, testing and survey requirements are already in place from the classification societies. Only a fuel cells' system which has been granted type approval can be installed and used. A relevant notation can also been given to a vessel, such as FC-E (For essential or emergency services use), FC-NE (Non-Essential Service) or a combined notation like LFFS(FC-E) in gas carrier cases (ABS,2023).

2.5 Magnetic Propulsion - PTI/PTO shaft generators and Magnetohydrodynamic Machines

Purely magnetic propulsion technologies have not been widely applied in the commercial shipping industry until recent years, mostly due to the high-power demands and the relevant costs involved, which render such a propulsion concept inefficient. On the other hand, pure electric propulsion through electric generators and motors has been a well-established and widely tested technology on board vessels. Nevertheless, as the future of shipping dictates reduced emissions and higher efficiency new magnetic technologies are becoming popular in shipping, mainly as supplementary boosters of the already installed propulsion and power production systems.

2.5.1 – PTI/PTO shaft generators

A recently introduced and promising technology, which has already been applied on board over 200 vessels, is the permanent magnet shaft generator system. By the installation of permanent magnet generators aligned with the main propulsion shaft and ship's main engine, a vessel can obtain supporting propulsion power during demanding situations (Power Take In/PTI mode) or generate auxiliary power from the rotation of the main shaft (Power Take Out/PTO mode), thus optimizing her consumption and efficiency (WE Tech Solutions, 2026). Optimization is not only focusing on power output and performance but on emissions too. Reusser, Perez and Perez (2018), demonstrated a Torque Field Oriented Control scheme with selective optimization strategy for installed permanent magnet drives, where the selection and utilization of PTI/PTO modes would be engaged and aligned with vessel's diesel generator optimum performance by continuously targeting lowest emission/output ratio.

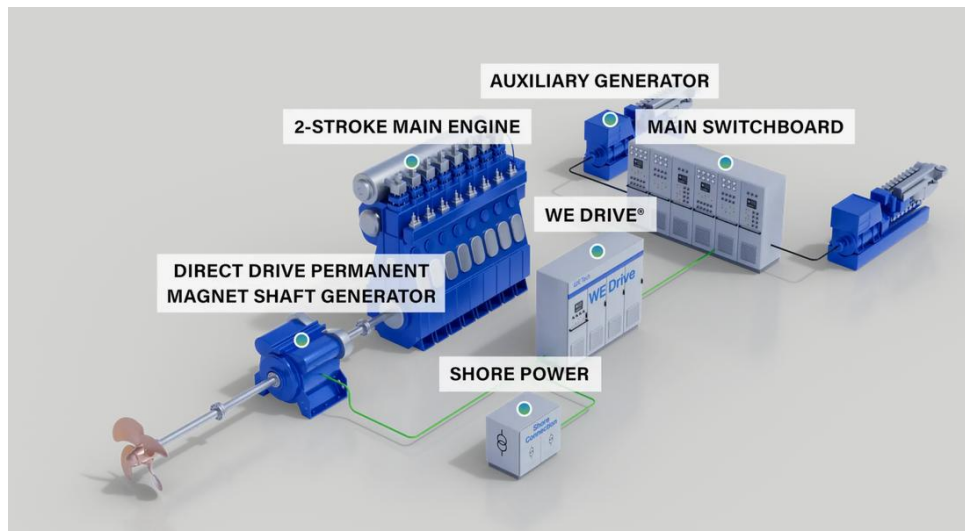


Figure 17. Permanent Magnet Shaft Generator System illustration (Source: We Tech Solutions, 2026)

2.5.2 – Magnetohydrodynamic (MHD) Propulsion

Another proven maritime magnetic propulsion technology is the Superconducting Magnetohydrodynamic Propulsion. A real experimental ship project has been developed and sea tested by Sasakawa et al. (1996) and the Ship & Ocean Foundation. Yamato-1 was the world's first Superconducting MHD Propulsion ship. The concept was briefly to create a magnetic field which would propel the sea water similarly to jet engines for thrust. The experimental sea trials provided an achieved speed of 7.5 knots created by a magnetic field of 4 Teslas strength. The research team concluded at that time that for such propulsion systems being commercially viable for shipping, the generated magnetic field should reach strengths of more than 20 Teslas. It is worth mentioning that the same research had also suggested that permanent magnets could replace the superconducting coils of the experiment in the future.

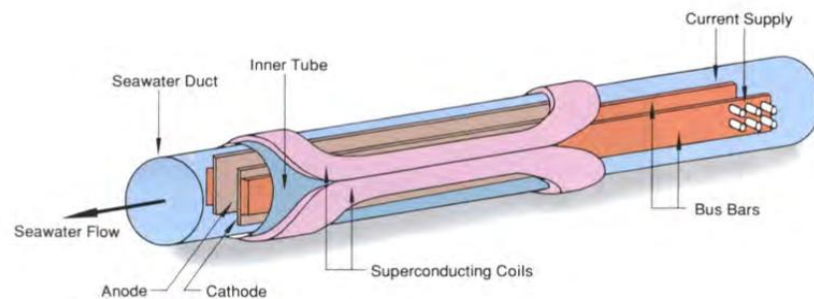
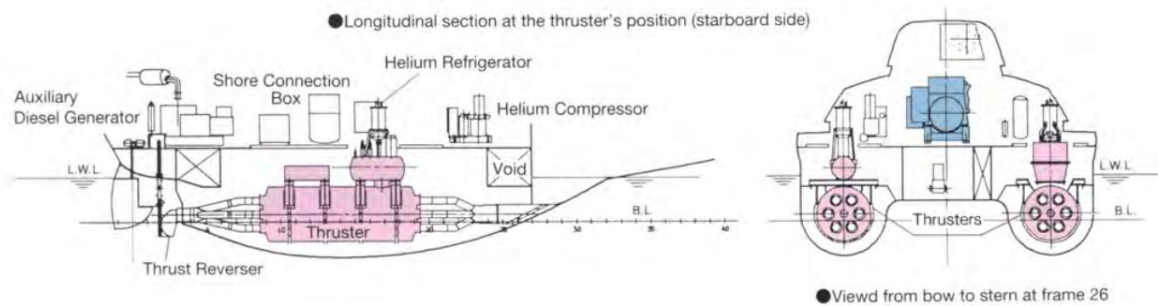
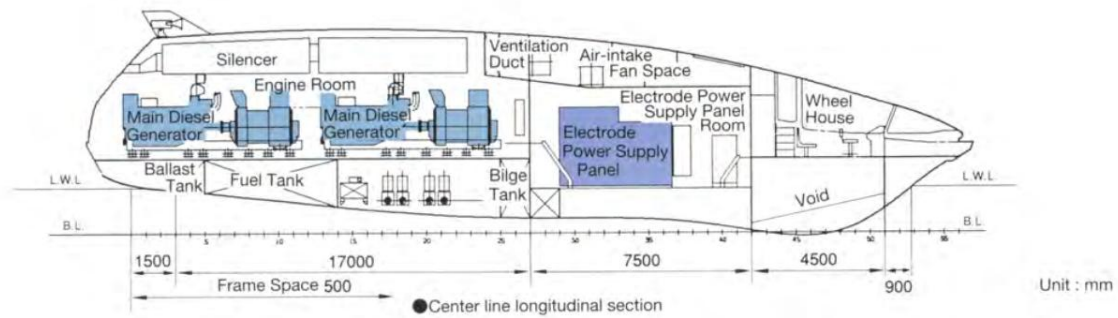


Figure 18. Yamato-1 General Arrangement and Superconducting MHD Jet Propulsion System

(Source: Sasakawa et al., 1996)

Chapter 3 – Methodology

The research methodology within this study has been a hybrid mixed approach, which includes both qualitative and quantitative research, as well as preliminary experimental research and case studies.

The data collection has been conducted mainly through literature review, but also through author's and other shipping professionals' personal experience, commercial documents, information and drawings which cannot be fully disclosed as part of the study, as well as raw data observations and collection.

For this study, two long established solar and wind technologies with imminent expansion and interconnectivity potentiality (Ahmed et al., 2025) and one potentially applicable technology, which would be able to cover a portion, if not all, of a vessel's auxiliary power demands and provide propulsion boosting power through electromagnetic propulsion systems, has been compiled and reviewed.

Due to flexibility and adaptability of the proposed systems in regards to size and power production, the vessel's specific installation arrangements and power production data will be incorporated into the technical study on a case vessel in Chapter 4. The study of the case vessel focuses on power generation, fuel consumption and emissions on a major bulk trade route, in conjunction with the total possible reduction of emissions.

The flow diagram of the methodology is illustrated in the next page.

3.1 Methodology Flow Diagram

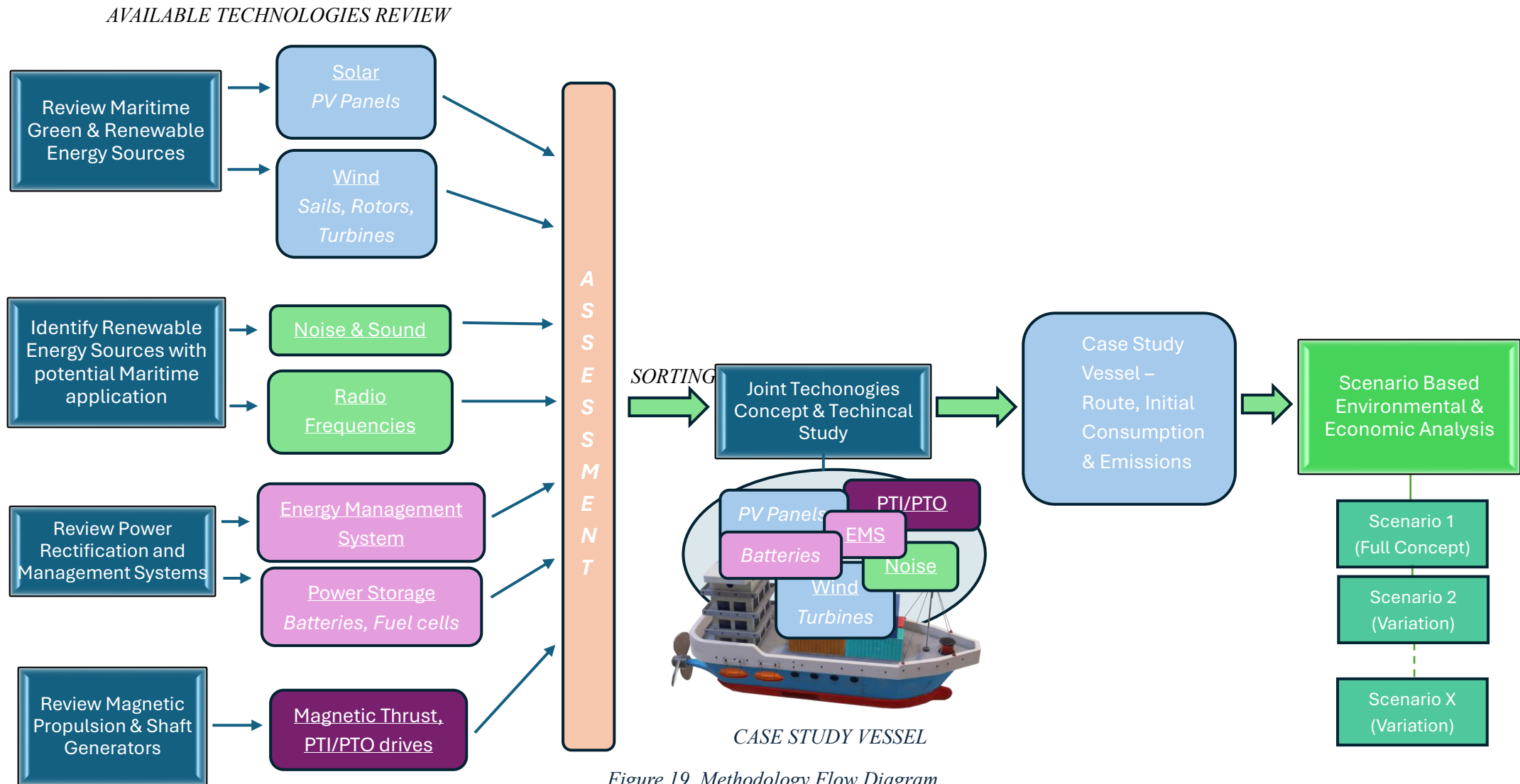


Figure 19. Methodology Flow Diagram

3.2 Renewable Energies' Sorting Assessment

Thus selecting the components of the joint technologies' concept, assessment and sorting of technologies has been done through a qualitative approach, based on the literature review, author's experience and discussions with other experts from the maritime industry. The comparison criteria for ranking the technologies were:

- Installation, Operational, Maintenance Complexity and Flexibility, Spatial Requirements
- Interconnectivity and Compatibility with other technologies
- Technical, Operational and economic data availability
- 24/7 hour operational capability

Rating was through 1 to 5 scaling similarly to Q sorting methodology (Lopes et al., 2022), where rating 1 is considered the most complex option and 5 the simplest achievable.

Table 1. Renewable Energies' Sorting Assessment (Author, 2026)

(1: Very Complex, 2: Complex, 3: Moderate, 4: Simple, 5: Very Simple)

Technology	Installation, Operation Complexity & Flexibility	System's Interconnectivity	Data Availability	24/7 Operation	<u>Total Score</u>
<i>PV Panels</i>	3	5	5	2	15
<i>Sails</i>	1	2	2	2	7
<i>Rotor Sails</i>	1	2	3	3	9
<i>Kites</i>	2	1	1	2	6
<i>HAWT Turbines</i>	1	4	3	3	11
<i>VAWT Turbines / (collapsible)</i>	1/ (3)	4/ (4)	3/(3)	4 /(4)	12 /(14)
<i>Noise Harvesters</i>	3	4	1	5	13
<i>RF Harvesters</i>	2	3	1	3	9
<i>Batteries</i>	3	5	5	4	17
<i>Fuel Cells</i>	2	3	3	5	13
<i>PTI/PTO Shaft Gen.</i>	2	4	2	4	12
<i>MHD Propulsion</i>	1	2	1	5	9

The rating and ranking of technologies have been made while considering possible installation on board a bulk carrier and according to this category of vessels operational needs and requirements.

PV panels are a long-established and used renewable energy source at land; therefore, operational and economic data are widely available for many possible configurations. The interconnectivity of the solar panels with power grids, battery packs and other renewable energy systems has been also tested and is considered very compatible. The PV panels option has been rated with a total of 15 rating points.

From wind-oriented energy sources, both sails, rotor sails and kites have the operational restriction that they are efficient only under specific wind directions. A vessel may indeed be able to move under sails' thrust; however, the speed and total distance sailed due to the necessary zigzag, tacking maneuvers (Chuang and Steen, 2012), may be operationally and commercially inefficient. Economic and operational information is also restricted due to the small number of installations on commercial vessels and as result feedback. On the contrary, wind turbines have been a long established and exploited energy source at shore, where technoeconomic data is widely available and their compatibility with power grids and other systems is also high. Nonetheless, all the above-mentioned wind related options, if not totally collapsible, may create operational difficulties, such as loading or discharging delays while a vessel is at port or even interact with vessel's navigation. As a result, the highest rated option, with 14 rating points, was the collapsible VAWTs due to their reduced size and less navigational and operational obstructions.

Between the two potential maritime usable technologies, the Radio frequency harvesters have been considered more complicated due to absence of relevant maritime studies and safety tests, including their possible interaction with other communicational and navigational signals. Despite the limited available data for both options, the Noise harvesters are considered a more viable option due to the minimum, if not zero, safety complications, in combination with the theoretically unceasing noise generation in a vessel's engine room.

Comparing the two energy storage equipment, batteries have been ranked higher than fuel cells due to flexibility and ease of rechargeability, as well as the available historic data.

Regarding the magnetic propulsion technologies, hydromagnetic propulsion is considered non-viable, due to the enormous power needs of such a system for commercial vessels, in conjunction with the limited data available of such technologies. Magnetic shaft generators on

the other hand, are a quite recent, though very promising technology, with several actual installations on ships.

Further installation operational complications and limitations are also included in the study and will be specifically analyzed for each selected component within the next chapter.

3.3 Scenario Based Environmental Analysis Methodology

The calculation of corresponding total emissions in CO₂ equivalent includes the Global Warming Potential (GWP) factor for Carbon Dioxide (CO₂), Nitrous Oxide (N₂O) and Methane (CH₄) emitted from vessel's VLSFO and LSMGO burning, in alignment with the Fifth Assessment Report - AR5 guideline of the Intergovernmental Panel on Climate Change (IPCC, 2014). The corresponding EUAs for each leg accounted at 50% for the whole EU-US-EU voyage, while port time accounted at 100% for EU ports and 0% for US ports.

The calculation of emissions in CO₂ equivalent will be according to *Equation 1*:

Total Emissions in Co2 Equivalent mt =

VLSFO cons mt x [(VLSFO CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂O CO₂ eq. factor) +

LSMGO cons mt x [(LSMGO CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂O CO₂ eq. factor)

Equation 1. Total Emissions in CO₂ equivalent

The reduction of daily consumption and emissions according to the various combinations of renewable energy technologies will be calculated basis the reduced daily generated power output from main engines and diesel generators respectively.

The reduced daily consumption will be calculated through *Equations 2* and *3*:

Main Engine Daily reduced consumption =

Initial ME Fuel Consumption mt X

[(Initial Daily ME Power Output – Ren. Energy Thrust) kwh / Initial Daily ME Power Output kwh]

Equation 2. Main Engine Daily reduced consumption

Diesel Generators Daily reduced consumption =

Initial DGs Fuel Consumption mt **X**

[(Initial Daily Aux. Power Output – Ren. Aux. Power) kwh / Initial Daily Aux. Power Output kwh]

Equation 3. Diesel Generators Daily reduced consumption

The reduced emissions will be then calculated by reapplying Equation 1 to the outcome of Equation 2 and 3. The total exploitable daily thrust or auxiliary power from renewable energy sources will be calculated according to the sum of each scenario's applicable technologies' total daily power output.

3.4 Scenario Based Economic Analysis Methodology

Ultimately, different installation scenarios of the concepts' elements will be explored, calculating the possible return on investment period (ROI). The ROI will be conducted by comparing the total costs of investment and maintenance of the systems with total fuel and emission costs savings, under the specific route. The study concludes by identifying the optimum combination and use of the compared technologies, with the minimum return on investment ROI period for the parties involved.

In order to compare the different cost and emissions' savings the daily consumption and subsequently reduced consumption will be multiplied with the number of total operating days. For ease of calculations and comparison, primarily, the total operating days under different consumption modes will be calculated within a defined Trading Route Cycle (TRC) period, prior vessel's initial loading till return at the same point.

The TRC duration will be calculated by ***Equation 4:***

Trade Route Cycle days =

Open Sea Sailing Days + ECAs Sailing Days + Port/ECA Maneuvering Days + Port Idle Days+
Port Ballasting/Deballasting Days

Equation 4. Trade Route Cycle

Thereafter, equation 4 outcome can be converted to years by dividing it with 365. Each specific period in years can be then divided with this figure thus providing the total number of TRCs per period or through **Equation 5**:

TRCs per period =

Period in years X 365 / Trade Route Cycle days

Equation 5. Trade Route Cycles per period

For calculating the total consumption and corresponding emissions per TRC, at first the daily consumption of each different leg⁶ is multiplied by each leg's duration, while then summing the respective consumption through **Equation 6**:

Total Consumption per TRC mt =

(Open Sea Sailing Days X Open Sea Sailing Cons. mt) + (ECAs Sailing Days X ECAs Sailing Cons. mt) + (Port/ECA Maneuvering Days X Port/ECA Maneuvering Cons. mt) + (Port Idle Days X Port Idle Cons. mt) + (Port Ballasting/Deballasting Days X Port Ballasting/Deballasting Cons. mt)

Equation 6. Total Consumption per Trade Route Cycle

Thereafter each leg's and total emissions per TRC are calculated by reapplying Equation 1.

The fuel savings and emissions' reduction daily or per TRC in mt are simply calculated by deducting the reduced consumption and emissions from the initial ones through **Equations 7 and 8**:

Total Fuel Savings per Day or TRC mt =

Total Initial Consumption mt - Total Reduced Consumption mt

Equation 7. Total Fuel Savings

⁶ Leg is a specific segment of a vessel's route.

Total Emissions' reduction per Day or TRC in Co2 Equivalent mt =

Total Initial Emissions in Co2 Equivalent mt

- Total Reduced Emissions in Co2 Equivalent mt

Equation 8. Total Emissions' reduction

In order to calculate the economic benefit and possible ROI of each scenario, initially the total savings per TRC or period are calculated as described below:

Variation XX TRC Benefit Euro per TRC or period =

(Total Fuel Savings mt X Fuel Price €) +

(Total Emissions' reduction in Co2 Equivalent mt X EUA Price €)

Equation 9. Technologies' Economic Benefit

Variation XX OPEX Euro per TRC or period =

[Variation XX total maintenance costs € X TRC or period duration(in years)]

+ additional OPEX costs per TRC or period €

Equation 10. Technologies' OPEX per Trade Route Cycle

Variation XX ROI period =
$$\frac{\text{Variation XX CAPEX X TRC duration (in years)}}{(\text{Variation XX TRC Benefit} - \text{Variation XX TRC OPEX})}$$

Equation 11. Technologies Return Of Investment period

Inflation, Net Present Value, fuel or components cost variations will not be included in the calculations of return of investment period, due to the high volatility and unpredictability of fuel prices.

Chapter 4 – Joint Technologies Concept Application and Technical Study on a Kamsarmax bulk carrier

4.1 Chapter 4 Introduction

In this chapter, the previously selected components will be demonstrated, along with different deployment options on board a 80,000 DWT Kamsarmax Bulk carrier. The combination of solar panels installed on hatch covers, Helical Savonius VAWTs on deck, noise and sound energy converters in engine room will be the possible energy harvesting sources in conjunction with a magnetic PTI/PTO shaft generator, thus supplying auxiliaries and providing thrust power. A centralized EMS installation option will also be reviewed.

A brief technical study on the installation requirements, independently for each component, will be presented, assuming no spatial or interconnectivity obstructions among the different elements, even if they were installed simultaneously. All systems' interconnection study and costs are assumed incorporated into the EMS technical study. Each energy harvesting element will be initially reviewed considering its maximum installation capabilities according to vessel's specifications, with lesser capacity options being also illustrated.

Subsequently, the auxiliary and propulsion power demands of the specific Kamsarmax vessel will be reviewed. A model simulation and deployment illustration of the VAWT technology is also demonstrated due to the limited relevant research and accessible data of this specific type of renewable energy systems on board vessels.

4.2 Solar Panels

For the solar panels' option, data from Di Piazza et al. (2025) case study will be used and demonstrated, as it had been based on a similar size Panamax bulk carrier. The configuration of 150W Flexible SP44 Solbian Maxeon Flexible Solar Panels (Solbian, 2026) installation exclusively on hatch covers has been selected for this specific study. Basis on the available data the final number of panels and hatch covers to be utilized will be explored in cost benefit analysis. The hatch covers' PV coverage area in open position is shown in below figure. For this study's specific case vessel, hatch covers' exploitable area is slightly expanded (1503 m² instead of 1486 m²) in comparison to Di Piazza's selected vessel, same number of maximum theoretical PV panels' coverage to be used.

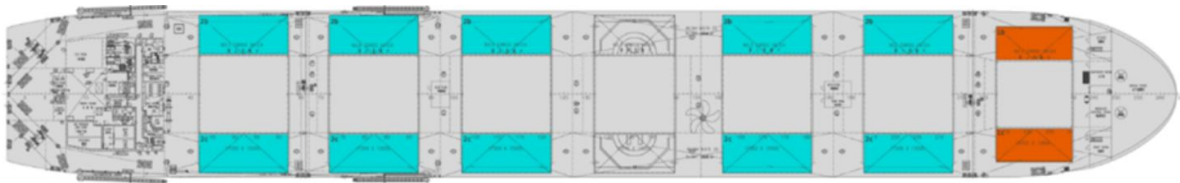
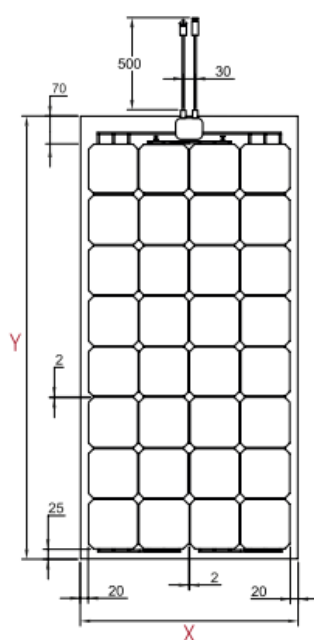


Figure 20. Photovoltaic panels installation on Panamax bulk carrier

(Source: Di Piazza et al., 2025)

By installing the maximum of 1746 panels with a 1405m² actual PV array area the generated peak power may reach 262 kW. As a secondary comparable option for this case study, a fifty percent exploitation of the available area will be utilized. This can be fully accommodated by 3 middle hatch covers (i.e. No 2, 3 and 5). Proportionally, the 873 installed panels should provide 131 kW of generated peak power.

For the purpose of this study a simulated 8 hour power production window at peak power per day has been calculated. Installation of panels' support bases on hatch covers, additional cabling as well as certification and class approval costs have been simulated and included in installation costs. The capability of removing the PVs in considered vital for maintenance purposes.



SOLBIANFLEX SP

SP Series **maxeon** inside

Maxeon cells used in SP series panels are high efficiency monocrystalline cells (the highest available on the market). The electric contacts create a thick pattern resembling two interpenetrating combs on the rear of the cell, this guarantees an optimal management of micro fractures, without power loss.

Back-contact cells are also the best choice when it comes to efficiency in low light and sensitivity at higher temperatures. In fact the temperature coefficient is 25% lower than the other crystalline cells.

MAXEON cell



No grid lines on the front of the cell means no obstacles to the absorption of sunlight.

Maximum efficiency and great aesthetics.



Solid copper backing.

Massive strength and resistance to corrosion.

Maximum power [W]	150
Length Y [mm]	1490
Width X [mm]	546
Thickness [mm]	2
Weight [kg]	2,0
Max power Voltage Vmp [V]	26,8
Max power Current Imp [A]	5,6
Open circuit voltage Voc [V]	32,0
Short circuit current Isc [A]	6,0
NOCT [°C]	45 ± 2
Operating temperature [°C]	-40/+85
Temp. coeff. Pmax [%/°C]	-0.35
Temp. coeff. Voc [%/°C]	-0.28
Temp. coeff. Isc [%/°C]	0.05
Columns x Rows (cells n°)	4x11 (44)
Maximum system voltage [V]	1000 V
Maximum reverse current [A]	12 A
Safety class	A

Figure 21. SP44 Solbian Maxeon Flexible Solar Panels Data Sheet (Source: Solbian, 2026)

The simulated costs and capacity are summarized in below table. The calculated power production is basis 8 hour continuous peak power operation for both options.

Table 2. PV Panels' Power and Costs (Author, 2026)

Option	Units Deployed	Total Units Purchase & Installation Cost (Euro)	Total Annual Maintenance Cost (Euro)	Total Estimated Power Output (KWh/day)	Estimated Added Weight (mt)
<i>Option A Full Hatch Coverage</i>	1746	1,796,000 €	18,210 €	2095	3.85 MT
<i>Option B 50% Hatch Coverage</i>	873	908,000 €	9,105 €	1047	1.92 MT

A single unit's purchase cost is calculated at 1,000 € (Solbian, 2026). The additional installation costs, which include class approval and documentation costs, at 50,000€ and 35,000€ for options A and B respectively. The estimated additional weight includes a 10% estimated increased weight of installation and is simulated at 3.85 tons and 1.92 respectively. Each unit's average annual maintenance costs is simulated at 10€ per panel with an additional annual sum of 750€ for option's A hatches panels' support maintenance and 375€ for option B.

Assuming that actual purchase, installation and maintenance costs may differ from the estimated ones, according to the exact retrofit drydock location and period, as well as the varying class approval, documentation and market's fluctuational costs. Actual costs' estimation have been simulated for academic purposes only.

The estimated total average power output may differ from the actual ones due to varying environmental conditions and possible power losses as a result of installation, maintenance and other operational causes.

The installation and maintenance of the panels while installed on board a bulk carrier needs to be further studied, as there are limited cases and available maritime data. There may be interference with hatch covers' steel maintenance or other operational restrictions, when in example, the covers are open during port operation. Protection covers may need to be temporarily placed during loading and discharging in order to protect panels' surface.

4.3 Helical Savonius VAWTs

The Helical Savonius VAWT has been chosen among the other wind assisted propulsion and energy exploitation systems due to its advantage of theoretically possible unceasing operation, as well as its relatively compact size and durability (Al-Rawajfeh and Gomaa, 2023). An onboard VAWT may efficiently operate both at idle port and sea sailing conditions with almost 360 degrees wind coverage. Additionally, the power generation system can be easily integrated and combined with other power systems on vessel's power grid.

For the purpose of the study, the Oy Windside Production's WS-12 Helical Savonius VAWT has been selected (Oy Windside Production, 2026). The vertical wind turbine, with 25KW maximum output, has been claimed to be able to produce up to 12 MWh of power output per year according to the location and average winds. In this study the total average rated output of a single unit will be simulated at 12 MWh per year and 32.8 KW per day with continuous operation. The 6 tons weight, 8 meters height wind turbine system is built from composite reinforced fiberglass, marine-grade aluminum generator casings and stainless-steel hardware which can render it operational under harsh environments with a rated constant winds endurance of 40 m/s and 60 m/s gusts. The system produces 3-phase AC via direct drive permanent magnet generators, which is then rectified to 12-48V DC for charging of battery banks or directly connected to grid. The technical data and a similar product's installation are shown in figure 17.

Onboard installation prerequisites a robust superstructure and protected cabling according to each specific deployment, taking also into consideration the total weight and deck's strength. In this study's Bulk carrier case two possible configurations of 3 and 6 WS-12 VAWTs will be explored. The initial deployment of the VAWTs, will be determined according to the available deck spaces, while always allowing at least 1m breadth safe walkway passage without obstructing emergency exits. The optimum location and height deployment of VAWTs is to be determined by a Computational Fluid Dynamics (CFD) aerodynamic analysis, however without restricting vessel's loading and discharging capabilities or navigational visibility from bridge level. In this study and for illustrational purposes only, Simflow's CFD software (Sim-Flow, 2026) has been used for optimizing the 6 VAWT's aerodynamic deployment option through a CFD simulation. Finally, the most cost efficient option of installed VAWTs is determined by the economic analysis in Chapter 6.

WINDSIDE

WS-12 dimensions and technical info

Windside WS-12 technical info:

- Weight: ~4600 kg (approx).
- Swept area: 12 m²
- Generator: customised
- Wind load, side force to the middle point of the vane, Calculated 3,3 m up from the generator: 3000 kg
- Max 400 rpm
- Guaranteed at constant wind speed of 40 m/s
- Guaranteed at wind gusts of 60 m/s

Power production:

- 6-12MWh per year depending on location

Materials:

- Vanes: Aluminium
- Shaft: Steel
- Generator and Generator end plates: hot dip galvanized steel
- All bolts stainless steel or hot dip galvanized (A4, A2, Zn)

Assets of Windside wind turbines

- No need to stop or secure during storms
- Produces max. amount of energy in storms
- No need to be turned to the wind direction
- Soundless; 0 dB, measured in 2 meters distance from the vane
- Stands snow, frost, heat and humidity
- Long lifespan
- Minimum need of maintenance, only lubrication
- Safe to people, animals and nature

Requirements:

- The turbine requires a chassis frame or a mast that the upper bearing can be attached to.

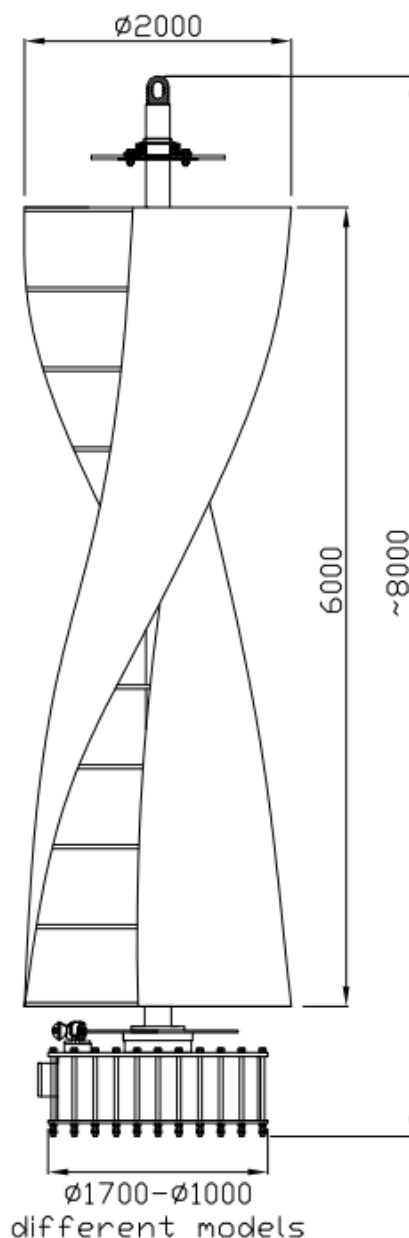
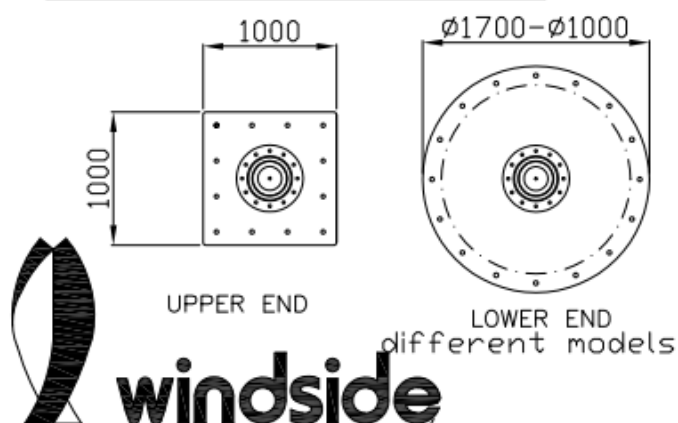


Figure 22. Windside Wind Turbine Technical data sheet (Source: Oy Windside Production, 2026)

The first deployment option, with 6 VAWTS, is targeting to create an aerodynamic draft on the vessel, thus simultaneously minimizing the wind resistance on vessel's accommodation and also harvesting wind power. For this option, VAWTS' masts will not be considered collapsible. The deployment height of each VAWT should not obstruct bridge view or decrease vessel's visibility range.

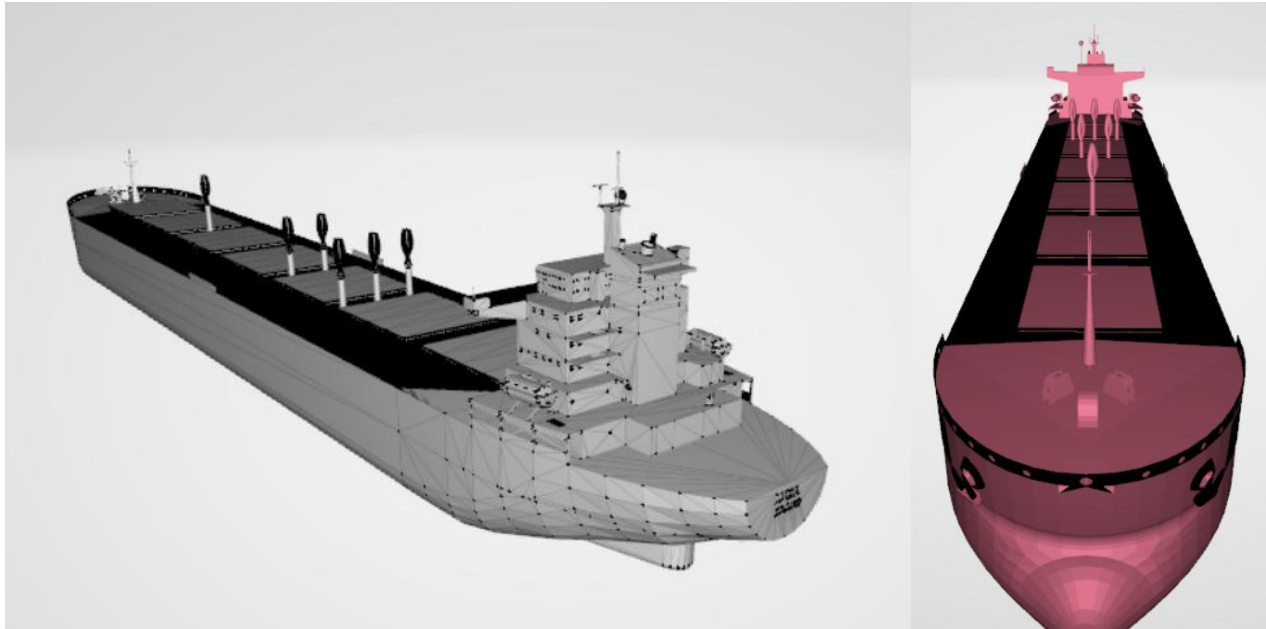


Figure 23. VAWTs possible aerodynamic deployment on Bulk carrier case (Author, 2026)

The experimental CFD analysis was run at 18 knots constant head wind by using the illustrated model, a similar size Panamax model. The VAWTs' models have been reconstructed using Windside's WS-12 dimensions. The vessel's 3D model has been simplified, maintaining only major equipment and superstructure on deck and hull, which could significantly affect airflow, thus optimizing software's computation time. The comparison of pressure and airflow's velocity results between the CFD simulations of the initial and the 6 VAWTs bulk carrier model, as illustrated in Figures 24 and 25, indeed indicate a beneficial aerodynamic effect. The detailed CFD process and simulation's data are included in Appendix 1. Nonetheless, a thorough, professional CFD analysis, using vessel's specific and VAWTs' data should be carried out prior an actual onboard application.

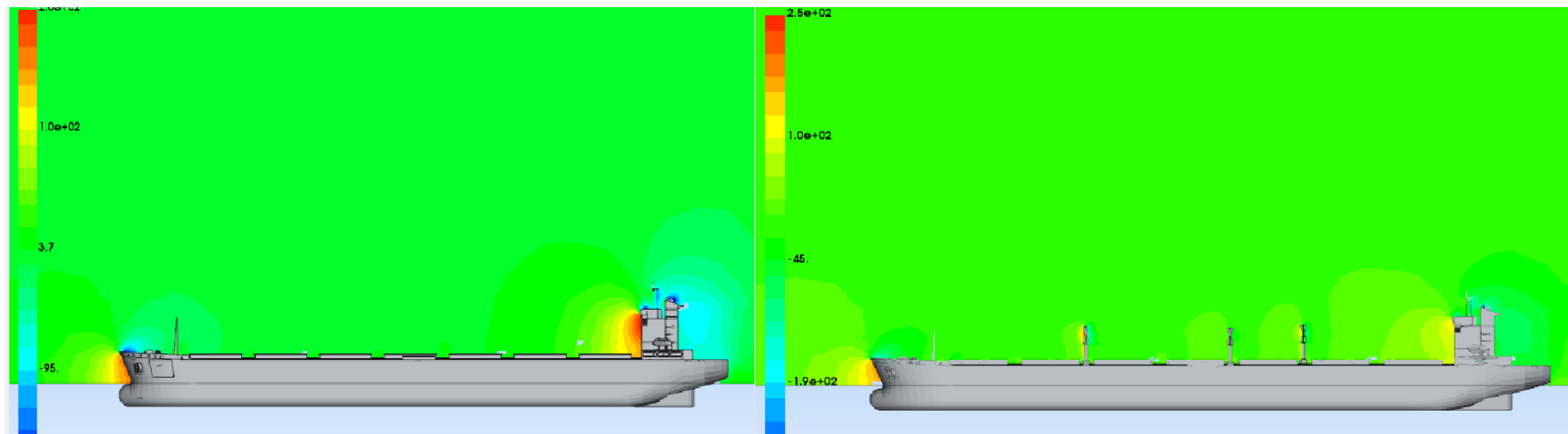
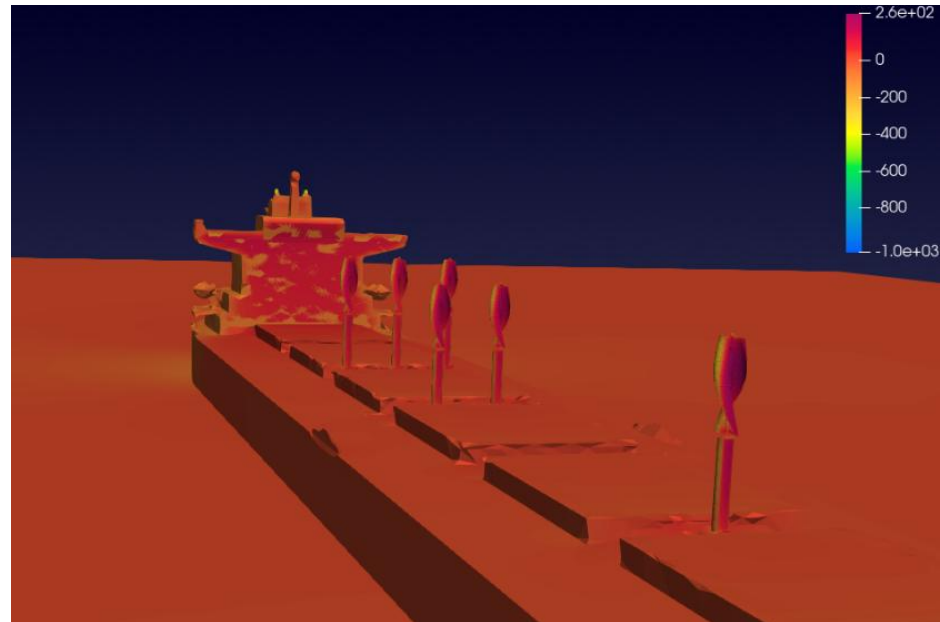


Figure 24. Computational Fluid Dynamics pressure results' comparison on Vertical Axis Wind Turbines' aerodynamic deployment (Author, 2026)

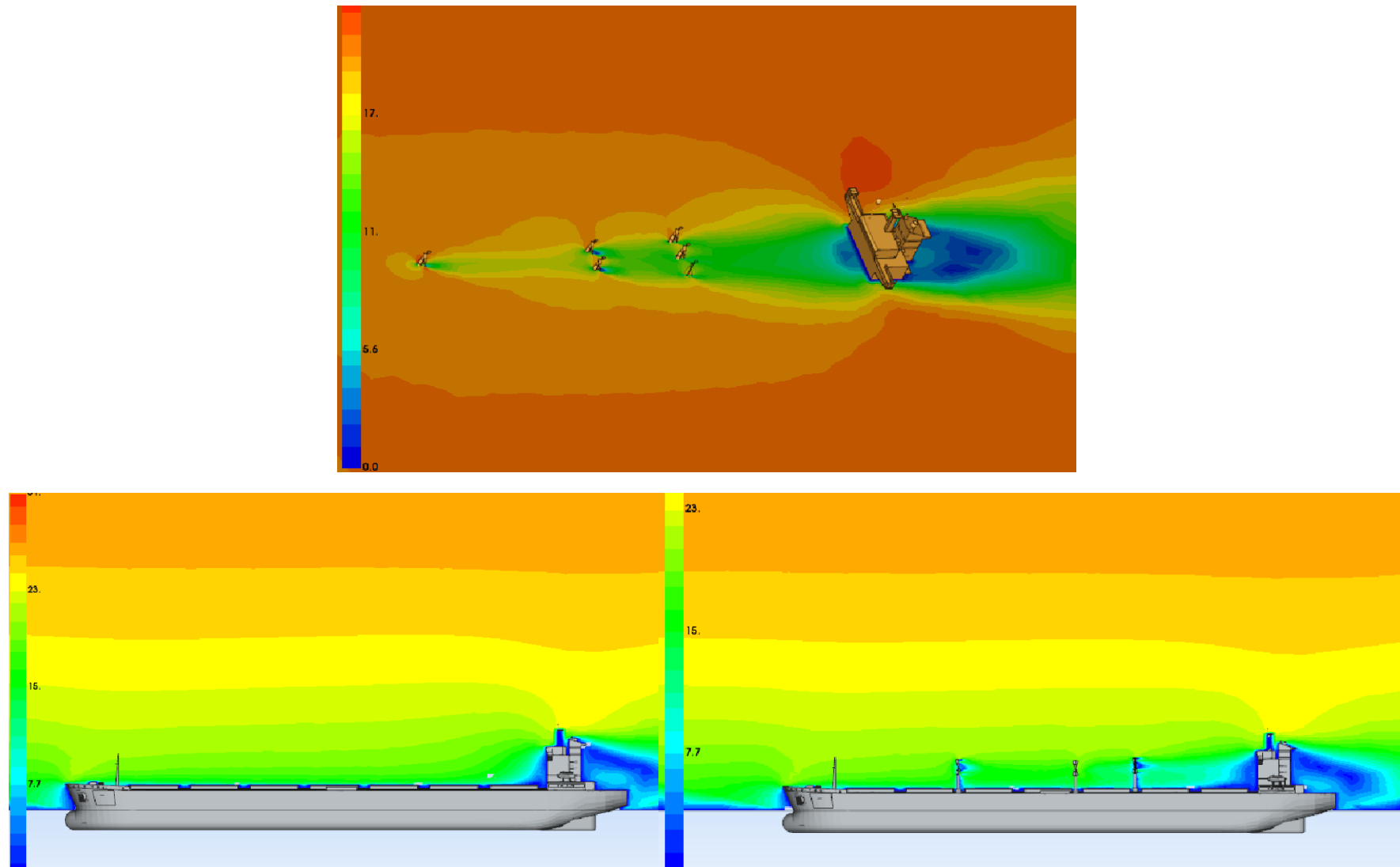


Figure 25. Computational Fluid Dynamics airflow velocity results' comparison on Vertical Axis Wind Turbines' aerodynamic deployment (Author, 2026)

The second option considers deployment of three single VAWTs between hatches on vessel's center line. This arrangement shall restrict bridge view similarly to cargo cranes installed on similar bulk carriers. The optimum deployment height should also be determined by an aerodynamic CFD analysis.

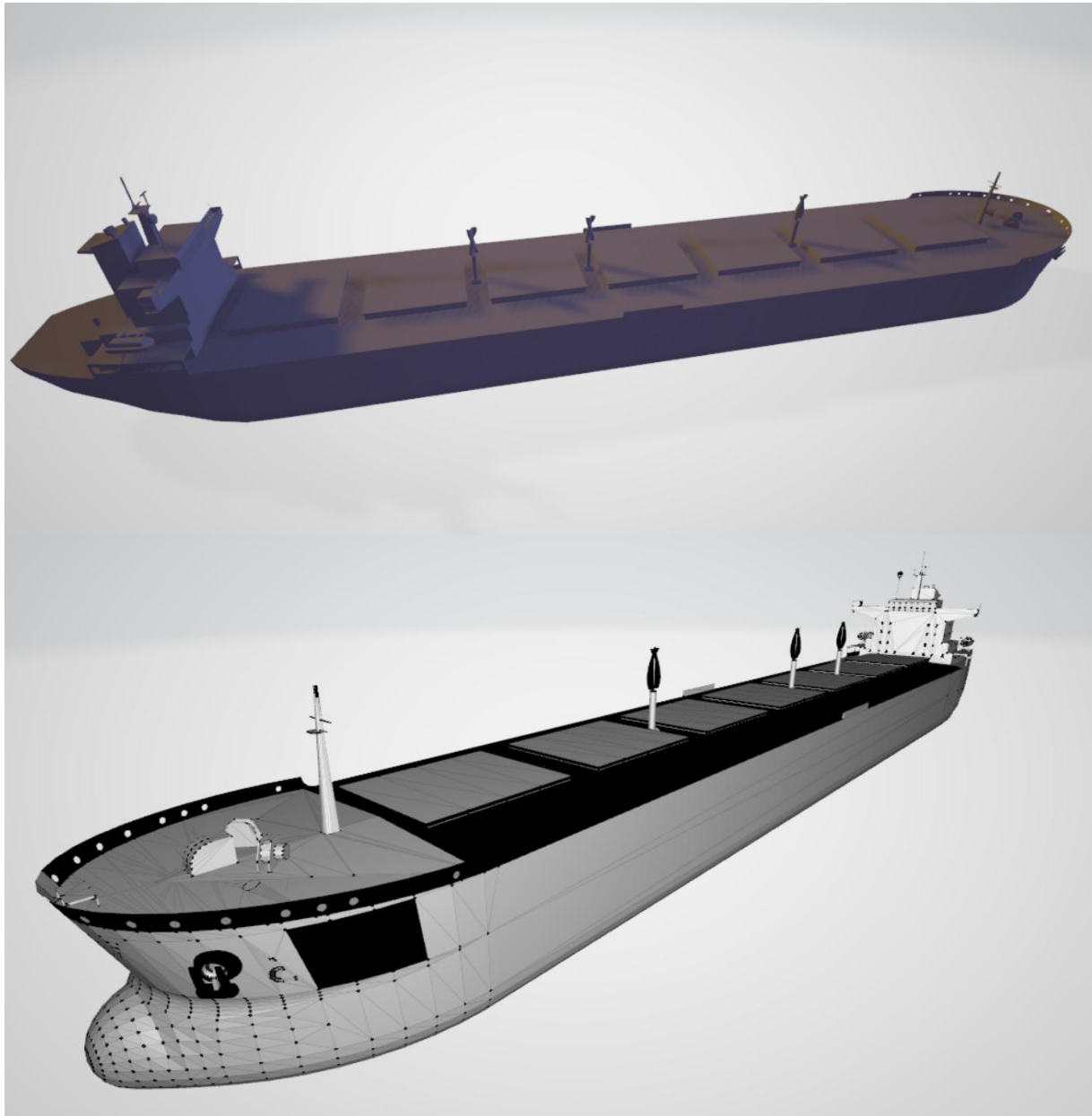


Figure 26. VAWTs possible centered deployment on Bulk carrier case (Author, 2026)

Both options are solely utilizing the available space between hatches and prerequisite deck reinforcements at a drydock. The deployment of VAWTs must neither interfere with other vessel's equipment such as the hatch cover openings, mooring lines and winches, nor obstruct safety walkways and emergency exit routes on deck, even when VAWTs are collapsible.

Following this requirement, for the collapsible VAWTs option, a fixed total deployment height of 13m has been utilized for illustration purposes. A possible height extension hydraulic system can be considered for achieving deployment at optimum height. Regarding cost, a hydraulic folding and securing system is simulated.

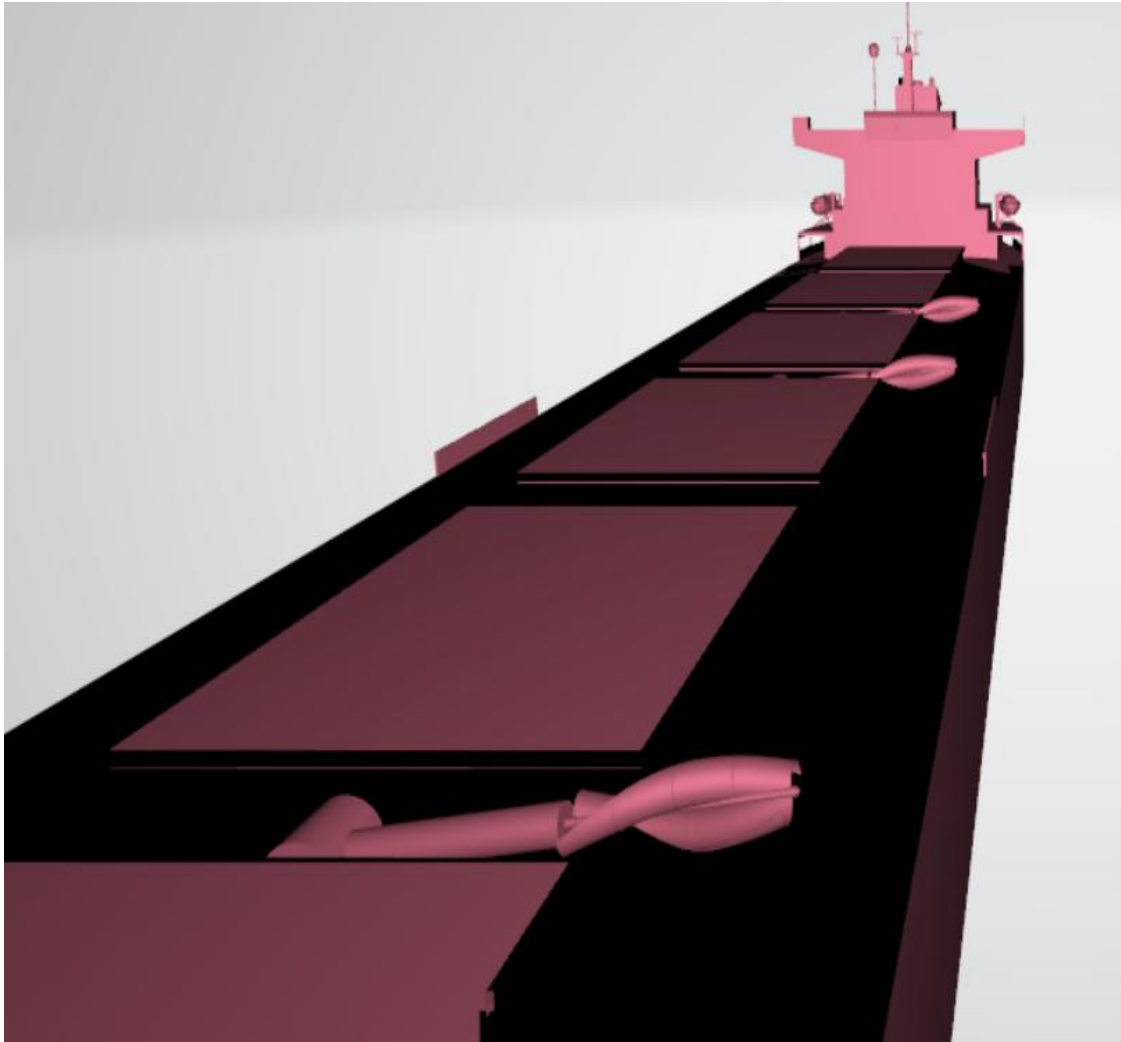


Figure 27. VAWTs possible centered(Collapsed) deployment on Bulk carrier case (Author, 2026)

The relevant options' simulated costs and capacity are summarized in Table 3. The calculated power production is basis 24 hour continuous operation for both options.

Table 3. Helical VAWTs' Power and Costs (Author, 2026)

Option	<i>Units Deplo yed</i>	<i>Total Units Purchase & Installation Cost (Euro)</i>	<i>Unit's Annual Maintenance Cost (Euro)</i>	<i>Total Estimated Power Production (KWh/day)</i>	<u>Estimated Added Weight (mt)</u>
<i>Option A VAWTs</i>	6	1,200,000 €	750 €	196.8	45
<i>Option B VAWTs (collapsible)</i>	3	675,000 €	3000 €	98.4	24

A single unit's purchase cost is simulated at 75,000 €. The additional installation costs, which include class approval and documentation costs, stand at 125,000€ per unit for the non-collapsible type and at 150,000€ for the collapsible one, while the estimated additional weight at 7.5 tons and 8 respectively. Each unit's average annual maintenance costs are simulated at 750€ for option A and 3000€ for option B.

Assuming that actual purchase, installation and maintenance costs may differ from the estimated ones, according to the exact retrofit drydock location and period, as well as the varying class approval, documentation and market's fluctuational costs. Actual costs' estimation has been requested from various industry's makers, however due to either non reply or commercially undisclosable information the relevant costs have been simulated for academic purposes only.

The estimated total average power output may differ from the actual ones due to varying weather conditions and possible power losses due to installation, maintenance and other operational causes. Due to lack of available economic data of the selected VAWT costs have been simulated based on data from a comparison study on wind turbines by Rosato et al. (2024).

The exact deck reinforcements' need and weight-force analysis on deck or supporting masts have not been calculated or included in this study.

The first deployment option will be encountering port operational delays due to non-collapsible masts and loading belt repositioning time. Same will be calculated by approximation and will be included in the cost benefit analysis as additional OPEX. The second deployment option will include increased installation CAPEX due to the folding system. The illustrated folding system is only a preliminary visual demonstration of the main pillar. A more detailed and thorough study should be conducted for the optimum folding system (i.e. hydraulic), maximum deployment height and securing points, according to each applicable case.

4.4 Piezo/Electromagnetic-based acoustic energy harvesters

From the various possible technologies of resonator based sound energy harvesters, which are summarized in below table in Figure 24, only the piezo/electromagnetic-based acoustic energy harvester by Khan and Izhar (2013) will be analyzed and considered viable for an on board application, due to its adequate Power Output to device size Ratio and voltage.

Type	Brief summary	Device size (cm ³)	SPL (dB)	Load resistance (Ω)	Resonant frequency (Hz)	Voltage (V)	Power output (μW)
Piezoelectric	A MEMS piezoelectric sound energy harvester	2.445	149	982.9	13,568	–	6×10^{-6}
	Sound energy harvester using PZT piezoelectric beam array in a quarter-wavelength resonator	840	110	19,371	199	15.689	12,697
	Sound energy harvester using PVDF piezoelectric beam array in a quarter-wavelength resonator	1500	110	1×10^6	146	1.48	2.2
	A broadband sound energy harvester using dual PZT piezoelectric beams located on the top of Helmholtz resonator	3972.22	100	38,000	170–206	–	137–1430
	Taped neck Helmholtz resonator based sound energy harvester with a flexible triangular foil	2477.78	103	–	99	0.842	–
	3 DOF sound energy harvester using a Helmholtz resonator and a piezoelectric plate with a circular block and a cantilever beam	13.12	130	1000	1453–1542, 1710–1780, 1848–1915	0.461	214.23
	Sound energy harvester using a helix structure	251	100	11,000	175	0.283	7.3
	Sound energy harvester based on a spiral Helmholtz resonator	200	100	10,000 6000	217 (acoustic resonance) 341 (mechanical resonance)	0.522 0.622	27.2 64.4
Electromagnetic	Electromagnetic based sound energy harvester	14.728	125	52	143	0.319	1960
	Micro-scale electromagnetic sound energy harvester	0.009	–	–	470	0.24×10^{-3}	–
	Electromagnetic sound energy harvester with a cone shaped cavity	43.1	100	147	330.3	0.182	212
Triboelectric	Triboelectric sound energy harvester by utilizing a Helmholtz resonator	570	110	6×10^6	240	47.5	376

Figure 28. Summary of resonator-based sound energy harvesters (Source: Choi et al., 2019)

The device uses a Helmholtz resonator with piezoelectric material as transducing element and can produce power of maximum 1.96 mW at 125 dB of 143Hz sound. An acoustic study of a merchant vessel's engine room by Vulliez et al. (2026), indicated most dominant noise frequencies at

the lower spectrum of frequencies, especially between 150 to 180 Hz. A visual illustration of the prototype device, as well as the trend of load voltage of a $52\ \Omega$ resistance as a function of frequency, at various Sound pressure levels are shown in below figures.

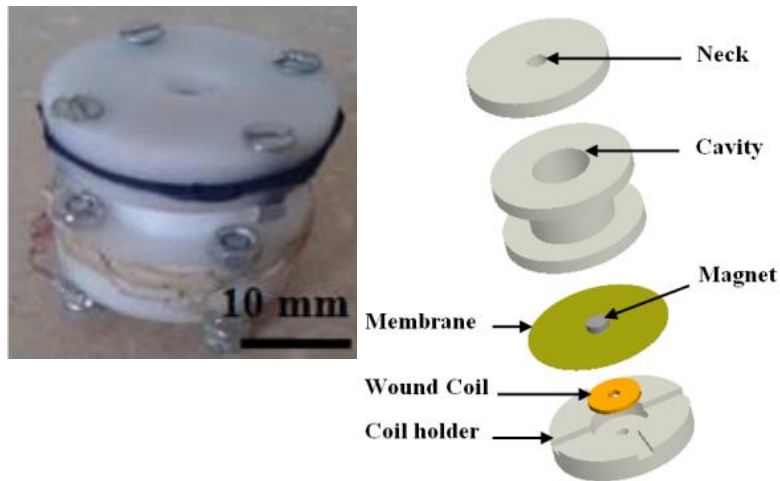


Figure 29. Actual and Exploded view of the acoustic energy harvester device

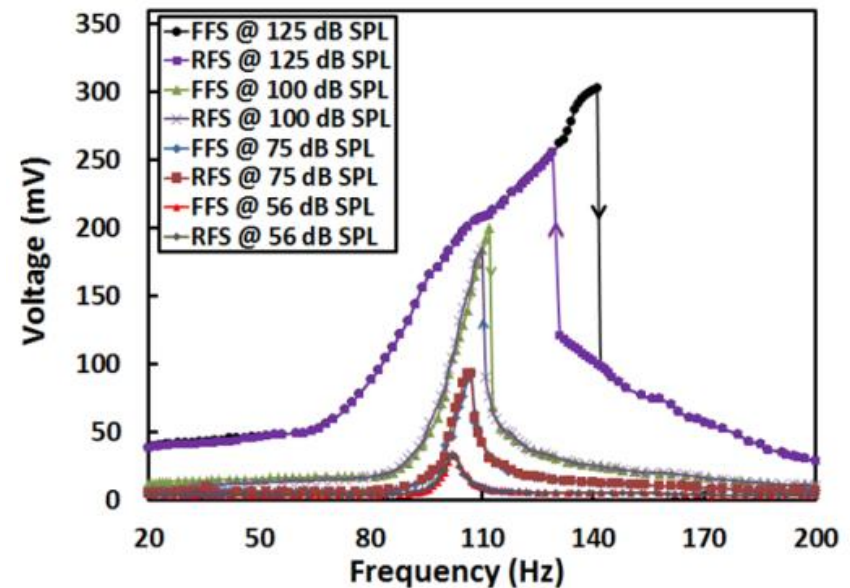


Figure 30. Load voltage of frequency at various Sound Pressure Levels

Considering single's device size at 30mm x 25mm of space needed for a single device 6 panels of 100 devices each will be considered deployable around engine room area for sound harvesting. Each panel's size is simulated with 4,500mm height and 4000mm width.

Four panels could be installed on the lower engine platform and two on the upper platform. A draft visual possible deployment of the panels around the engine room place is demonstrated in the following drawings:

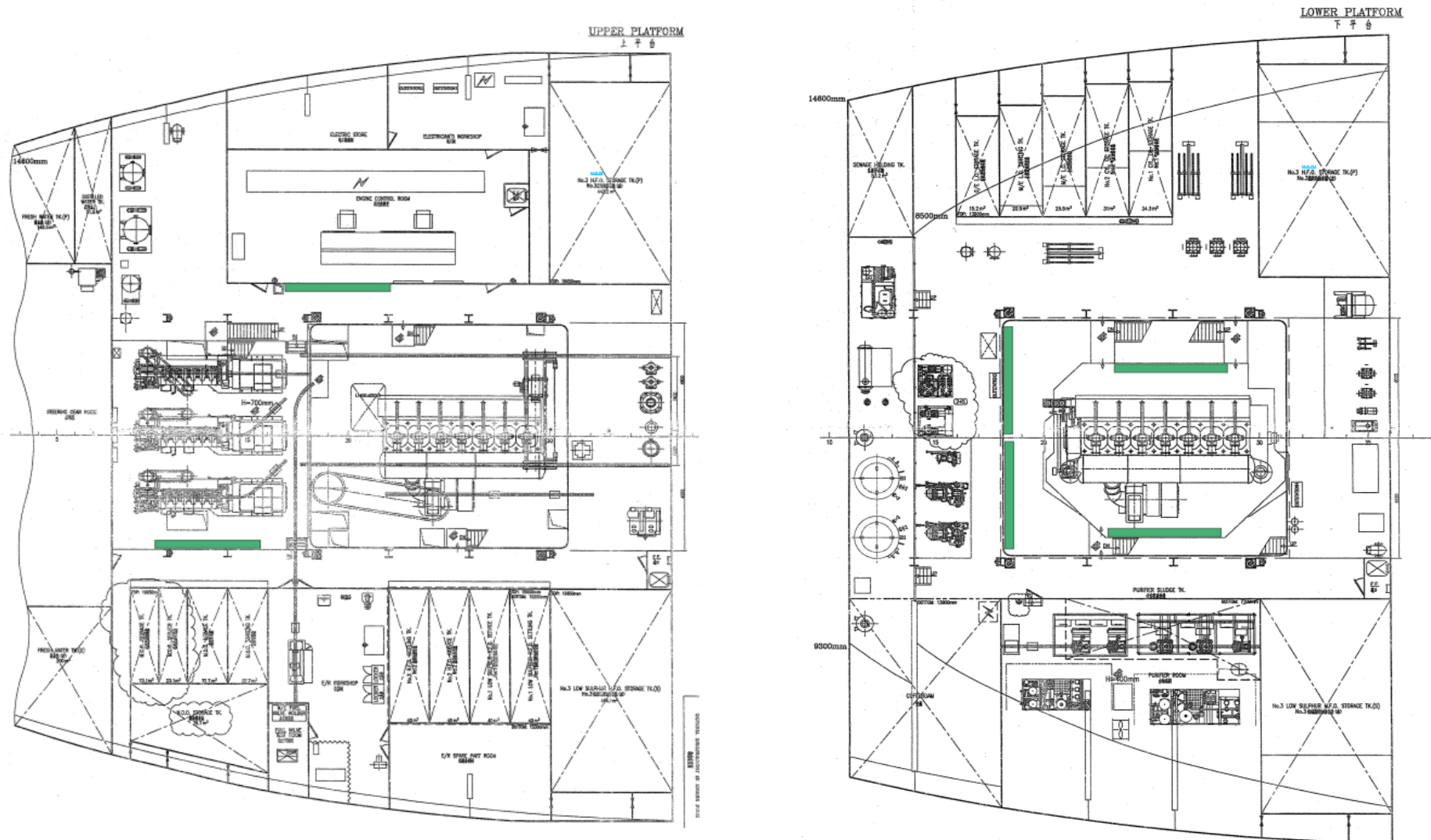


Figure 31. Visual deployment of Piezo Acoustic Harvesting Panels in Engine Room

The relevant options' simulated costs and capacity are summarized in below table. The calculated power production is basis 24 hours continuous peak power operation.

Table 4. Piezo Acoustic Panels' Power and Costs (Author, 2026)

Option	Units Deployed	Total Units Purchase & Installation Cost (Euro)	Total Annual Maintenance Cost (Euro)	Total Estimated Power Output (KWh/day)	Estimated Added Weight (mt)
<i>Option A 6 panels</i>	600	140,000 €	1,500 €	0.028	0.5 MT

A single unit's purchase cost is simulated at 200 € (Piezo, 2026). The additional installation costs, which include class approval and documentation costs at 20,000€. The estimated additional weight is simulated at 0.5 ton. Each unit's average annual maintenance costs is simulated at 250€ per panel.

Assuming that actual purchase, installation and maintenance costs may differ from the estimated ones, according to the exact retrofit drydock location and period, as well as the varying class approval, documentation and market's fluctuational costs. Actual costs' have been simulated for academic purposes only.

For the purpose of the study the total produced output will strictly reproduce and simulate the initial prototype's data at maximum power without considering power losses or dominant frequency variations. The estimated total average power output may differ from the actual ones due to varying acoustic conditions and possible power losses due to installation, maintenance and operational causes. A specific acoustic study would be needed for the optimum deployment of panels and resonators' tuning according to vessel's specific engine room space and dominant frequencies while vessel's engines are in operation.

Cabling towards DC converters and batteries through engine room, as well as panels' weight support will not be analyzed in this study.

4.5 Power Storage and Management

The harvested energy will be initially directly feeding the grid for auxiliaries' demands, while any accumulated excess will be stored through DC converters to battery packs for later use or towards the PTI shaft generator. Ideally, when the vessel is at open sea vessel's auxiliary power needs should be completely covered by renewable energy and the batteries.

The installable option for this study will be represented by the ABB's Flex-40-2070 energy storage system (ESS), which integrates all required components of a 2MW energy storage system, including firefighting systems, with 1,3 MW max power output, into a 40ft container (ABB, 2024). However, due to space availability and deck strength limitations the integrated components will be considered possibly deployable within two 20ft containers, similarly to the ABB's Flex 20-660 ESS option ESS. One 20ft Battery energy storage system (BESS) will be considered installed at AFT deck and one ESS on the starboard side of funnel, while any additional components such as EMS switchboard, necessary inverters and operation control station will be located inside an EMS room next to Engine control room as indicated in below drawings. Basis on the 20ft ESS container dimensions, an additional third possible deployable location has also been identified in between No5 and No6 cargo holds, despite the fact that same may interfere with VAWTs' deployment.

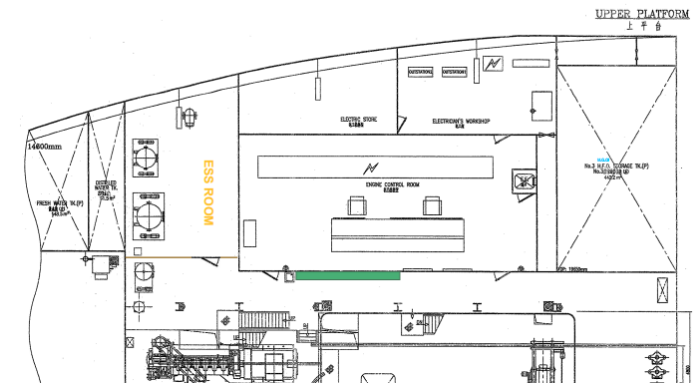
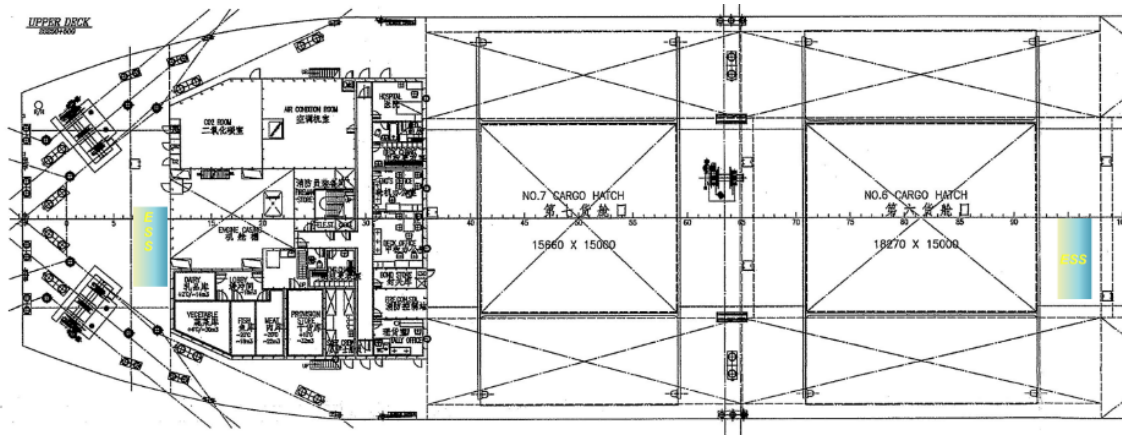
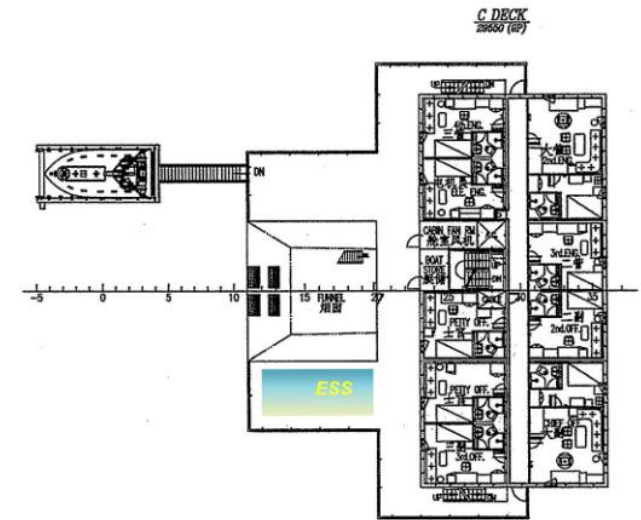
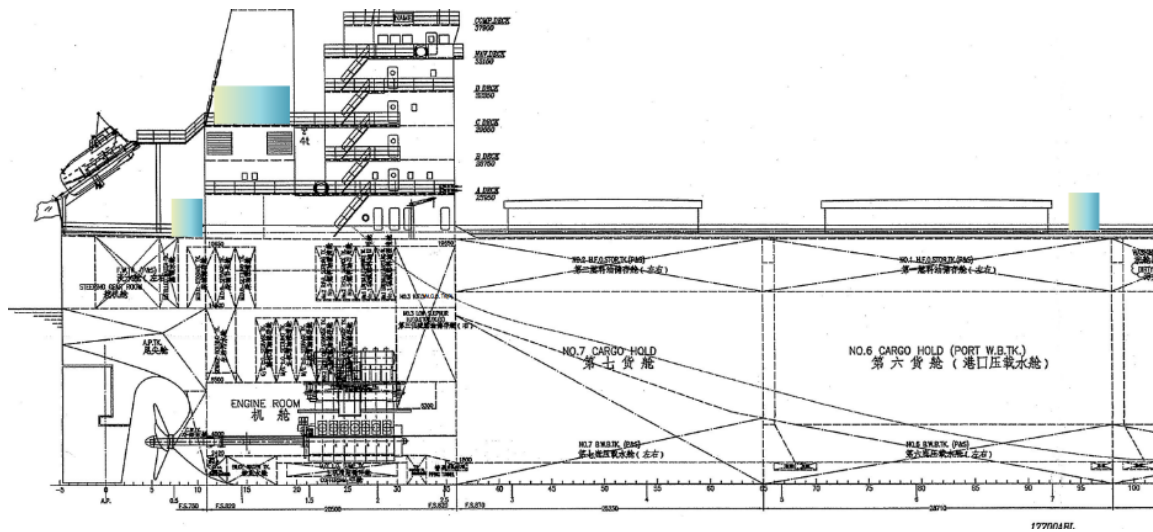


Figure 32. Possible deployment of ESS components (Author, 2026)

The relevant options' simulated costs and capacity are summarized in below table:

Table 5. Energy Storage System Capacity and Costs (Author, 2026)

Option	Units Deployed	Total Units Purchase & Installation Cost (Euro)	Total Annual Maintenance Cost (Euro)	Total Estimated Recharge Cycles	<u>Estimated Added Weight (mt)</u>
<i>Option A 2 MW ESS</i>	2	850,000 €	3,600 €	7000	47 MT
<i>Option B 1 MW ESS</i>	1	435,000 €	1,800 €	7000	24 MT

For the purpose of this study and ease of calculations, the average daily possible number of batteries' charge/discharge cycles will be initially simulated at four cycles per day. The four cycles scenario derives from the division of the batteries' lifespan with a routine five-year drydock interval schedule, due to the fact battery packs' exchange process can be considered both expensive and complex, while a vessel is under normal operational condition.

A single 1MW/1MWh ESS unit's purchase cost is simulated at 400,000 € (Author, 2026). The additional installation costs, which include class approval and documentation costs at 50,000€ for two units and 35,000€ for a single one. The estimated additional weight is simulated at a total of 47 tons considering 23 tons of each 20ft container plus additional installation equipment, cabling and reinforcements. Total ESS units' average annual maintenance costs has been simulated at 3,600€ and at 1,800€ or 0.43% of the initial capital cost (Viswanathan et al., 2022).

Assuming that actual purchase, installation and maintenance costs may differ from the estimated ones, according to the exact retrofit drydock location and period, as well as the varying class approval, documentation and market's fluctuational costs. Actual costs' estimation has been requested from various industry's makers, however due to either non reply or commercially undisclosable information the relevant costs have been simulated for academic purposes only.

Actual deployment and other installation limitations (i.e. maximum capacity) of ESS and BESS containers may differ from illustrated locations and would be identified during an actual

installation study by the maker. Cabling, interconnectivity of switchboards with BESSs and overall EMS software for power grid and batteries will not be analyzed in this study. Nevertheless, relevant simulated costs are included in the total purchase and installation costs. The establishment of interconnection and universal software costs between all other systems will also be considered included in ESS costs.

4.6 PTI/PTO Shaft Generator

The shaft generator option simulated in this study will be an asynchronous type, variable speed PTI/PTO 1MW permanent magnet shaft generator (ABB, 2026). The shaft generator shall be able to deliver 1000 KW propeller thrust in PTI mode, while in PTO mode the generated power output will be simulated at 920KW or 92% efficiency at the optimum MCR level (Everllence, n.d.).

While the vessel is at sea, with PTO mode engaged, the shaft generator can also be considered capable for both supplying the 230 KW daily auxiliary power demand and simultaneously charging the 2 MW batteries, without any assistance from the previously mentioned renewable energy technologies or the diesel generators. Once the 2MW batteries are charged, then the PTI mode can be then engaged. Considering the optimum usage of batteries the optimum charge/discharge cycle range will be simulated between 20 to 80% (Vasylyev et al., 2025) or 400 to 1600 KW, meaning 1200KW of usable power per discharge cycle. Each PTO/charging cycle will endure 1.74 hours, while each PTI/discharge cycle 0.97 hours respectively, without utilizing any other system (i.e. VAWTs), as calculated below:

$$\textbf{\textit{PTO\&Batteries Charge Cycle Time= 1200KW/ (920KW – 230KW)= 1.74 hours}}$$

$$\textbf{\textit{PTI\&Batteries Discharge Cycle Time= 1200KW/ (1000KW + 230KW)= 0.97 hours}}$$

Basis above calculated times, a total of either 4 or maximum 8 charge/discharge cycles per 24 hour will be simulated with remaining time being considered as idle/PTI-PTO modes' changeover time (i.e. 8'42"). The total exploitable power output per day is calculated as the sum of the hotel/auxiliaries' load during each PTO/batteries charge cycle plus the total power supply during each PTI/batteries discharge cycle.

4 cycle:

$$\text{Total Daily Thrust Output} = 4 \times 1000\text{KW} = 1000 \text{ KWh}$$

$$\text{Total Daily Auxiliary Power Output} = (4 + 4) \times 230\text{KW} = 1840 \text{ KWh}$$

$$\text{Total Daily Power Output} = 4 \times 230\text{KW} + 4 \times 1230\text{KW} = 5840 \text{ KWh}$$

8 cycle:

$$\text{Total Daily Thrust Output} = 8 \times 1000\text{KW} = 8000 \text{ KWh}$$

$$\text{Total Daily Auxiliary Power Output} = 16 \times 230\text{KW} = 3680 \text{ KWh}$$

$$\text{Total Daily Power Output} = 8 \times 230\text{KW} + 8 \times 1230\text{KW} = 11680 \text{ KWh}$$

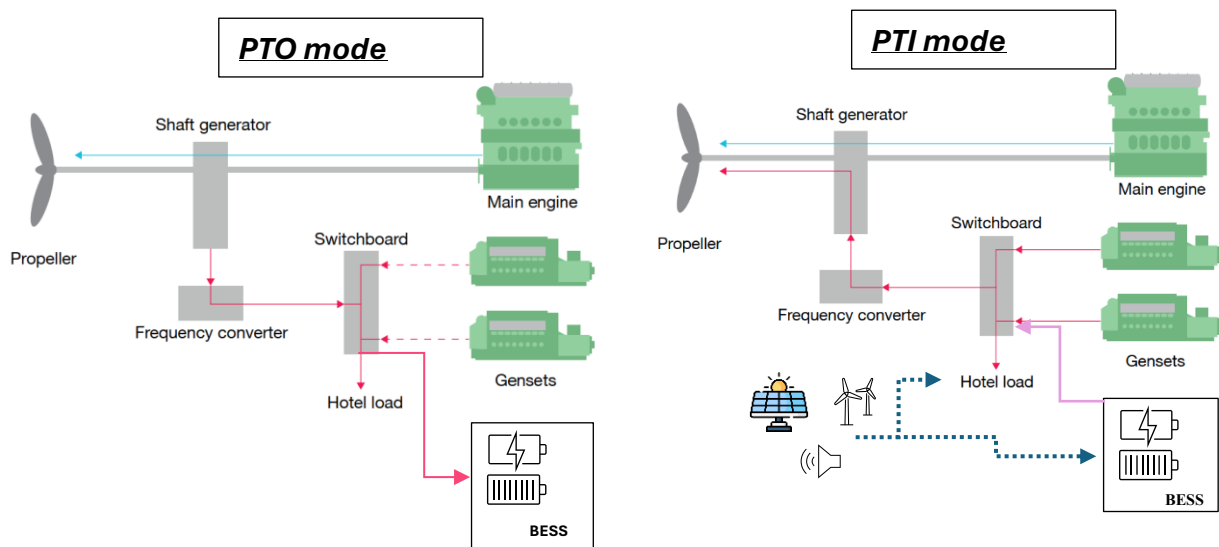


Figure 33. Schematic diagram of Power Take In/Power Take Out Shaft generator (Source: Everllence, 2026)

Relevant variations of cycles' times, according to each specific combination and joint operation of all renewable energy technologies, will be calculated and included in the case study and cost benefit analysis.

The simulated costs and capacity are summarized in below table:

Table 6. Power Take In/Power Take Out Shaft Generator Power and Costs (Author, 2026)

Option	<i>Total Units Purchase & Installation Cost (Euro)</i>	<i>Total Annual Maintenance Cost (Euro)</i>	<i>Total Estimated Power Output (KWh/day)</i>	<u>Daily running hours</u>	<u>Estimated Added Weight (mt)</u>
<i>PTI/PTO Shaft Generator</i>	4,000,000 €	7,500 €	11680	21.68	15 MT

Unit's purchase cost is simulated at 2,500,000 €. The additional installation costs, which include class approval and documentation costs at 1,500,000€. The estimated additional weight is simulated at 15 tons while the average annual maintenance cost has been simulated at 7,500€, which includes 5 year overhauling costs. The 4 cycles utilization mode's annual maintenance costs have been simulated at 4,000€.

Assuming that actual purchase, installation and maintenance costs may differ from the estimated ones, according to the exact retrofit drydock location and period, as well as the varying class approval, documentation and market's fluctuational costs. Actual costs' estimation has been requested from various industry's makers, however due to either non reply or commercially undisclosable information the relevant costs have been simulated for academic purposes only.

Actual deployment and other installation limitations are not included in the study and would be identified during an actual installation study by the maker. Sole operation of PTO mode, its relevant efficiency and cost benefit will not be included in this study. Possible thrust/speed loss from PTO mode operation will not be simulated. BESS systems will always be considered installed in this study. Operating limitations of system due to environmental and other factors will not be calculated in daily operation, however the total operating hours of the system will be simulated accordingly to the BESS system's hypothetical lifecycle.

4.7 Bulk Carrier Power Demands – Propulsion and Auxiliary Power Demands

For this study, the respective propulsion and auxiliary power demands of a **80,000 tons** DWT Kamsarmax bulk carrier will be reviewed. Thereafter, I will explore which percentage of that power would be efficient and profitable for shipowners while being covered by the previously mentioned renewable energy technologies.

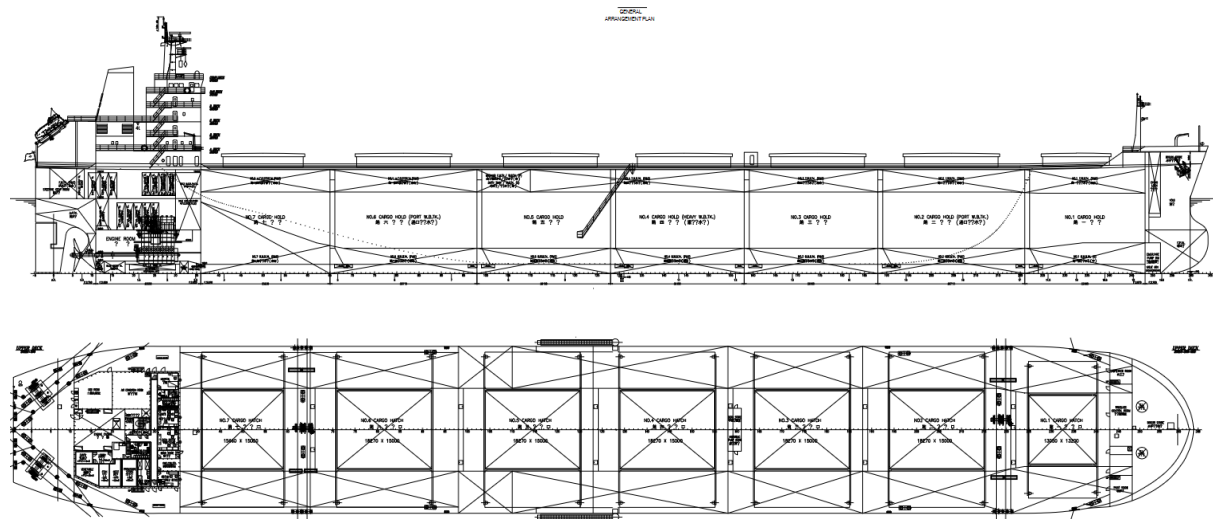


Figure 34. General Arrangement Plan of case study Panamax Bulk Carrier (Source: Author, 2026)

The case study vessel is using the WARTSILA - 7RT-FLEX50 of 11620KW rated power at 124 RPMs as main engine. The main engine propulsion consumption is 45.1 metric tons of FO per day at 85% load of MCR (Author, 2026). VLSFO of 42590 Kj/Kg LCV has been utilized during trial reports. The corresponding speeds at the 85% load are 15.8 knots during normal ballast condition and 14.0 knots while fully laden.

For auxiliary power, the vessel utilizes three ZHENJIANG CME - HFC6 504-14E Generators of 700KW power each. At 100% Load the corresponding LSMGO consumption is 3.6 mt per day. LSMGO of 42700 Kj/Kg LCV has been utilized during trial reports. At sea, vessel's auxiliaries require minimum 1.3 mt of VLSFO with an addition of 0.1 mt of LSMGO daily, while at port the additional consumption varies from 3.5 up to 5.0 mt of VLSFO/LSMGO per day, according to ballasting/deballasting operations. For this study all port operations will be considered with LSMGO compliance.

The total daily VLSFO and LSMGO consumption, as well as the produced thrust and auxiliary power output is illustrated in below table:

Table 7. 80,000 Kamsarmax Bulk Carrier Power Demands (Author, 2026)

	M/E daily consumption (mt VLSFO)	M/E Avg. Output (kWh)	DGs daily Consumption (mt VLSFO)	DGs daily Consumption (mt LSMGO)	DGs Avg. Load (kWh)	Total Consumption (mt VLSFO equivalent)	Total Avg. Power (kWh)
Ballast at 85% MCR	45.1	9877	1.3	0.1	227	46.5	10104
Laden at 85% MCR	45.1	9877	1.3	0.1	227	46.5	10104
Port Maneuvering at 50% MCR	26.5 ⁷	5810	-	3.5	680	30.0	6490
Idle at port	-	-	-	3.5	680	3.5	680
Ballasting/ Deballasting at port	-	-	-	5.0	972	5.0	972

⁷ Assumed LSMGO consumption only in port/ECA areas.

The sum of total daily emissions in CO2 equivalent is shown below:

Table 8. 80,000 Kamsarmax Bulk Carrier Daily Emissions (Author, 2026)

	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.
At Sea Outside ECAs	142.66	-	4.11	0.33	147.10
At Sea Inside ECAs	-	146.81	-	4.56	151.37
Port Maneuvering Inside ECAs	-	86.26	-	11.39	97.65
Idle at port (ECA)	-	-	-	11.39	11.39
Ballasting/ Deballasting at port ECA)	-	-	-	16.28	16.28

The detailed calculations are included in Appendix 2.

Chapter 5 – Case Study Trade Route Initial Consumption & Emissions

5.1 Chapter 5 Introduction

In Chapter 5 the daily consumptions of the Kamsarmax bulk carrier will be applied on a case study trade route, thus calculating the initial total consumptions and emissions prior applying any mentioned technology.

The case study route considers the vessel being under firm time charterer contract, loading at a bulk terminal in the port of South Louisiana (i.e. Globalplex Intermodal Terminal) in United States and discharging at the port of Rotterdam (i.e. HES Bulk Terminal) in Netherlands. Each Trading Route Cycle (TRC) will commence at the entry point of US ECA prior loading port and will be completed at the same point after discharging.

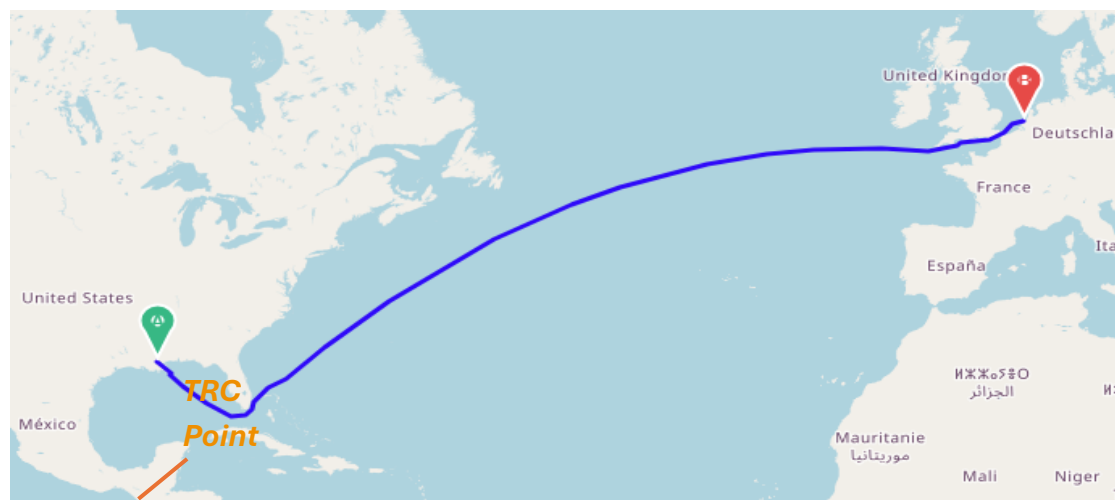


Figure 35. South Louisiana to Rotterdam route example (Source: searoutesnav.com, 2026)



Figure 36. ECAs' map (Marked with dark blue), (Source: meoexamz.co.in, 2026)

5.2 Trade Route's duration

The total mileage, duration of each voyage leg per TRC, including time spent within ECAs and port stay times are shown below:

Table 9. Trade Route Cycle's Legs & Total Duration

Voyage Leg	Nautical Miles	Average Speed	hours	days
<i>ECA Sail. Loading Port in Ballast</i>	210	15.01	14.99 ⁸	<u>0.625</u>
<i>Port Maneuvering Loading</i>	139	-	16.00 ⁹	<u>0.667</u>
<i>Port Stay Laden (Iddle)</i>	0	0	12.00	<u>0.500</u>
<i>Port Stay Laden (Debal)</i>	0	0	60.00	<u>2.500</u>
<i>Port Maneuvering Loading Port</i>	139	-	15.00	<u>0.625</u>
<i>ECA Sail. Loading Port in Laden</i>	210	13.3	15.79	<u>0.658</u>
<i>Open Sea Sail. Laden</i>	4364	13.3	328.12	<u>13.672</u>
<i>ECA Sail. Disch. Port in Laden</i>	350	13.3	26.32	<u>1.096</u>
<i>Maeuvering Eng.Ch.in Laden</i>	120	12.5	9.60	<u>0.400</u>
<i>Port Maneuvering Dischagre</i>	20	-	5.00 ¹⁰	<u>0.208</u>
<i>Port Stay Discharging Port (Idle)</i>	0	0	12.00	<u>0.500</u>
<i>Port Stay Discharging Port (Ball)</i>	0	0	60.00	<u>2.500</u>
<i>Port Maneuvering Discharge Port</i>	20	-	4.00	<u>0.167</u>
<i>Maneuvering Eng.Ch.in Ballast</i>	120	12.5	9.60	<u>0.400</u>
<i>ECA Sail Disch. Port in Ballast</i>	350	15.01	23.32	<u>0.972</u>
<i>Open Sea Sail. Ballast</i>	4364	15.01	290.74	<u>12.114</u>
Total TRC				37.603

The total duration of each of the 5 different consumption modes of the vessel, basis tables 7 and 9 within each TRC, are summed and illustrated in Table 10.

Table 10. Consumption modes periods per Trade Route Cycle

Open Sea Sailing Days	ECAs Sailing Days	Port/ECA Maneuvering Days	Port Idle Days	Port Ball./Debal. Days
25.786	3.351	2.467	1.000	5.000

⁸ One hour has been added for slow down/testing

⁹ One hour has been added due to berth approaching

¹⁰ One hour has been added due to berth approaching

All port stay and maneuvering are considered within ECAs, while the ECA sailing days are considered with full speed within ECA areas. The half period of the Port Idle days and Port Ballasting/Deballasting days is also considered as the EU port stay period for EUAs later calculations. The port days are considered the days while the vessel is alongside berth. During an EU to US trade route the EU port stay period EUAs are charged at 100% CO₂ equivalent, while the US port stay period at 0%. The remaining sailing periods' EUAs are charged at 50% CO₂ equivalent (EU Commission, 2025).

Table 11. EU Port Stay periods per Trade Route Cycle

EU port (idle) Days	EU Port Ba.l/Debal. Days
0.500	2.500

The total number of possible TRCs is shown in table 12:

Table 12. Total Trade Route Cycles per period

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
37.603	0.103	9.7	48.53	97.07

For the ease of calculations and academic comparison reasons, assuming that total mileage has been considered identical for both laden and ballast legs. The corresponding open sea speed will be calculated at 85% MCR speed for laden and ballast legs, after subtracting a five percent reduction due to weather factor and other possible operational restrictions. Extreme weather or other operationally necessary deviation or slowdowns have not been taken into consideration in this study. The simulated average speeds are 13.3 knots for laden and 15.01 knots for ballast legs. Port maneuvering speed will be calculated at 12.5 knots without losses.

5.3 Trade Route's initial consumption and emissions

By applying Equation 6 on daily consumption and TRC legs figures, the total VLSFO and LSMGO consumption per period is calculated:

Table 13. Vessel's Initial total consumption per trade route period

PER TRC	M/E Total (mt VLSFO)	M/E Total (mt LSMGO)	M/E Total Thrust Output (MWh)	DGs total Consumption (mt VLSFO)	DGs total Consumption (mt LSMGO)	DGs Total Load (MWh)	Total VLSFO (mt)	Total LSMGO (mt)	Total Power Output (MWh)
Open Sea Sailing	1162.9	0.0	6112.5	33.5	2.6	140.5	1196.5	2.6	6,253.0
ECAs Sailing	0.0	151.1	794.2	0.0	4.7	18.3	0.0	155.8	812.5
Port/ECA Maneuvering	0.0	65.4	344.0	0.0	8.6	40.3	0.0	74.0	384.2
Port Idle	0.0	0.0	0.0	0.0	3.5	16.3	0.0	3.5	16.3
Port Ball./Debal.	0.0	0.0	0.0	0.0	25	116.6	0.0	25.0	116.6
TOTAL PER TRC							1196.5	260.9	7582.6

TOTAL PER YEAR	11,614	2,532	73,602
TOTAL PER 5 YEAR	58,068	12,661	368,010
TOTAL PER 10 YEAR	116136	25323	736020

By applying Equation 1 on Table 13 figures, the corresponding emissions in CO₂ equivalent are calculated.

Table 14. Vessel's initial emissions per trade route period

	M/E daily VLSFO total emissions mt CO ₂ eq.	M/E daily LSMGO emissions mt CO ₂ eq.	DGs daily VLSFO total emissions mt CO ₂ eq.	DGs daily LSMGO emissions mt CO ₂ eq.		Total emissions mt CO₂ eq.
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92
ECAs Sailing	0.00	491.88	0.00	15.27		507.15
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88
Port Idle	0.00	0.00	0.00	11.39		11.39
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38
					TOTAL PER TRC	4,633.7

TOTAL PER YEAR	44,978
TOTAL PER 5 YEAR	224,890
TOTAL PER 10 YEAR	449,779

The vessel should require 1196.5 mt of VLSFO and 260.9 mt of LSMGO per each TRC. This corresponds to an average of 11,614 mt of VLSFO and 2,532 mt of LSMGO per year or 58,068 mt of VLSFO and 12,661 mt of LSMGO during a 5 year period. The corresponding emissions in CO₂ equivalent, are 4,633.7 mt per TRC, 44,978 mt annually and 224,890 mt during a 5 year period.

The detailed calculation tables of TRC duration are included in Appendix 3, while for the initial consumption and emission tables are incorporated in Appendix 4.

Chapter 6 – Scenario Based Environmental and Economic Analysis

6.1 Chapter 6 Introduction

In total, ten different scenarios have been analyzed. The first scenario is the full concept's implementation, with simultaneous use of all technologies at their maximum possible capacity as described in Chapter 4. Thereafter, four more main scenarios will be reviewed separately for each harvesting technology. Four sub-scenarios, with lesser installable capacity will also be calculated for the solar, the VAWTs and shaft generator technologies. Finally, a last scenario will be analyzed which will only include the two most cost-efficient technologies.

Table 15. List of Environmental and Economic Analysis Scenarios

Environmental and Economic Analysis Scenarios
1 - Full Concept - (2MWh ESS)
2 - Photovoltaic Panels Full Hatch Coverage - (1MWh ESS)
2a - Photovoltaic Panels 50% Hatch Coverage - (1MWh ESS)
3 - Helical Savonious VAWTs (6) Non-Collapsible - (1MWh ESS)
3a - Helical Savonious VAWTs (3) Collapsible - (1MWh ESS)
4 - Piezoacoustic harvesting panels - (NO ESS)
5 - Magnetic Shaft Generator PTI/PTO (8 cycles) - (2MWh ESS)
5a - Magnetic Shaft Generator PTI/PTO (4 cycles) - (2MWh ESS)
5b - Magnetic Shaft Generator PTI/PTO (7.5 cycles) - 2MWh ESS)
6 - Photovoltaic Panels Full Hatch Coverage & Magnetic Shaft Generator PTI/PTO (7.5 cycles) - (2MWh ESS)

Assuming that ESS installation option is applicable to all scenarios with capability of power generation exceeding 1MW per month. Possible Deadweight/Cargo losses due to additional weight are not included in the simulations of this study.

Environmental limitations effect, such as cloud coverage or extreme weather conditions are not incorporated into the assumed performance of the technologies. Operational port delays will only be calculated as extra time in the scenarios incorporating the non-collapsible VAWTs. 12 hours will be accounted in the calculation for loading/discharging belts' and equipment deployment delays due to obstruction from the VAWTs. The additional port dues cost will not be included in calculation.

PTI/PTO mode operation will not be considered operating during vessel's maneuvering or reduced speed periods. In the scenarios, where ESS usage exceeds the batteries' life cycle additional OPEX costs will be included for batteries renewal. These costs will be simulated at 200,000 Euro per 1MW BESS renewal at each 7000 cycles' completion period (Author, 2026).

Fuel and EUAs prices will be simulated fixed at 700 €/mt for VLSFO, at 1200 €/mt for LSMGO (BunkerIndex.com, 2026) and 80 €/EUA (Tradeconomics, 2026).

The detailed calculation tables of each scenario are included in Appendix 4.

6.2 Scenarios

The summarized costs, total savings and emissions' reduction of all scenarios are illustrated below:

Table 16. Scenarios' Summary

Scenario	CAPEX €	TOTAL OPEX (PER YEAR) €	TOTAL SAVINGS (PER YEAR) €	EMISSIONS REDUCTION %	ROI (YEARS)
1 - Full Concept (2MWh ESS)	7,986,000	157,499	796,277	6.26%	12.5
2 - PV Panels Full Hatch Cov. (1MWh ESS)	2,231,000	20,010	188,612	1.34%	13.2
2a - PV Panels 50% Hatch Cov. (1MWh ESS)	1,343,000	10,905	94,261	0.67%	16.1
3 - VAWTs (6) Non-Collapsible (1MWh ESS)	1,635,000	2,550	12,766	0.10%	160.0
3a - VAWTs (3) Collapsible (1MWh ESS)	1,100,000	4,800	6,553	0.05%	633.0
4 - PZ acoustic panels (NO ESS)	140,000	1,500	0	0.00002%	v
5 - PTI/PTO (8 cycles - 2MWh ESS)	4,850,000	140,388	625,782	4.90%	10.0
5a - PTI/PTO (4 cycles - 2MWh ESS)	4,850,000	75,744	312,891	2.50%	20.5
5b - PTI/PTO (7.5 cycles - 2MWh ESS)	4,850,000	140,388	657,856	5.20%	9.4
6 - PV Panels Full Hatch & PTI/PTO (7.5 cycles - 2MWh ESS)	6,646,000	158,598	792,666	6.10%	10.5

As illustrated above, the magnetic shaft generator technology, despite having the highest CAPEX and OPEX, is the most efficient technology cost wise, with a minimum possible ROI period at 9.4 years. Nonetheless, once combined with the PV panels option under optimum scenario 6, the emissions' reduction is increased by 17% and the annual savings by 20% compared to scenario 5b. Due to the increased CAPEX the ROI has increased by almost 12% though. All things considered, the optimum scenario 6 is the most efficient in the long term.

6.2.1 Scenario 1 – Full concept application

The first scenario considers full concept application with maximum PV panels hatch coverage, six non-collapsible VAWTs on deck, the Piezoacoustic panels in engine room and the PTI/PTO shaft generator. The 2 MWh ESS option will be considered installed for this scenario.

The maximum possible generated power output from renewable energy sources is illustrated below:

Table 17. Scenario 01 - Full Concept - Power Generation

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
<i>PV Panels Full Hatch Coverage</i>	2095	2095	0	8	8
<i>VAWTs (6)</i>	0	196.8	0	-	24
<i>PZ acoustic Panels</i>	0.028	0.028	0	24	24
<i>PTI/PTO (8 cycle operation)</i>	0	3180	8400	-	22.14
<i>Total</i>	2095.03	5471.83	8400.00		

Due to the total maximum possible generated power from all renewable energy sources, which oversuffices vessel's daily auxiliary needs, while the vessel is at sea, the PTI/PTO mode operation can be optimized providing more thrust power, totaling at 8.4 MW within 8 batteries charge/discharge cycles. Consequently, 2 out of the 8 PTI/battery discharge cycles can be theoretically extended up to 1.2 hours instead of 0.97 hours, as the auxiliaries would be fully covered by the other sources (i.e. solar, wind) during that period.

$$\text{PTI \& Batteries Discharge Cycle Time} = 1200\text{KW} / 1000\text{KW} = 1.2 \text{ hours}$$

$$\text{Batteries LifeSpan} = 7000 \text{ cycles} / 8 \text{ cycles per sailing day} = 875 \text{ sailing days}$$

Considering maximum utilization of batteries under this configuration, renewal of BESS will be needed every 875 sailing days period.

By applying Equations 2, 3 and 7 on Table 17 figures, the reduced daily VLSFO and LSMGO consumption are calculated. Additionally, the total reduced auxiliary power load of DGs are illustrated below:

Table 18. Scenario 1 - Full Concept - Reduced Consumption

	M/E daily red. cons (mt Vlsfo)	M/E daily red. Cons. (mt Lsmgo)	Total Daily Thrust Output (kWh)	M/E Total Daily Red. Output (kWh)	DGs daily red. cons (mt Vlsfo)	DGs daily red. cons (mt Lsmgo)	Aux. total Load (kWh)	DGs total red. Load (kWh)	Thrust % from renew.	Aux. % from renewables	Daily VLSFO Saving (mt)	Daily LSMGO Saving (mt)
Open Sea Sailing	43.50	0.00	237048	228648	0.00	0.00	5448	0	3.5%	100.4%	2.90	0.10
ECAs Sailing	0.00	43.50	237048	228648	0.00	0.00	5448	0	3.5%	100.4%	0.00	3.00
Port/ ECA Manvr.	0	26.5	139440	139440	0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Idle	0	0	0	-	0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Ball./Debal.	0	0	0	-	0.00	4.55	23328	21233	0	9.0%	0.00	0.45

By applying Equations 1 and 8 on Table 18 figures, the corresponding daily emissions' reduction in CO2 equivalent is illustrated in below table:

Table 19. Scenario 1 - Full Concept - Reduced Emissions

	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	137.60	-	0.00	0.00	137.60	9.49	6.5%
ECAs Sailing	-	141.60	-	0.00	141.60	9.76	6.4%
Port/ ECA Manvr.	-	86.26	-	9.93	96.19	1.46	1.5%
Port Idle	-	-	-	9.93	9.93	1.46	12.8%
Port Ball./Debal.	-	-	-	14.81	14.81	1.46	9.0%

Considering the maximum possible installable options and simultaneous optimum utilization of all components' power capabilities, the daily reduction of emissions on the case study vessel could theoretically reach 6.5% at sea and 12.8% while idle at port. The total average reduction of emissions has been calculated at **6.3%** per TRC, while the fuel savings at 707 mt of VLSFO and 160 mt of LSMGO per year.

In order to calculate the economic benefits per TRC period and the ROI period, initially the TRC's duration and the total number of TRC per period will be recalculated, incorporating 12 hours operational delays due to the non-collapsible masts, during each port operation.

The amended periods are shown in below tables:

Table 10.1. Scenario 1 Consumption modes periods per Trade Route Cycle

Open Sea Sailing Days	ECAs Sailing Days	Port/ECA Maneuvering Days	Port Idle Days	Port Ball./Debal. Days
25.786	3.351	2.467	1.000	6.000

Table 11.1. Scenario 1 EU Port Stay periods per Trade Route Cycle

EU port (idle) Days	EU Port Ba.l/Debal. Days
0.500	3.000

Table 12.1 Scenario 1 Total Trade Route Cycles per period

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
38.603	0.106	9.5	47.28	94.55

The total number of TRCs per each period has been reduced due to the port operational delays. Additionally, the summed 29.136 sailing days per TRC will result in consuming the BESS lifecycle every 3 years. The BESS renewal frequency is calculated basis the total sailing days and divided with the batteries' life span in sailing days.

Table 20. Scenario 1 Battery Energy Storage System Renewals per period

Sailing Days per TRC	Total Sailing days			
		per year	days per 5 years	Total Sailing days per 10 years
29.136		275.5	1377.45	2754.91
BESS RENEWALS		0.31	1.57	3.15

By applying Equations 9 and 10 on above figures the total savings and OPEX per period are calculated.

Table 21. Scenario 1 Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	52,312	20,251	11,653	84,216	16,657
PER YEAR	494,621	191,478	110,178	796,277	157,499
PER 5 YEARS	2,473,103	957,392	550,890	3,981,385	787,493
PER 10 YEARS	4,946,205	1,914,785	1,101,780	7,962,770	1,574,986

The total OPEX figures include the annual maintenance costs and BESS renewal costs proportionally for each period. It is worth mentioning that the savings are overcovering the OPEX by 5 times or 505%.

In order to calculate the ROI period through equation 11 the total CAPEX are also included.

Table 22. Scenario 1 Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX</u> (PER YEAR) €
2MWh EMS & BESS	850,000	129,539
PV Panels Full Hatch Coverage	1,796,000	18,210
VAWTs (6) Non-collapsible	1,200,000	750
PZ acoustic Panels	140,000	1,500
PTI/PTO (8 cycle operation)	4,000,000	7,500
<i>Total</i>	7,986,000	157,499

The resulting **ROI period** is **12.5 years**.

Scenario 1 Outcome

With the maximum possible installable options and optimum utilization, the emission of 27,545 mt of CO₂ equivalent emissions could theoretically be avoided within a 10-year period. Furthermore, the total cost savings are surpassing the relevant calculated OPEX reaching almost 8 million. On the contrary, the enormous amount of the initial required investment is creating a return of investment period of more than 12 years, which cost wise could deter shipowners from such a long-term investment, especially for older vessels.

6.2.2 Scenarios 2, 2a – PV Panels

The second scenario considers only PV panels installation with either full or 50% hatch coverage. The 1MWh ESS option will be considered installed for this scenario for grid's and power supply stability.

The maximum possible generated power output from renewable energy sources is illustrated below:

Table 23. Scenario 2 - Photovoltaic Panels Full Coverage - Power Generation

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i><u>Daily running hours (at port)</u></i>	<i><u>Daily running hours (at sea)</u></i>
PV Panels Full Hatch Coverage	2095	2095	0	8	8
Total	2095.00	2095.00	0.00		

Table 23a. Scenario 2a - Photovoltaic Panels 50% Coverage - Power Generation

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i><u>Daily running hours (at port)</u></i>	<i><u>Daily running hours (at sea)</u></i>
PV Panels 50% Hatch Coverage	1047	1047	0	8	8
Total	1047.00	1047.00	0.00		

Considering the 8 hours of PV panels peak power production and optimum daily utilization of batteries under this configuration, the vessel will be able to totally avoid DGs' operation for approximately 9 hours continuously. Under the full hatch coverage application and simulated peak power or 261.85 KW hourly production, the 1MWh BESS could be fully charged from 20% to 80% capacity within 2.29 hours. However, in order to achieve the simultaneous full

coverage of vessel's auxiliary hourly power needs of 227 KW at open sea, after the first 1.5 hours of full batterie's charging rate with PVs, the rate should be reduced to 34.85 KWh, which is the remaining balance from the PVs peak power production minus vessel auxiliaries' load. After the batteries are fully charged and the solar panels are not longer operational, the 1MW batteries utilization in discharge mode will cover vessel needs for additional 2.64 hours.

PV Full & Batteries Full Charge Cycle Time =

$$600KWh / 261.85 KW = 2.29 \text{ hours}$$

PV Full & Batteries Optimum Charge Cycle Time =

$$1.5 + [(600KWh - 1.5 \times 268KWh) / 34.85KW] = 7.44 \text{ hours}$$

$$\text{PV Full \& Batteries Discharge Cycle Time} = 600KWh / 227KW = 2.64 \text{ hours}$$

With a 50% hatch coverage and a 130.875 KW hourly peak power output of the panels the batteries should be first fully charged prior stopping DGs, vessel's auxiliaries load cannot be fully covered by solar energy. The batteries could be fully charged after 4.58 hours and then the diesel generators could remain stopped for 4.61 hours, considering that batteries are operating in alignment with the PV panels for the next 3.42 hours.

PV 50 & Batteries Full Charge Cycle Time =

$$600KWh / 130.875 KW = 4.58 \text{ hours}$$

PV 50 & Batteries Discharge Cycle Time =

$$[600KWh + (3.42 \times 130.875 KWh)] / 227 KW = 4.61 \text{ hours}$$

During port operations no batteries discharge mode is expected as the produced power production covers only a portion (less than 50%) of the total power needs with both options. Renewal of BESS will not be needed prior a 19 years period¹¹ even with a daily full cycle utilization.

Under this configuration, there is no thrust power produced from renewables and as a result main engines' consumption is considered unaffected.

¹¹ 7000 cycles/ 365 days = 19.17 years.

By applying Equations 2, 3 and 7 on Tables 23 & 23a figures, the reduced daily VLSFO and LSMGO consumption are calculated. Additionally, the total reduced auxiliary power load of DGs is calculated:

Table 24. Scenario 2 – Photovoltaic Panels Full Hatch Coverage - Reduced Consumption

	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt LSMGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Auxiliaries % from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	0.80	0.06	5448	3353	38.5%	0.50	0.04
ECAs Sailing	0.00	0.86	5448	3353	38.5%	0.00	0.54
Port/ECA Maneuvering	0.00	3.05	16320	14225	12.8%	0.00	0.45
Port Idle	0.00	3.05	16320	14225	12.8%	0.00	0.45
Port Ball./Debal.	0.00	4.55	23328	21233	9.0%	0.00	0.45

Table 24a. Scenario 2a – Photovoltaic Panels 50% Hatch Coverage - Reduced Consumption

	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt LSMGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Auxiliaries % from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1.05	0.08	5448	4401	19.2%	0.25	0.02
ECAs Sailing	0.00	1.13	5448	4401	19.2%	0.00	0.27
Port/ECA Maneuvering	0.00	3.28	16320	15273	6.4%	0.00	0.22
Port Idle	0.00	3.28	16320	15273	6.4%	0.00	0.22
Port Ball./Debal.	0.00	4.78	23328	22281	4.5%	0.00	0.22

By applying Equations 1 and 8 on Tables 24 and 24a figures, the corresponding daily emissions' reduction in CO₂ equivalent is calculated:

Table 25. Scenario 2 - Photovoltaic Panels Full Hatch Coverage - Reduced Emissions

	DGs daily VLSFO total emissions mt CO ₂ eq.	DGs daily LSMGO emissions mt CO ₂ eq.	Total emissions mt CO₂ eq.	Total Reduction of emissions mt CO₂ eq.	Total Reduction % emissions mt CO₂ eq.
Open Sea Sailing	2.53	0.20	145.39	1.71	1.2%
ECAs Sailing	0.00	2.80	149.61	1.75	1.2%
Port/ECA Maneuvering	0.00	9.93	96.19	1.46	1.5%
Port Idle	0.00	9.93	9.93	1.46	12.8%
Port Ball./Debal.	0.00	14.81	14.81	1.46	9.0%

Table 25a. Scenario 2a - Photovoltaic Panels 50% Hatch Coverage - Reduced Emissions

	DGs daily VLSFO total emissions mt CO ₂ eq.	DGs daily LSMGO emissions mt CO ₂ eq.	Total emissions mt CO₂ eq.	Total Reduction of emissions mt CO₂ eq.	Total Reduction % emissions mt CO₂ eq.
Open Sea Sailing	3.32	0.26	146.24	0.85	0.6%
ECAs Sailing	0.00	3.68	150.49	0.88	0.6%
Port/ECA Maneuvering	0.00	10.66	96.92	0.73	0.7%
Port Idle	0.00	10.66	10.66	0.73	6.4%
Port Ball./Debal.	0.00	15.55	15.55	0.73	4.5%

With the full hatch coverage option, the daily reduction of emissions on the case study vessel could theoretically reach 1.2% at sea and 12.8% while idle at port. The total average reduction of emissions has been calculated at **1.3%** per TRC, while the fuel savings at 125 mt of VLSFO and 64 mt of LSMGO per year.

With the 50% hatch coverage option these figures are almost halved. The total average reduction of emissions has been calculated at **0.67%** per TRC, while the fuel savings at 63 mt of VLSFO and 32 mt of LSMGO per year.

In this scenario the TRC legs and duration remain unchanged as prior any installation, therefore the figures from tables 10,11 and 12 still apply.

By applying Equations 9 and 10 on these figures the total savings and OPEX per period are calculated.

Table 26. Scenario 2 Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	9,023	7,918	2,490	19,431	2,061
PER YEAR	87,587	76,855	24,170	188,612	20,010
PER 5 YEARS	437,934	384,274	120,851	943,059	100,050
PER 10 YEARS	875,869	768,548	241,702	1,886,118	200,100

Table 26a. Scenario 2a Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	4,510	3,957	1,244	9,711	1,123
PER YEAR	43,773	38,409	12,079	94,261	10,905
PER 5 YEARS	218,863	192,045	60,397	471,305	54,525
PER 10 YEARS	437,725	384,090	120,793	942,609	109,050

The total OPEX figures include annual maintenance costs for each period. The savings are overcovering the OPEX by 9 times or 942 % on the full coverage and by 8 times or 864% on the half hatch coverage scenario.

In order to calculate the ROI period through equation 11 the total CAPEX are also included.

Table 27. Scenario 2 Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX (PER YEAR) €</u>
1MWh EMS & BESS	435,000	1,800
PV Panels Full Hatch Coverage	1,796,000	18,210
<i>Total</i>	<i>2,231,000</i>	<i>EUR 20,010</i>

Table 27a. Scenario 2a Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX (PER YEAR) €</u>
1MWh EMS & BESS	435,000	1,800
PV Panels 50% Hatch Coverage	908,000	9,105
<i>Total</i>	<i>1,343,000</i>	<i>EUR 10,905</i>

The resulting **ROI period** is **13.2 years** for Scenario 2 and **16.1 years** for Scenario 2a.

Scenario 2 Outcome

With the full hatch coverage option, the emission of 6,043 mt of CO₂ equivalent emissions could theoretically be avoided within a 10-year period. Furthermore, the total cost savings are surpassing the relevant calculated OPEX reaching almost 2 million. On the contrary, the amount of the initial required investment is creating a return of investment period of more than 13 years, which cost wise could deter shipowners from such a long-term investment, especially for older vessels.

The 50% hatch coverage option is reducing initial investment cost by 40%, however the ROI period is increased by almost 3 years.

6.2.3 Scenarios 3, 3a – VAWTs

The third scenario considers only VAWTs installation with either 6 non-collapsible VAWTs or 3 collapsible ones. The 1MWh ESS option will be considered installed for this scenario for grid's and power supply stability.

The maximum possible generated power output from renewable energy sources is illustrated in the tables below:

Table 28. Scenario 3 – Vertical Axis Wind Turbines (6) - Power Generation

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i><u>Daily running hours</u> (at port)</i>	<i><u>Daily running hours</u> (at sea)</i>
VAWTs (6) Non-Collapsible	0	196.8	0	-	24
<i>Total</i>	0.00	196.80	0.00		

Table 28a. Scenario 3a – Vertical Axis Wind Turbines (3) Collapsible - Power Generation

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i><u>Daily running hours</u> (at port)</i>	<i><u>Daily running hours</u> (at sea)</i>
VAWTs (3) Collapsible	0	98.4	0	-	24
<i>Total</i>	0.00	98.40	0.00		

Considering 24 hours of VAWTs power production at sea, corresponding to an average 8.2 KW per hour for the 6 VAWTs and 4.1 for the 3 VAWTs option, the 1 MWh BESS can be fully charged within 73 and 146 hours respectively, thus possibly allowing vessel to totally avoid DGs' operation for 2.64 hours within a day at sea. During port operation VAWTs will be considered stopped for safety reasons. Using the charged batteries' energy during port operation will not be included in calculations, due to the minimum effect in total TRC consumption.

6 VAWTs & Batteries Full Charge Cycle Time =

$$600KWh / 8.2 KW = 73.17 \text{ hours}$$

3 VAWTs & Batteries Full Charge Cycle Time =

$$600KWh / 4.1 KW = 146.34 \text{ hours}$$

BESS renewal will not be needed prior a 19 years period even with daily full cycles utilization, similarly to scenario 2.

Under this configuration, there is no thrust power produced from renewables and as a result main engines' consumption is considered unaffected. Benefit of possible positive aerodynamic effect from VAWTs deployment will not be included in calculations, due to unpredictability and variation of wind's direction.

By applying Equations 2, 3 and 7 on Tables 28 and 28a figures the reduced daily VLSFO and LSMGO consumption are calculated. Additionally, the total reduced auxiliary power load of DGs is calculated and illustrated in below tables:

Table 29. Scenario 3 – Vertical Axis Wind Turbines (6) - Reduced Consumption

	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt LSMGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust % from renewable	Auxiliaries % from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1.25	0.10	5448	5251	0.0%	3.6%	0.05	0.00
ECAs Sailing	0.00	1.35	5448	5251	0.0%	3.6%	0.00	0.05
Port/ECA Maneuvering	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Idle	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Ball./Debal.	0.00	5.00	23328	23328	0	0.0%	0.00	0.00

Table 29a. Scenario 3a – Vertical Axis Wind Turbines (3) - Reduced Consumption

	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt LSMGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentage from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1.28	0.10	5448	5350	0.0%	1.8%	0.02	0.00
ECAs Sailing	0.00	1.37	5448	5350	0.0%	1.8%	0.00	0.03
Port/ECA Maneuvering	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Idle	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Ball./Debal.	0.00	5.00	23328	23328	0	0.0%	0.00	0.00

By applying Equations 1 and 8 on Tables 29 and 29a figures, the corresponding daily emissions' reduction in CO₂ equivalent is illustrated in below tables:

Table 30. Scenario 3 - Vertical Axis Wind Turbines (6) - Reduced Emissions

	DGs daily VLSFO total emissions mt CO ₂ eq.	DGs daily LSMGO emissions mt CO ₂ eq.	Total emissions mt CO ₂ eq.	Total Reduction of emissions mt CO ₂ eq.	Total Reduction % emissions mt CO ₂ eq.
Open Sea Sailing	3.96	0.31	146.93	0.16	0.11%
ECAs Sailing	0.00	4.39	151.20	0.16	0.11%
Port/ECA Maneuvering	0.00	11.39	97.65	0.00	0.0%
Port Idle	0.00	11.39	11.39	0.00	0.0%
Port Ball./Debal.	0.00	16.28	16.28	0.00	0.0%

Table 30a. Scenario 3a - Vertical Axis Wind Turbines (3) - Reduced Emissions

	DGs daily VLSFO total emissions mt CO ₂ eq.	DGs daily LSMGO emissions mt CO ₂ eq.	Total emissions mt CO ₂ eq.	Total Reduction of emissions mt CO ₂ eq.	Total Reduction % emissions mt CO ₂ eq.
Open Sea Sailing	4.04	0.32	147.01	0.08	0.054%
ECAs Sailing	0.00	4.47	151.28	0.08	0.054%
Port/ECA Maneuvering	0.00	11.39	97.65	0.00	0.0%
Port Idle	0.00	11.39	11.39	0.00	0.0%
Port Ball./Debal.	0.00	16.28	16.28	0.00	0.0%

With the 6 non-collapsible VAWTs option, the daily reduction of emissions on the case study vessel could theoretically reach 0.11% at sea. The total average reduction of emissions has been calculated at **0.10%** per TRC, while the fuel savings at 11 mt of VLSFO and 2 mt of LSMGO per year. With 3 collapsible VAWTs option these figures are halved.

In this scenario the TRC legs and duration remain unchanged for the collapsible masts option and the figures from tables 10,11 and 12 apply, while the non-collapsible masts option the tables 10.1, 11.1 and 12.1 from Scenario 1 apply.

By applying Equations 9 and 10 on these figures the total savings and OPEX per period are calculated:

Table 31. Scenario 3 Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	848	315	187	1,350	270
PER YEAR	8,015	2,979	1,772	12,766	2,550
PER 5 YEARS	40,073	14,897	8,860	63,830	12,750
PER 10 YEARS	80,146	29,795	17,719	127,660	25,500

Table 31a. Scenario 3a Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	424	158	94	675	495
PER YEAR	4,114	1,529	910	6,553	4,800
PER 5 YEARS	20,569	7,647	4,548	32,764	24,000
PER 10 YEARS	41,139	15,293	9,095	65,527	48,000

Total OPEX includes annual maintenance costs for each period. The savings are overcovering the OPEX by 5 times on the 6 non-collapsible VAWTs option, while they are covering the 136% of OPEX on the 3 collapsible VAWTs option.

For calculating the ROI period through equation 11 the total CAPEX are also included.

Table 32. Scenario 3 Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX</u> (PER YEAR) €
1MWh EMS & BESS	435,000	1,800
VAWTs (6) Non-collapsible	1,200,000	750
<i>Total</i>	<i>1,635,000</i>	<i>EUR 2,550</i>

Table 32a. Scenario 3a Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX</u> (PER YEAR) €
1MWh EMS & BESS	435,000	1,800
VAWTs (3) Collapsible	675,000	3,000
<i>Total</i>	<i>1,110,000</i>	<i>EUR 4,800</i>

The resulting **ROI period** is **160 years** for Scenario 3 and **633 years** for Scenario 3a.

Scenario 3 Outcome

Both VAWTs installation options have low OPEX which are covered by savings. Nevertheless, the small amount of emissions' reduction at 0.11%, combined with the very high initial CAPEX result into non-viable ROI periods. Worths mentioning that the collapsible VAWTs option is considered the most inefficient option cost wise, due to lower savings to OPEX ratio and high CAPEX per installable unit.

In addition, the complexity of these systems for on board operation, may also create port operational delays.

Consequently, both above-mentioned options, under the demonstrated deployments, are not recommended for application on bulk carrier vessels.

6.2.4 Scenario 4 – Piezoacoustic Panels

The fourth scenario considers only the Piezoacoustic panels installation without an ESS installed, due to the very small amount of produced energy which will be directly feeding a small portion of hotel load.

The maximum possible generated power output from renewable technologies is illustrated in below table:

Table 33. Scenario 4 – Piezoacoustic Panels - Power Generation

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
<i>PZ acoustic Panels</i>	0.028	0.028	0	24	24
<i>Total</i>	0.028	0.028	0.00		

Due to the extremely low harvested power amount, by applying the figures of Table 29 into Equations 2, 3 and 7 the reduced daily VLSFO, LSMGO consumption and the corresponding emissions' reduction through Equations 1 and 8, are calculated to almost zero. Therefore, the relevant tables are not illustrated.

For reference only, by using the initial TRC figures, the corresponding fuel savings per TRC are **0.000172 mt** of VLSFO and **0.000088** mt of LSMGO. The savings figure is 25 € in a 10 year period.

For calculating the ROI period through equation 11 the total CAPEX are also included.

Table 34. Scenario 4 Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX</u> (PER YEAR) €
PZ acoustic panels	140,000	1,500
<i>Total</i>	<i>140,000</i>	<i>EUR 1,500</i>

The resulting **ROI period** figure is **Negative**.

Scenario 4 Outcome

Despite the theoretically continuous harvesting operation of the system, the almost 0% fuel savings, combined with the initial CAPEX and OPEX result into a negative ROI period.

As a result, the above-mentioned option and deployments is not recommended for bulk carrier vessels' application.

6.2.5 Scenarios 5, 5a, 5b – PTI/PTO Shaft Generator

The 5th scenario considers only the shaft generator installed installation with either 8 or 4 cycles operational mode. The 2 MWh ESS option will be considered installed for this scenario.

The maximum possible generated power output from renewable energy sources is illustrated in below table:

Table 35. Scenario 5 – PTI/PTO Shaft Generator (8 cycles) - Power Generation

Component	Estimated Auxiliary Power (at port) (KWh/day)	Estimated Auxiliary Power (at sea) (KWh/day)	Estimated Thrust Power (at sea) (KWh/day)	Daily running hours (at port)	Daily running hours (at sea)
PTI/PTO (8 cycle operation)	0	3680	8000	-	21.68
Total	0	3680.00	8000.00		

Table 35a. Scenario 5a – PTI/PTO Shaft Generator (4 cycles) - Power Generation

Component	Estimated Auxiliary Power (at port) (KWh/day)	Estimated Auxiliary Power (at sea) (KWh/day)	Estimated Thrust Power (at sea) (KWh/day)	Daily running hours (at port)	Daily running hours (at sea)
PTI/PTO (4 cycle operation)	0	1840	4000	-	10.84
Total	0	1840.00	4000.00		

The PTO&Batteries Charge and PTI&Batteries discharge Cycle Times are identical to Chapter 4, at 1.74 and 0.97 hours respectively. No operation of the system is considered during maneuvering or port stay.

While the system is in operation at sea, all vessel's auxiliary power needs are covered both during charging and discharging cycles, thus only needing to use DGs for 2.32 hours per day with the 8 cycles operation and 13.16 hours with the 4 cycles operation. Considering 5.45 MWh of auxiliaries' total daily load at sea, completely avoiding the use of DGs is also possible, if the

usage of the produced energy, stored in the BESS is always prioritized towards fully covering the auxiliary needs, while only the excess is to be used for thrust power.

Worth mentioning that fuel utilization efficiency¹² in Main Engine is greater than in Diesel generators.

Consequently, another optimum sub-scenario is also explored:

Table 35b. Scenario 5b – PTI/PTO Shaft Generator (7.5 cycles) - Power Generation

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
<i>PTI/PTO (7.5 cycle operation)</i>	0	5450	6200	-	21.68
<i>Total</i>	0	5450.00	6200.00		

In this sub-scenario the exact 100.0% daily auxiliary needs are calculated being covered by initially 6 full PTO & batteries charge/PTI & batteries discharge cycles, followed by two more PTO/charge cycles with only 0.2 hours of PTI mode during the batteries discharge. The batteries will be carrying out 8 complete charge/discharge cycles, in the range of 20% to 80% capacity, every 24 hours.

Considering maximum utilization of batteries under this configuration, renewal of BESS will be needed every 875 sailing days period for the 8 and 7.5 cycles operation and every 1750 sailing days for the 4 cycles operation.

Batteries LifeSpan= 7000 cycles/8 cycles per sailing day= 875 sailing days

Batteries LifeSpan= 7000 cycles/4 cycles per sailing day= 1750 sailing days

¹² Basis Vessel's daily consumption, while sailing at sea @ 85% MCR, 1mt of fuel equivalent can produce 5,256 MWh of power Output in ME, while in DG 1mt of fuel equivalent can produce 3,891 MWh.

By applying Equations 2, 3 and 7 on Tables 35, 35a and 35b figures, the reduced daily VLSFO and LSMGO consumption are calculated. Additionally, the total reduced auxiliary power load of DGs is calculated and illustrated in below tables:

Table 36. Scenario 5 – PTI/PTO Shaft Generator (8 cycles) - Reduced Consumption

	M/E daily reduced consum. (mt VLSFO)	M/E daily reduced consum. (mt LSMGO)	Total. Thrust Output (kWh)	M/E Total. Red. Output (kWh)	DGs daily Red. Cons. (mt VLSFO)	DGs daily red. Cons. (mt LSMGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percent age from renewa ble	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	43.58	0.00	237048	229048	0.42	0.03	5448	1768	3.4%	67.5%	2.40	0.07
ECAs Sailing	0.00	43.58	237048	229048	0.00	0.45	5448	1768	3.4%	67.5%	0.00	2.47

Table 36a. Scenario 5a – PTI/PTO Shaft Generator (4 cycles) - Reduced Consumption

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt LSMGO)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Red. Cons. (mt VLSFO)	DGs daily red.Cons. (mt LSMGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percent. from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	44.34	0.00	237048	233048	0.86	0.07	5448	3608	1.7%	33.8%	1.20	0.03
ECAs Sailing	0.00	44.34	237048	233048	0.00	0.93	5448	3608	1.7%	33.8%	0.00	1.23

Table 36b. Scenario 5b – PTI/PTO Shaft Generator (7.5 cycles) - Reduced Consumption

	M/E daily reduced consump tion (mt VLSFO)	M/E daily reduced consumpti on (mt LSMGO)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Red. Cons. (mt VLSFO)	DGs daily red.Cons. (mt LSMGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percent age from renewa ble	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMG O Savings (mt)
Open Sea Sailing	43.92	0.00	237048	230848	0.00	0.00	5448	0	2.6%	100.0%	2.48	0.10
ECAs Sailing	0.00	43.92	237048	230848	0.00	0.00	5448	0	2.6%	100.0%	0.00	2.58

By applying Equations 1 and 8 on Tables 32, 32a and 32b figures, the corresponding daily emissions' reduction in CO2 equivalent is illustrated in below tables:

Table 37. Scenario 5 – PTI/PTO Shaft Generator (8 cycles) - Reduced Emissions

	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	137.84	0.00	1.33	0.11	139.28	7.81	5.3%
ECAs Sailing	0.00	141.85	0.00	1.48	143.33	8.03	5.3%

Table 37a. Scenario 5a – PTI/PTO Shaft Generator (4 cycles) - Reduced Emissions

	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	140.25	0.00	2.72	0.22	143.19	3.91	2.7%
ECAs Sailing	0.00	144.33	0.00	3.02	147.35	4.02	2.7%

Table 37b. Scenario 5b – PTI/PTO Shaft Generator (7.5 cycles) - Reduced Emissions

	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	138.92	0.00	0.00	0.00	138.92	8.17	5.6%
ECAs Sailing	0.00	142.97	0.00	0.00	142.97	8.40	5.5%

With 8 cycles operation mode, the daily reduction of emissions could theoretically reach 5.3% at sea, while 2.7% with the 4 cycles operation. The total average reduction of emissions has been calculated at **4.9% and 2.5%** respectively per TRC, while the fuel savings at 601 or 300 mt of VLSFO and 97 or 49 mt of LSMGO per year.

With the 7.5 cycles optimized operation mode for full auxiliaries' coverage the total average reduction of emissions has been calculated at **5.2%** per TRC, while the fuel savings at 621 mt of VLSFO and 109 mt of LSMGO per year. This optimized mode is more energy efficient, achieving also no running hours of diesel generators while at sea.

In the sub-scenarios the TRC legs and duration remain unchanged as prior any installation, therefore the figures from tables 10,11 and 12 still apply. The required number of BESS Renewals for the 8 and 4 cycles modes are calculated and shown in the table below:

Table 38. Scenario 5 Battery Energy Storage System Renewals per period

Sailing Days per TRC		Total Sailing days per year	Total Sailing days per 5 years	Total Sailing days per 10 years
29.136		275.5	1377.45	2754.91
BESS RENEWALS	8 cycles	0.32	1.62	3.23
	4 cycles	0.16	0.81	1.62

Every approximately 3 years the BESS would need batteries replacement with the 8 and 7.5 cycles operation, while every 6 years with the 4 cycles operation.

By applying Equations 9 and 10 on these figures the total savings and OPEX per period are calculated.

Table 39. Scenario 5 Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	43,323	12,012	9,134	64,469	14,463
PER YEAR	420,525	116,597	88,660	625,782	140,388
PER 5 YEAR	2,102,624	582,985	443,302	3,128,911	701,939
PER 10 YEAR	4,205,248	1,165,970	886,604	6,257,822	1,403,878

Table 39a. Scenario 5a Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	21,662	6,006	4,567	32,235	7,803
PER YEAR	210,262	58,299	44,330	312,891	75,744
PER 5 YEAR	1,051,312	291,493	221,651	1,564,456	378,719
PER 10 YEAR	2,102,624	582,985	443,302	3,128,911	757,439

Table 39b. Scenario 5 Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	44,757	13,466	9,551	67,774	14,463
PER YEAR	434,439	130,710	92,707	657,856	140,388
PER 5 YEAR	2,172,196	653,551	463,534	3,289,280	701,939
PER 10 YEAR	4,344,392	1,307,101	927,067	6,578,561	1,403,878

The total OPEX figures include the annual maintenance costs for each period including BESS renewal costs. The savings are overcovering the OPEX by 446% on the 8 cycles operation option, while they are covering 413% of OPEX on the 4 cycles operation option. On the 7.5 optimization scenario the OPEX are covered by 469% by savings.

For calculating the ROI period through equation 11 the total CAPEX are also included. The CAPEX and OPEX for 8 and 7.5 cycles are considered same.

Table 40. Scenario 5 & 5b Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX</u> (PER YEAR) €
2MWh EMS & BESS	850,000	132,888
PTI/PTO (8 cycle operation)	4,000,000	7,500
<i>Total</i>	4,850,000	140,388

Table 40a. Scenario 5a Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX</u> (PER YEAR) €
2MWh EMS & BESS	850,000	68,244
PTI/PTO (4 cycle operation)	4,000,000	7,500
<i>Total</i>	4,850,000	75,744

The **ROI period** is **10 years** for Scenario 5, **20.5 years** for Scenario 5a and **9.4 years** for Scenario 5b.

Scenario 5 Outcome

All installation options' OPEX are covered by savings, with emissions reduction up to 5.2% per year. Nevertheless, by not using the system at its maximum possible capacity the ROI period is increased, despite the expansion of batteries lifespan. Furthermore, optimizing system's usage, thus always covering auxiliary power needs with remaining capacity for propulsion boost, is the most cost and environmentally efficient option, resulting in a ROI shorter than 10 years.

6.2.6 Scenario 6 – Optimum Technologies Configuration - PV Panels & PTI/PTO Shaft Generator

The last scenario combines the two most environmental and cost efficient scenarios' technologies. These are the photovoltaic panels at full hatch coverage and the PTI/PTO shaft generator in 7.5 cycles operational mode optimized for full coverage of auxiliary needs. The 2 MWh ESS option will also be considered installed for this scenario.

The sum of the maximum possible generated power output from renewable energy sources is illustrated in below table:

Table 41. Scenario 6 – Optimum configuration - Power Generation

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
<i>PV Panels Full Hatch Coverage</i>	2095	2095	0	8	8
<i>PTI/PTO (7.5 cycle operation)</i>	0	3353	8001	0	20.35
<i>Total</i>	2095.00	5448.00	8001.00		

Taking advantage of the total maximum possible generated power from both renewable energy sources, which over suffices vessel's total daily auxiliary needs while the vessel is at sea, and in order to totally avoid DGs' usage, the PTI/PTO mode operation is optimized providing thrust power totaling at 8.0 MW within 8 batteries charge/discharge cycles.

Considering optimum usage within 24 hours and by taking advantage of the PV panels' 35 KW per hour positive power production balance¹³, 2 out of the 8 PTI/battery discharge cycles can be extended up to 1.235 hours instead of 0.97, if the auxiliaries are fully covered by the PV panels during that period. Similarly, 3 full PTO/batteries charge cycles can be shortened to 1.25

¹³ PV panels hourly power output 261.875 KW – Auxiliaries Hourly Power Load 227 KW = 34.875 KWh

hours instead of 1.74. The last 2 PTI cycles' power thrust output will be reduced and adjusted accordingly, thus power supply to auxiliaries always remains uninterrupted.

The two extended PTI and the two shortened PTO/charging cycles must only take place during the PV panels' 8 daylight operational hours.

$$\textbf{\textit{PTO\&Batteries Short. Charge Cycle Time}} = 1200KW / (920KW + 35 KW) = \textbf{\textit{1.25 hours}}$$

$$\textbf{\textit{PTI\&Batteries Ext. Disch. Cycle Time}} = 1200 KW / (1000 - 35) KW = \textbf{\textit{1.235 hours}}$$

Considering maximum utilization of batteries under this configuration, renewal of BESS will be needed every 875 sailing days period.

By applying Equations 2, 3 and 7 on Table 41 figures, the reduced daily VLSFO and LSMGO consumption are calculated. Additionally, the total reduced auxiliary power load of DGs is illustrated in below tables:

Table 42. Scenario 6 – Optimum configuration - Reduced Consumption

	M/E daily red. cons (mt Vlsfo)	M/E daily red. cons (mt Lsmgo)	Total Daily Thrust Output (kWh)	M/E Total Daily Red. Output (kWh)	DGs daily red. cons (mt Vlsfo)	DGs daily red. cons (mt Lsmgo)	Aux. total Load (kWh)	DGs total red. Load (kWh)	Thrust % from renew.	Aux. % from renew.	Daily VLSFO Saving (mt)	Daily LSMGO Saving (mt)
Open Sea Sailing	43.58	0.00	237048	229047	0.00	0.00	5448	0	3.4%	100.0%	2.82	0.10
ECAs Sailing	0.00	43.58	237048	229047	0.00	0.00	5448	0	3.4%	100.4%	0.00	2.92
Port/ ECA Manvr.	-	26.5	139440	-	0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Idle	-	-	-	-	0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Ball./De bal.	-	-	-	-	0.00	4.55	23328	21233	0	9.0%	0.00	0.45

By applying Equations 1 and 8 on Table 42 figures, the corresponding daily emissions' reduction in CO2 equivalent is illustrated in below tables:

Table 43. Scenario 6 – Optimum configuration - Reduced Emissions

	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	137.84	0.00	0.00	0.00	137.84	9.25	6.3%
ECAs Sailing	0.00	141.85	0.00	0.00	141.85	9.51	6.3%
Port/ECA Maneuvering	0.00	86.26	0.00	9.93	96.19	1.46	1.5%
Port Idle	0.00	0.00	0.00	9.93	9.93	1.46	12.8%
Port Ball./Debal.	0.00	0.00	0.00	14.81	14.81	1.46	9.0%

With optimum configuration the daily reduction of emissions could theoretically reach 6.3% at sea and 12.8% at port. The total average reduction of emissions has been calculated at **6.1%** per TRC, while the fuel savings at 706 mt of VLSFO and 157 mt of LSMGO per year.

TRC legs and duration remain as per initial, therefore the figures from tables 10,11 and 12 apply. The required BESS Renewals for the 7.5 cycles remain as per Table 38, with replacement needed every approximately 3 years.

By applying Equations 9 and 10 on these figures the total savings and OPEX per period are calculated.

Table 44. Scenario 6 Total Savings and OPEX

	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX €
PER TRC	50,942	19,407	11,313	81,662	16,339
PER YEAR	494,474	188,377	109,815	792,666	158,598
PER 5 YEAR	2,472,370	941,885	549,075	3,963,329	792,989
PER 10 YEAR	4,944,739	1,883,769	1,098,150	7,926,658	1,585,978

Total OPEX figures include the annual maintenance costs for each period and BESS renewal costs. Savings are overcovering the OPEX by 5 times.

For calculating the ROI period through equation 11 the total CAPEX are incorporated.

Table 45. Scenario 6 Total CAPEX & OPEX

Component	<u>CAPEX</u> €	<u>Total OPEX</u> <u>(PER YEAR)</u> €
2MWh EMS & BESS	850,000	132,888
PV Panels Full Hatch Coverage	1,796,000	18,210
PTI/PTO (7.5 cycle operation)	4,000,000	7,500
<i>Total</i>	6,646,000	158,598

The resulting **ROI period** is **10.5 years**.

Scenario 6 Outcome

With the optimum utilization of the two most environmentally and cost environmentally efficient technologies, the emission of 27,454 mt of CO₂ equivalent emissions could theoretically be avoided within a 10-year period. Furthermore, the total cost savings are surpassing the relevant calculated OPEX by 5 times, reaching almost 8 million euros. Nevertheless, the amount of 6.6 million of the initial required investment is creating a return of investment period of 10.5 years, which cost wise could deter shipowners from such a long-term investment, especially for older vessels.

Chapter 7 – Discussion, Conclusion and Future Research

The aim of this study was to explore the fine balance between commercial profit which is the main drive of all business, including shipping and the necessary need for environmental sustainability.

Through literature review of existing and potentially applicable maritime renewable energy technologies in Chapter 2, a joint technologies concept has been then developed. There have been various promising and tested renewable energy technologies for the maritime sector, however the range of commercial applicability has been low, mainly due to the high initial required investment costs and the non-availability of onboard operation and economic historical data.

The comparison, review and sorting of the identified technologies led into a selection of four energy harvesting and one storage option, which comprise the full concept. The sorting and selection of technologies was done through a qualitative approach and based on factors such as systems' interconnectivity, operational flexibility and others, without considering costs.

These technologies are the photovoltaic panels, the helical vertical-axis wind turbines, the piezoacoustic panels and magnetic shaft generators. All four of them can be combined thus harvested energy can then supply a vessel's auxiliary power needs or provide her with propelling thrust power, while also being stored into batteries through energy storage and management system.

A Kamsarmax bulk carrier was chosen as case study vessel for reviewing retrofit applicability of the concept. A brief technical study of the applicability and installation requirements on each concept's component was conducted, for academic purposes. However, a more thorough technical study would be needed prior to a final application on a commercial vessel. Installation and maintenance costs simulation has also been included, based on available and commercially disclosable data.

In continuation, a scenario-based environmental and economic analysis of the joint technologies concept has been conducted on the full concept but also on different variations of included components. In order to proceed, a case study major trade route between Louisiana and Rotterdam has been analyzed and later applied on the scenarios.

Among the 6 different main scenarios, with 4 additional sub-scenarios, only the scenarios including photovoltaics or magnetic shaft generator result in a considerable environmental benefit and commercially viable outcome, with ROI periods within vessel's possible life time. Nonetheless, due to the high required CAPEX, deriving from technologies' and retrofit costs, the resulting ROIs from even the most optimum configurations, are close to 10 years period. On the contrary, the corresponding savings are exceeding OPEX by 5 times, while the environmental benefits are very promising with a possible 6.3% vessel's emissions reduction at sea and 12.8% at port, at optimum configuration. Optimization on the usage of technologies and the accompanying battery storage system, was primarily targeting full coverage of vessel's auxiliary load at open sea, thus achieving double benefits of reduced consumption and emissions, by simultaneously reducing the diesel generator operating hours.

The most efficient technology at open sea is the magnetic shaft generator, while during port stay only the PV panels could provide a considerable power output resulting to the 12.8% emissions' reduction. However, if isolated installed, the PV panels at full hatch coverage may only provide a 1.3% average reduction of emissions, with 13.2 years ROI period. Nonetheless, the energy storage systems' purchase and necessary batteries' replenishment costs, also play a significant role in the prolonged ROI periods.

Considering that these technologies could also be directly being installed on newbuilt vessels, the corresponding CAPEX would be reduced and as a result ROI period would be reduced, making such an investment much more tempting for shipowners. Joint mass installation projects from pools of different shipowners could probably assist in achieving lower initial required investment costs.

Concluding, this study has illustrated that the renewable energy technologies are here and can provide both actual environmental and economic benefits. The shipping industry though, similarly to most business, is reluctant to take big steps towards a more environmentally orientated operation mode due to the maximizing profits' operational mode preference. The fine balance between business and environmental sustainability is possible, with various options, once all involved parties are aligned.

In example, in an ideal world, the high required CAPEX of such investments can be split between shipowners and possible long-time charterers for the benefit of the environment and sacrifice of some profit percentage. Tax incentives or even subsidies by governments or vessels'

flag administration could also be great motivational tools for shipowners, in order to quickly adapt and embrace such renewable energy technologies.

Finally, the more the actual onboard installations will be taking place, the more the feedback and historical data which will be accumulated and assist in further evolution of the green maritime technologies.

7.1 Future Research

Wishing this study to be considered one more step towards that direction, while passing some valuable data for future research and on field tests.

Despite the optimum suggested configuration, further studies could explore the mitigation of costs for the technologies mentioned, as the high required initial investment seem to be a major obstruction towards a rapid transition to “greener” vessels. Full technical and feasibility studies on the application of these technologies on the same and other types of vessels (i.e. tankers), should also be carried out. New construction studies for newbuilding vessels, which could incorporate as many as possible renewable energy technologies should be conducted, thus also taking advantage of any available, unexploited on board areas.

Additionally, despite VAWTs being considered non-viable cost wise, different wind turbine configurations and installation options could be explored, manufactured for example from lighter materials, which would then require less deck reinforcements.

Advanced CFD studies on vessels’ aerodynamics could also assist minimizing the loss of speed due to counter wind and therefore result in less fuel consumption and emissions.

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APPENDIXES

Appendix 1 – Computational Fluid Dynamics Simulation on Vertical Axis Wind Turbines' Aerodynamic Deployment

Here below, the 3d model creation, CFD process, input data and errors' troubleshooting are briefly described.

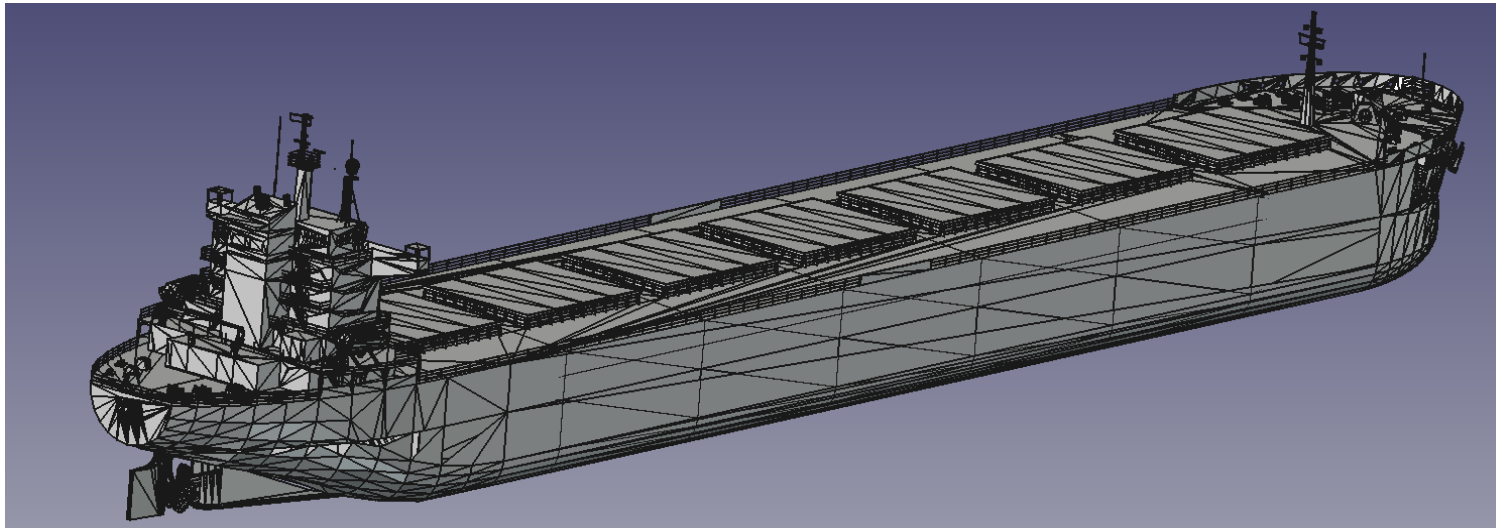
Model Creation

The 3D model was developed basis a similar size Panamax Bulk carrier. The initial model was simplified for computation time optimization and errors' avoidance during mesh creation, within the CFD software. The simplification was carried out through FreeCad Software (FreeCad, 2026) by manually deleting elements, such as stern railings, ladders and superstructure, which would not significantly affect the airflow from a head wind. This stage was time consuming, however vital, as the initial model could not be successfully loaded into the CFD software.

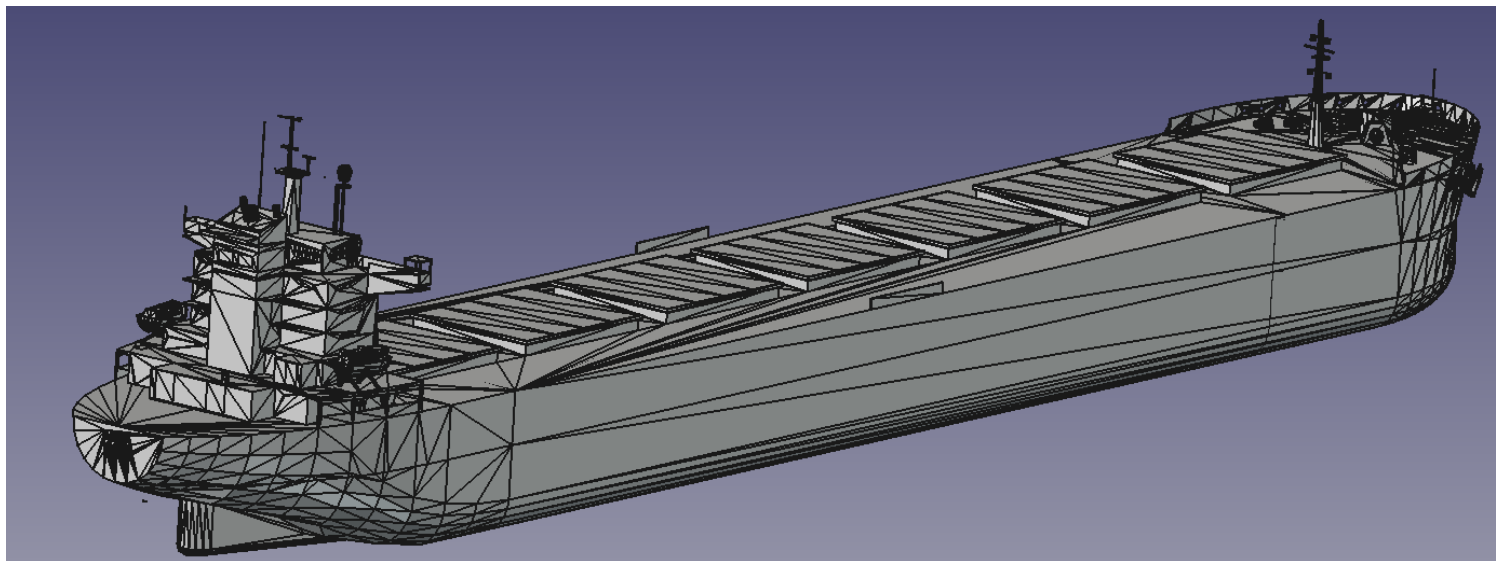
The helical VAWTs were redesigned according to WS-12 technical data sheet and by also adding a support pillar of half diameter (1 m) of the WS-12 VAWT's. The total deployment height was set at 13.13 m max, thus not exceeding forward mast's height and also not obstructing bridge visibility. The on deck deployment was only considered for the spaces between hatches No 2 to No 3, No 4 to 5 and No 5 to No 6, due to deck equipment and superstructure, based on the case study vessel's drawings. The transverse deployment of VAWTs aimed to create an aerodynamic cone deployment, thus redirecting most of head wind flow towards the sides of accommodation, thus reducing air resistance on the superstructure. Small variations of the initial deployment, in regards to VAWTs' deployment height and transverse distance have been created for the CFD simulation.

Sample pictures of the model creation process are illustrated below.

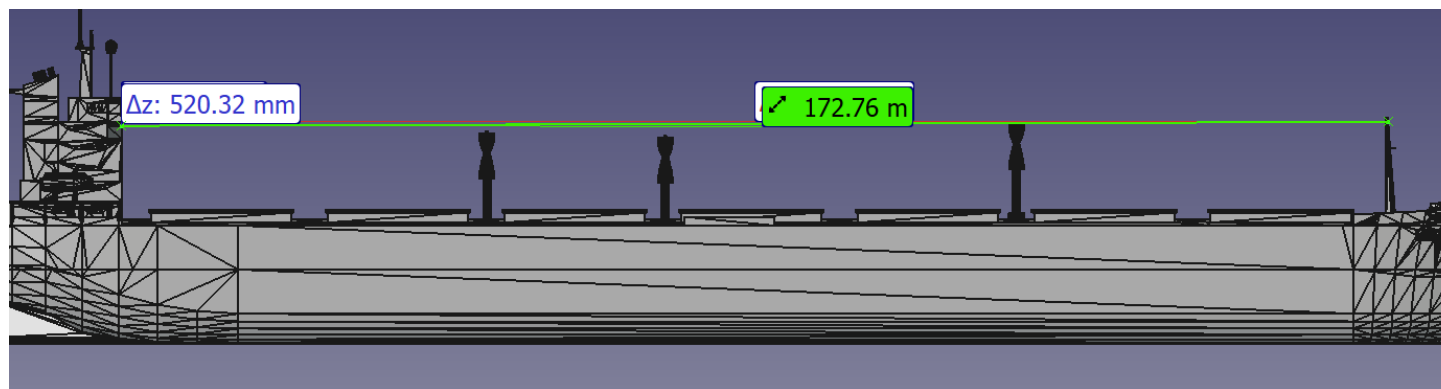
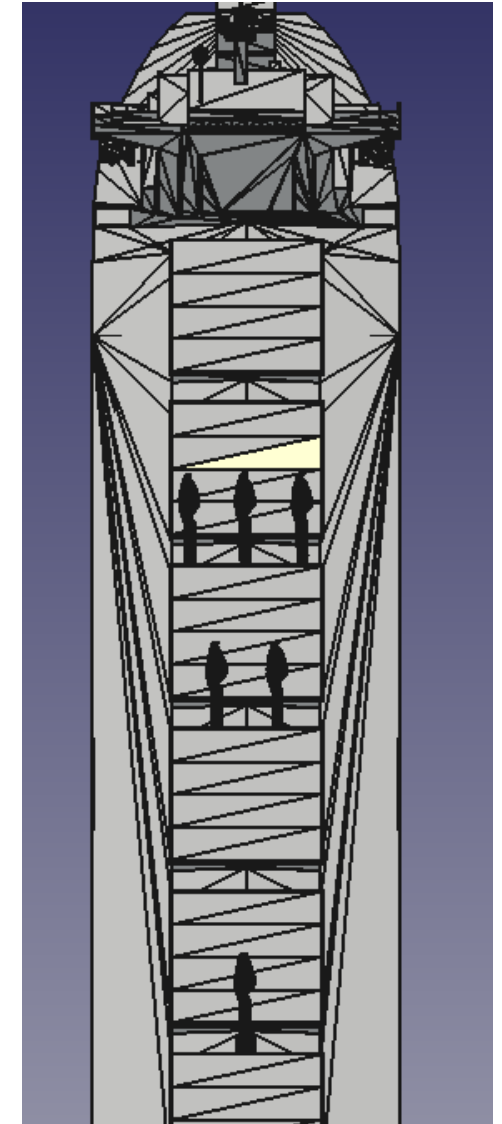
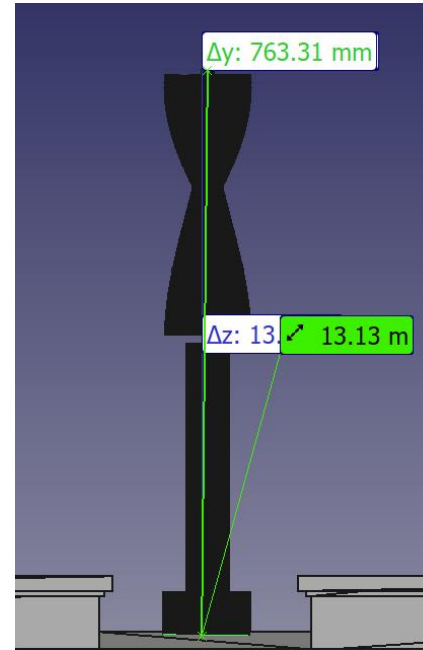
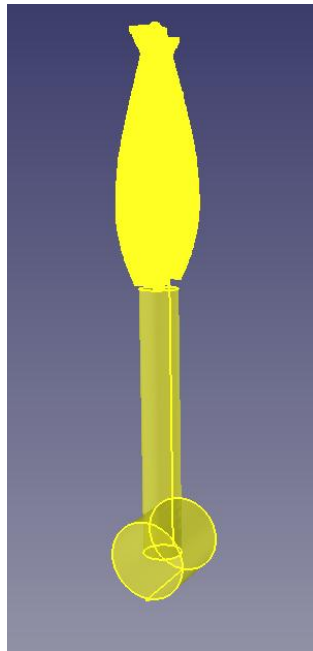
INITIAL 3D MODEL

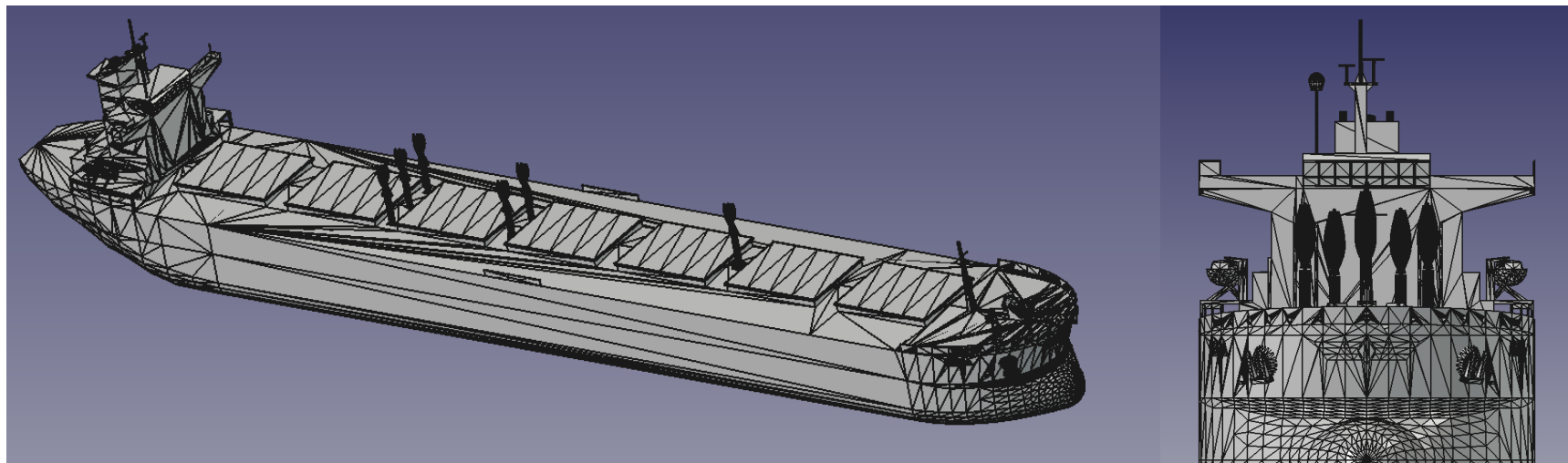
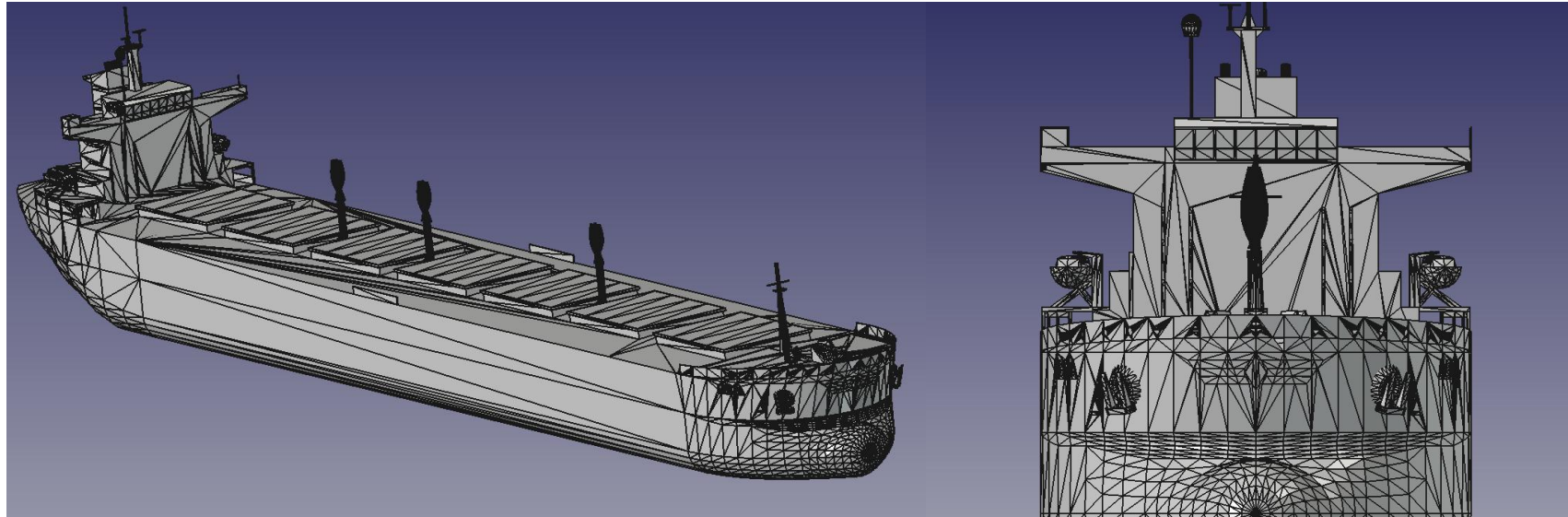


SIMPLIFIED 3D MODEL



HELICAL VAWTs





CFD Simulation

The most important stage for the CFD simulation was to successfully import the vessel's models into the software and create a complete 3D mesh for analysis. Due to complexity of the 3D models the import and mesh creation could only be completed without errors, under the professional version of the program, which was gratefully provided by SimFlow (SimFlow, 2026), for a trial period and for academic purpose.

The initial simplified Panamax 3D model could be directly installed and its mesh being created without errors, however the VAWTs installed models' meshes could not be successfully created. Therefore, the VAWTs' models were independently reimported and relocated on top of the initial simplified Panamax 3D model. The complete 3D mesh could then be created.

The simulation was based on the Sim Flow's CFD tutorial for wind around buildings. The head wind's velocity, Geometries and Mesh parameters have been changed, thus better applying onto the bulk carrier's case while sailing at sea and under a theoretical 8 m draft. The data input, parameters, as well as sample pictures of the CFD simulation process and results are illustrated in the following pages.



INITIAL DATA, PARAMETERS

GeometryBasePointMesh

Base Mesh Type

BoxCylinderPlateWedge

Geometry

Min [m]-300-3008

Max [m]500300400

Autosize

Mesh

Division322418

Grading111.07

Cell Size [m]252521.778

Lock Cell Size

SolversSIMPLEResidualsRelaxationLimits

pUkε

SolverGAMG

SmootherGauss-Seidel

Cache Agglomeration

AgglomeratorFace Area Pair

Cells In Coarsest Level10

Merge Levels1

Pre Sweeps0

Post Sweeps1

Finest Sweeps2

Max Iterations100

Tolerance1e-06

Relative Tolerance1e-02

SolversSIMPLEResidualsRelaxationLimits

pUkε

SolverPBiCG Stabilized

PreconditionerDILU

Max Iterations100

Tolerance1e-06

Relative Tolerance0.1

TURBULENCE

Enable Turbulence Equations

Turbulence Modeling

LaminarRANSLES

Modeling Options

ModelRNG k-ε

C_μ0.0845

C₁1.42

C₂1.68

σ_k0.71942

σ_ε0.71942

η₀4.38

β0.012

BOUNDARY CONDITIONS

Boundaries

bottominletleftoutletpanamax_components_min_reduced_Solid001savonius_vawt_ws12_solid_Compound001_Solid_savonius_vawt_ws12_solid_Compound001_Solid_...

FlowTurbulence

pTypeZero Gradient

UTypeAtmospheric Inlet

Flow Dir. [-]100

Vertical Dir. [-]001

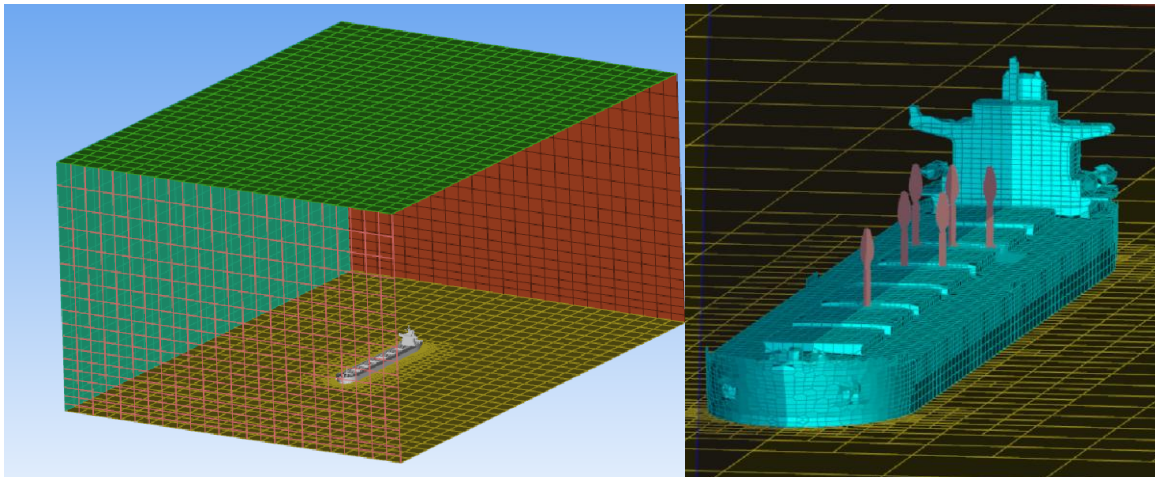
U_{ref} [m/s]9

z_{ref} [m]1

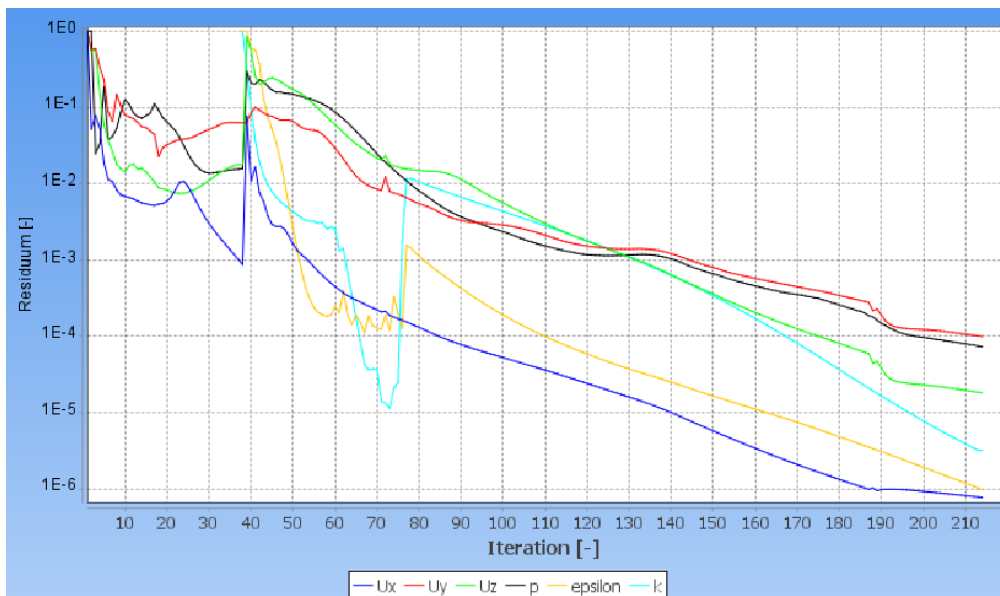
z₀ [m]0.1

z_{ground} [m]0

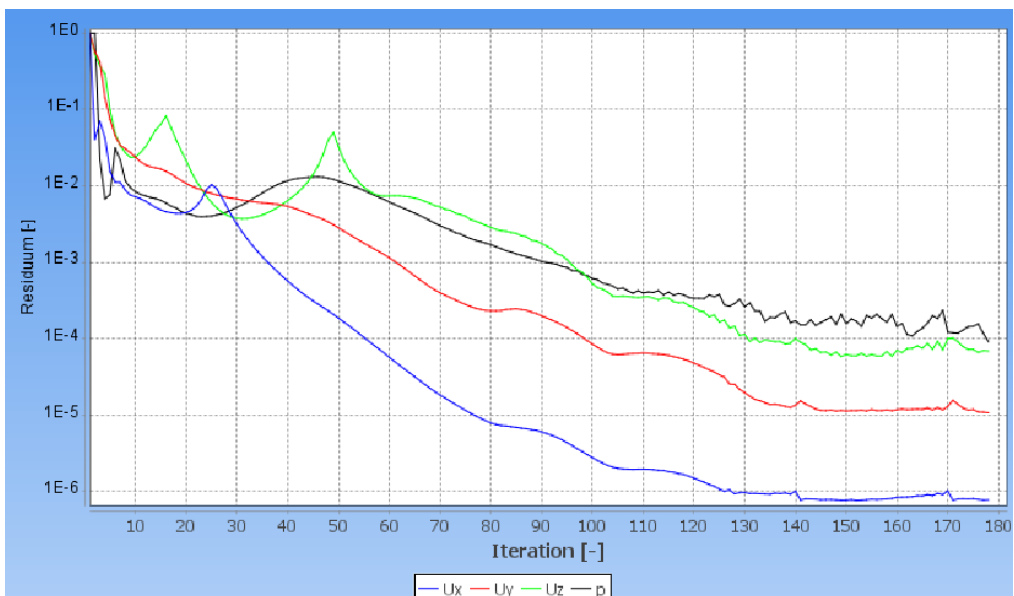
CFD RUNS



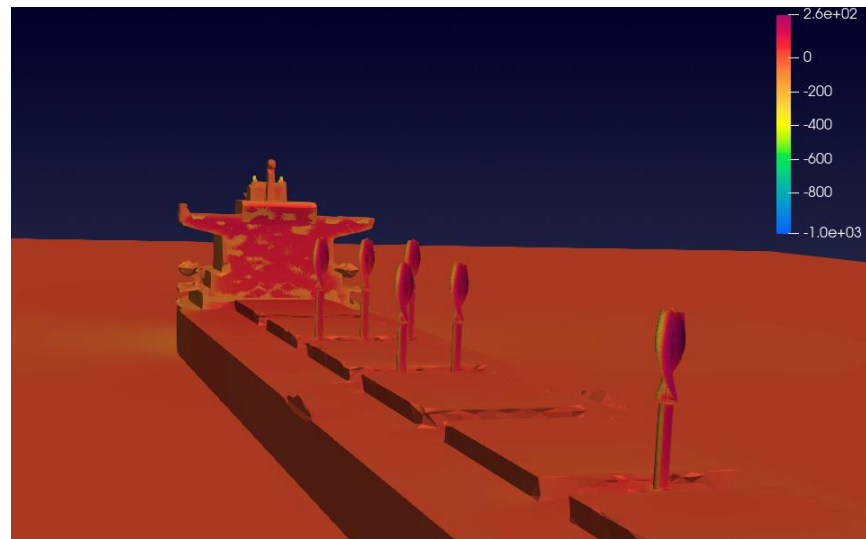
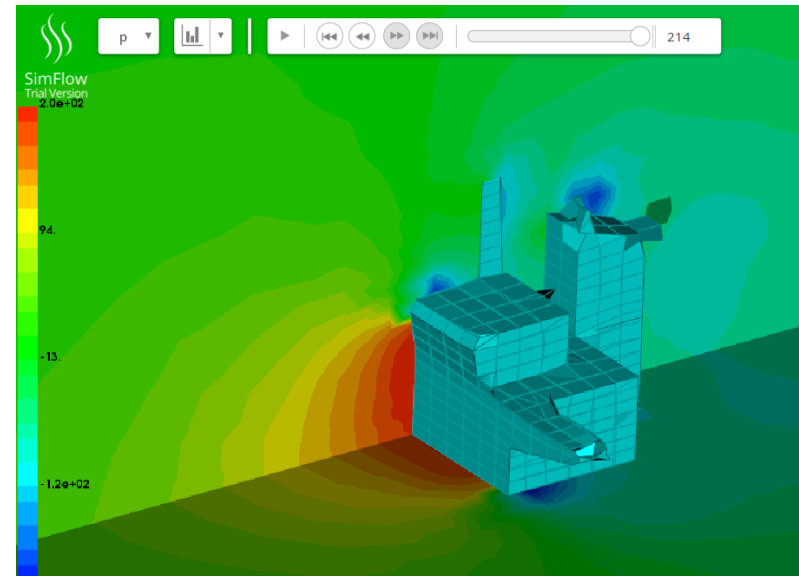
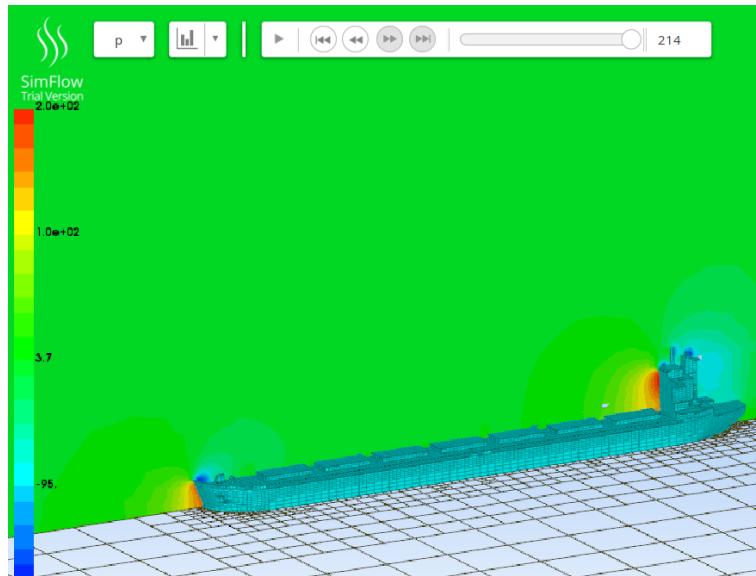
NO VAWTs MODEL SIMULATION

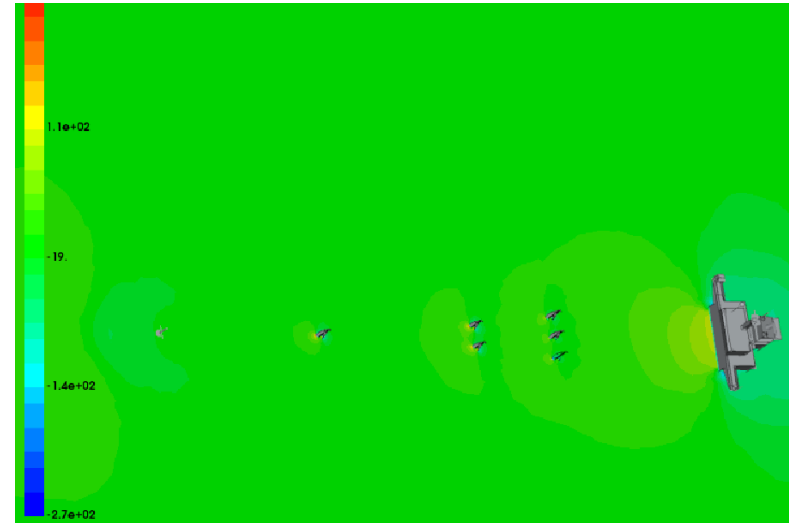


6 VAWTs MODEL SIMULATION

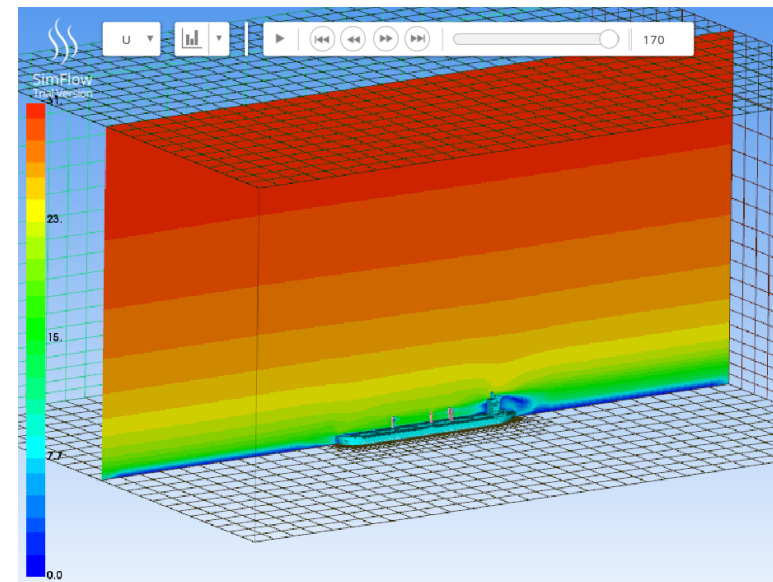
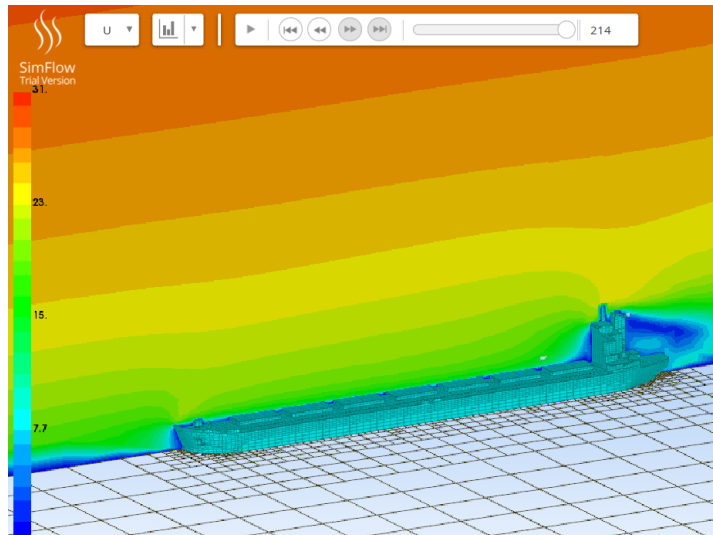
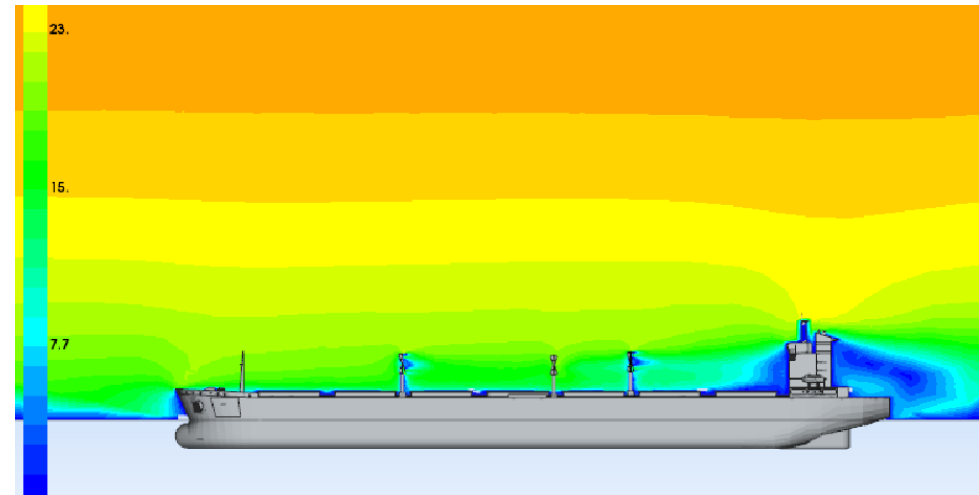
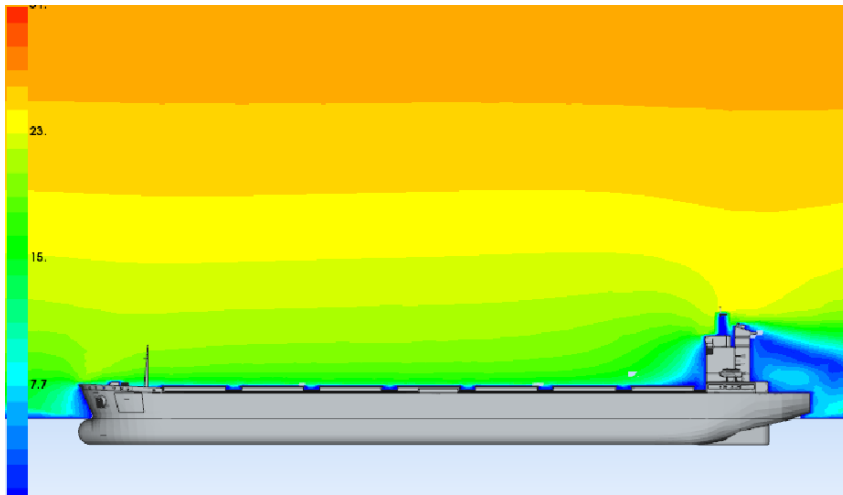


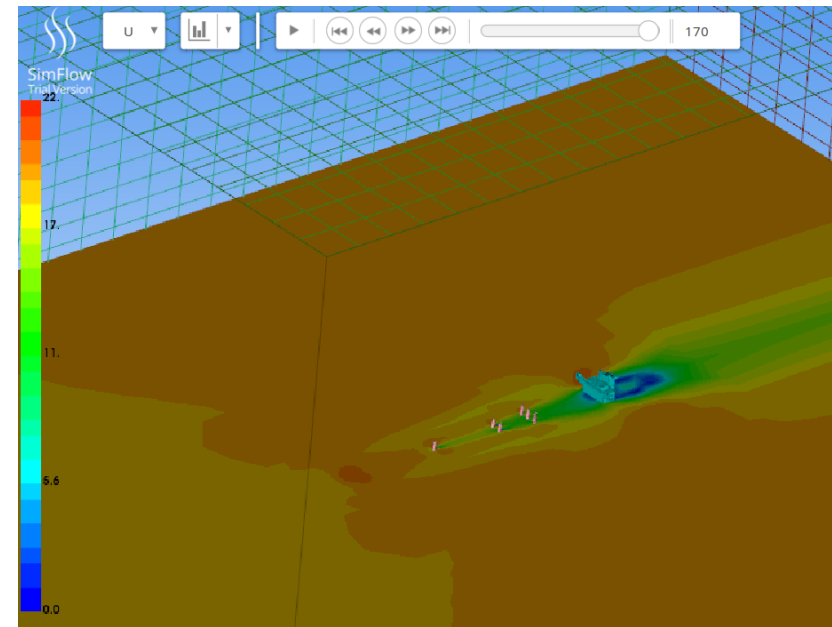
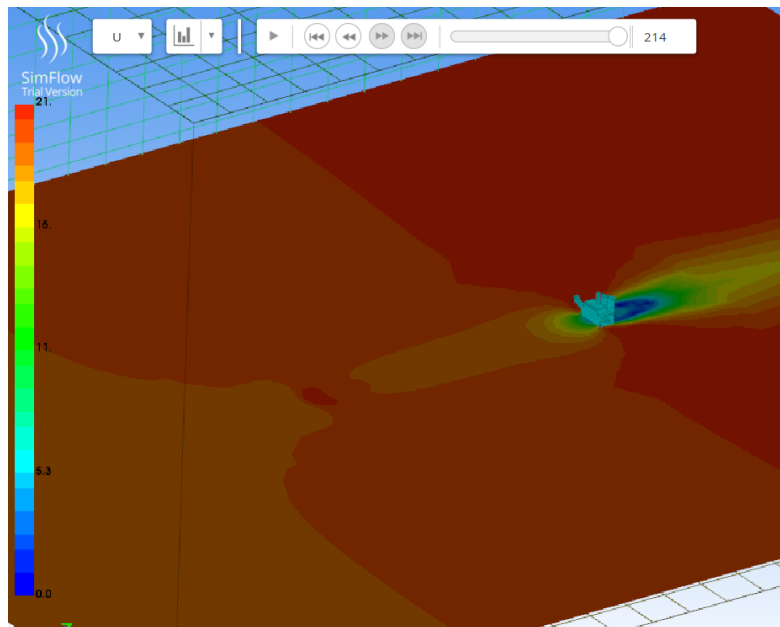
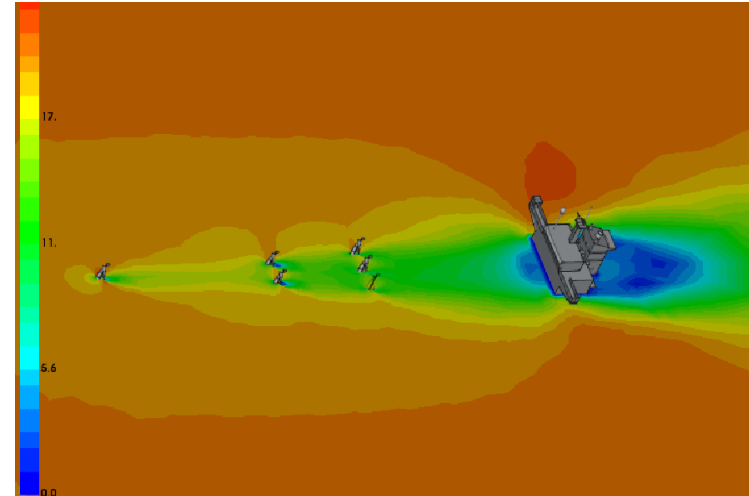
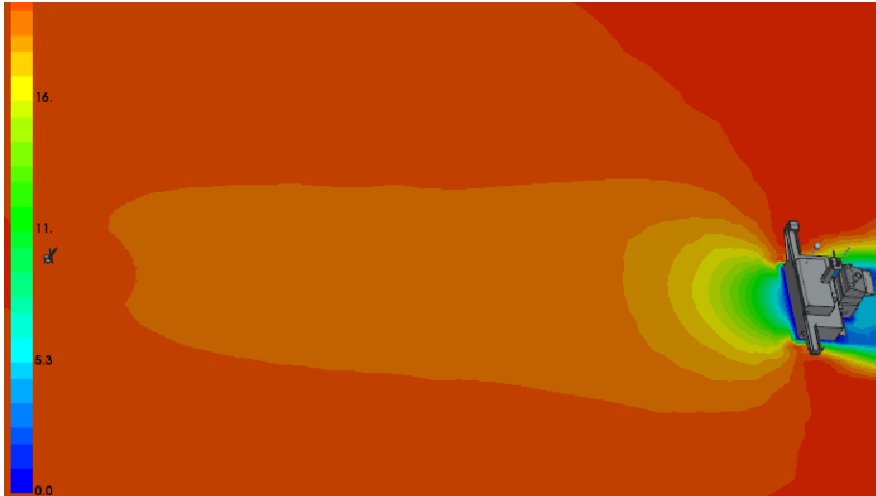
PRESSURE RESULTS





AIR FLOW VELOCITY RESULTS





Appendix 2 – Emissions and EU/ETS Calculation

Basic Assumptions

<i>Basis</i>	Emissions from	Emissions from
<i>(EU) 2023/1805</i>	VLSFO	LSMGO
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206
Cf CH ₄ (gCH ₄ /gFuel)	0.00005	0.00005
Cf N ₂ O (gN ₂ O/gFuel)	0.00018	0.00018

GWP factor	CO₂ Equivalent
CO₂	1
CH₄	28
N₂O	265

Calculations for 24 hours day. Two decimals rounding.

Kamsarmax At Sea (Outside ECAs)

Main Engine:

VLSFO cons x [(CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂O CO₂ eq. factor)] = 45.1 x [(3.114 x 1) + (0.00005 X 28) + (0.00018 X 280)] = **142.66** mt CO₂ eq

Diesel Generators:

VLSFO cons x [(CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂O CO₂ eq. factor)] = 1.3 x [(3.114 x 1) + (0.00005 X 8) + (0.00018 X 280)] = **4.11** mt CO₂ eq

+

LSMGO cons x [(CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂O CO₂ eq. factor)] = 0.1 x [(3.206 x 1) + (0.00005 X 8) + (0.00018 X 280)] = **0.33** mt CO₂ eq

Total Main Engine and Diesel Generators = 142.66 + 4.11 + 0.33 = **147.10** mt CO₂ eq.

Kamsarmax At Sea (Inside ECAs)

Main Engine:

LSMGO cons x [(CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂OCO₂ eq. factor)] = 45.1 x [(3.206 x 1) + (0.00005 X 28) + (0.00018 X 280)] = **146.81** mt CO₂ eq

Diesel Generators:

LSMGO cons x [(CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂OCO₂ eq. factor)] = 1.4 x [(3.206 x 1) + (0.00005 X 8) + (0.00018 X 280)] = **4.56** mt CO₂ eq

Total Main Engine and Diesel Generators = 146.81 + 4.56 = 151.37 mt CO₂ eq.

Kamsarmax At Port Maneuvering (Inside ECAs)

Main Engine:

LSMGO cons x [(CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂OCO₂ eq. factor)] = 26.5 x [(3.206 x 1) + (0.00005 X 28) + (0.00018 X 280)] = **86.26** mt CO₂ eq

Diesel Generators:

LSMGO cons x [(CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂OCO₂ eq. factor)] = 3.5 x [(3.206 x 1) + (0.00005 X 8) + (0.00018 X 280)] = **11.39** mt CO₂ eq

Total Main Engine and Diesel Generators = 86.26 + 11.39 = 97.65 mt CO₂ eq.

Kamsarmax At Port (Inside ECAs)

Diesel Generators (IDLE AT PORT):

LSMGO cons x [(CO₂ emissions X GWP CO₂ eq. factor) + (CH₄ emissions X GWP CH₄CO₂ eq. factor) + (N₂O emissions x GWP N₂OCO₂ eq. factor)] = 3.5 x [(3.206 x 1) + (0.00005 X 8) + (0.00018 X 280)] = **11.39** mt CO₂ eq

Diesel Generators (BALLASTING AT PORT):

$$\text{LSMGO cons} \times [(\text{CO}_2 \text{ emissions} \times \text{GWP CO}_2 \text{ eq. factor}) + (\text{CH}_4 \text{ emissions} \times \text{GWP CH}_4 \text{CO}_2 \text{ eq. factor}) + (\text{N}_2\text{O emissions} \times \text{GWP N}_2\text{OCO}_2 \text{ eq. factor})] = 5 \times [(3.206 \times 1) + (0.00005 \times 8) + (0.00018 \times 280)] = \mathbf{16.28 \text{ mt CO}_2 \text{ eq}}$$

Appendix 3 – Case Study Route & TRC Calculations

INITIAL ROUTE & TRC DURATION

Voyage Leg	Nautical Miles	Average Speed	hours	days
<i>ECA Sail. Loading Port in Ballast</i>	210	15.01	14.99 ¹⁴	<u>0.625</u>
<i>Port Maneuvering Loading</i>	139	-	16.00 ¹⁵	<u>0.667</u>
<i>Port Stay Laden (Idle)</i>	0	0	12.00	<u>0.500</u>
<i>Port Stay Laden (Debal)</i>	0	0	60.00	<u>2.500</u>
<i>Port Maneuvering Loading Port</i>	139	-	15.00	<u>0.625</u>
<i>ECA Sail. Loading Port in Laden</i>	210	13.3	15.79	<u>0.658</u>
<i>Open Sea Sail. Laden</i>	4364	13.3	328.12	<u>13.672</u>
<i>ECA Sail. Disch. Port in Laden</i>	350	13.3	26.32	<u>1.096</u>
<i>Maneuvering Eng.Ch.in Laden</i>	120	12.5	9.60	<u>0.400</u>
<i>Port Maneuvering Discharge</i>	20	-	5.00 ¹⁶	<u>0.208</u>
<i>Port Stay Discharging Port (Idle)</i>	0	0	12.00	<u>0.500</u>
<i>Port Stay Discharging Port (Ball)</i>	0	0	60.00	<u>2.500</u>
<i>Port Maneuvering Discharge Port</i>	20	-	4.00	<u>0.167</u>
<i>Maneuvering Eng.Ch.in Ballast</i>	120	12.5	9.60	<u>0.400</u>
<i>ECA Sail Disch. Port in Ballast</i>	350	15.01	23.32	<u>0.972</u>
<i>Open Sea Sail. Ballast</i>	4364	15.01	290.74	<u>12.114</u>
Total TRC				37.603

Open Sea Sailing Days = Open Sea Sail. Laden + Open Sea Sail. Laden = 13.672 + 12.114

= 25.786 Days

ECA Sailing Days = ECA Sail. Loading Port in Ballast + ECA Sail. Loading Port in Laden + ECA Sail. Disch. Port in Laden + ECA Sail Disch. Port in Ballast = 0.625 + 0.658 + 1.096 + 0.972 = **3.351 Days**

¹⁴ One hour has been added for slow down/testing

¹⁵ One hour has been added due to berth approaching

¹⁶ One hour has been added due to berth approaching

Port/ECA Maneuvering Days = Port Maneuvering Loading + Port Maneuvering Loading Port + Maneuvering Eng.Ch.in Laden + Port Maneuvering Discharge + Port Maneuvering Discharge Port + Maneuvering Eng.Ch.in Ballast = $0.667 + 0.625 + 0.4 + 0.208 + 0.167 + 0.4 = 2.467$
Days

Port Idle Days = Port Stay Laden (Idle) + Port Stay Discharging Port (Idle) = $0.5 + 0.5 = 1.0$
Day

Port Ballasting./Deballasting Days = Port Stay Laden (Debal) + Port Stay Discharging Port (Ball) = $2.5 + 2.5 = 5.0$
Days

EU Port Idle Days = Port Stay Discharging Port (Idle)

EU Port Ballasting/Deballasting Days = Port Stay Discharging Port (Ball)

Open Sea Sailing Days	ECAs Sailing Days	Port/ECA Maneuvering Days	Port Idle Days	Port Ball./Debal. Days
25.786	3.351	2.467	1.000	5.000

EU port (iddle) Days	EU Port Ba.l/Debal. Days
0.500	2.500

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
37.603	0.103	9.7	48.53	97.07

PROLONGED ROUTE & TRC DURATION DUE TO PORT DELAYS (6 VAWTs)

Voyage Leg	Nautical Miles	Average Speed	hours	days
<i>ECA Sail. Loading Port in Ballast</i>	210	15.01	14.99 ¹⁷	<u>0.625</u>
<i>Port Maneuvering Loading</i>	139	-	16.00 ¹⁸	<u>0.667</u>
<i>Port Stay Laden (Idle)</i>	0	0	12.00	<u>0.500</u>
<i>Port Stay Laden (Debal)</i>	0	0	72.00	<u>3.000</u>
<i>Port Maneuvering Loading Port</i>	139	-	15.00	<u>0.625</u>
<i>ECA Sail. Loading Port in Laden</i>	210	13.3	15.79	<u>0.658</u>
<i>Open Sea Sail. Laden</i>	4364	13.3	328.12	<u>13.672</u>
<i>ECA Sail. Disch. Port in Laden</i>	350	13.3	26.32	<u>1.096</u>
<i>Maneuvering Eng.Ch.in Laden</i>	120	12.5	9.60	<u>0.400</u>
<i>Port Maneuvering Discharge</i>	20	-	5.00 ¹⁹	<u>0.208</u>
<i>Port Stay Discharging Port (Idle)</i>	0	0	12.00	<u>0.500</u>
<i>Port Stay Discharging Port (Ball)</i>	0	0	72.00	<u>3.000</u>
<i>Port Maneuvering Discharge Port</i>	20	-	4.00	<u>0.167</u>
<i>Maneuvering Eng.Ch.in Ballast</i>	120	12.5	9.60	<u>0.400</u>
<i>ECA Sail Disch. Port in Ballast</i>	350	15.01	23.32	<u>0.972</u>
<i>Open Sea Sail. Ballast</i>	4364	15.01	290.74	<u>12.114</u>
Total TRC				37.603

Port Ballasting./Deballasting Days = Port Stay Laden (Debal) + Port Stay Discharging Port (Ball) = 3.0 + 3.0 = **6.0 Days**

¹⁷ One hour has been added for slow down/testing

¹⁸ One hour has been added due to berth approaching

¹⁹ One hour has been added due to berth approaching



Open Sailing Days	Sea Days	ECAs Days	Sailing Days	Port/ECA Maneuvering Days	Port Idle Days	Port Ball./Debal. Days
25.786		3.351		2.467	1.000	6.000

EU port (iddle) Days	EU Ba.l/Debal. Days
0.500	3.000

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
38.603	0.106	9.5	47.28	94.55

Appendix 4 – Scenarios’ Calculation Tables

The calculation tables below have been created in Excel sheets, using the Methodology and equations 1 to 11, as described in Chapter 3. For yearly, 5 yearly and 10 yearly results of each scenario ,the corresponding TRC results have been simply multiplied with the TRCs per year number and then with 5 or 10.

SCENARIO 1 FULL CONCEPT

INITIAL CONSUMPTION/EMISSIONS PER TRC/1 YEAR/5 YEARS/10 YEARS

<i>(EU) 2023/1805</i>	Emissions from VLSFO	Emissions from LSMGO
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206
Cf CH ₄ (gCH ₄ /gFuel)	0.00005	0.00005
Cf N ₂ O (gN ₂ O/gFuel)	0.00018	0.00018

GWP factor	CO ₂ Equivalent
CO₂	1
CH₄	28
N₂O	265

Open Sailing	Sea Days	ECAs Days	Sailing Port/ECA Maneuvering Days	Port Days	Idle	Port Days	Ball./Debal
25.786		3.351	2.467	1.000		6.000	

EU port (iddle)	EU Bal/Debal
0.500	3.000



TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
38.603	0.106	9.5	47.28	94.55

PER TRC	M/E Total (mt VLSFO)	M/E Total (mt LSMGO)	M/E Total Thrust Output (MWh)	DGs total Consumption (mt VLSFO)	DGs total Consumption (mt LSMGO)	DGs Total Load (MWh)	Total VLSFO (mt)	Total LSMGO (mt)	Total Power Output (MWh)
Open Sea Sailing	1162.9	0.0	6112.5	33.5	2.6	140.5	1196.5	2.6	6,253.0
ECAs Sailing	0.0	151.1	794.2	0.0	4.7	18.3	0.0	155.8	812.5
Port/ECA Maneuvering	0.0	65.4	344.0	0.0	8.6	40.3	0.0	74.0	384.2
Port Idle	0.0	0.0	0.0	0.0	3.5	16.3	0.0	3.5	16.3
Port Ball./Debal.	0.0	0.0	0.0	0.0	30	140.0	0.0	30.0	140.0
TOTAL PER TRC							1196.5	265.9	7606.0

TOTAL PER YEAR	11,313	2,514	71,916
TOTAL PER 5 YEAR	56,564	12,570	359,579
TOTAL PER 10 YEAR	113128	25140	719159



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.		Total emissions mt CO2 eq.	EU/ETS FACTOR		
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92	50%		
ECAs Sailing	0.00	491.88	0.00	15.27		507.15	50%		
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	50%		
Port Idle	0.00	0.00	0.00	11.39		11.39	50%	EU 100%	US 0%
Port Ball./Debal.	0.00	0.00	0.00	97.65		97.65	50%	EU 100%	US 0%
					TOTAL PER TRC	4,650.0			
					TOTAL PER YEAR	43,967			
					TOTAL PER 5 YEAR	219,833			
					TOTAL PER 10 YEAR	439,667			



SCENARIO 1 RENEWABLE TECHNOLOGIES OUTPUT

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i>Daily running hours (at port)</i>	<i>Daily running hours (at sea)</i>
<i>PV Panels Full Hatch Coverage</i>	2095	2095	0	8	8
<i>VAWTs (6)</i>	0	196.8	0	-	24
<i>PZ acoustic Panels</i>	0.028	0.028	0	24	24
<i>PTI/PTO (4 cycle operation)</i>	0	3180	8400	-	22.14
Total	2095.03	5471.83	8400.00		

Saling Days per TRC	Total Saling days per year	Total Saling days per 5 years	Total Saling days per 10 years
29.136	275.5	1377.45	2754.91

BESS RENEWALS	0.31	1.57	3.15
--------------------------	------	------	------

BESS lifespan 875



SCENARIO 1 REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentage from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	43.50	0.00	237048	228648	0.00	0.00	5448	0	3.5%	100.4%	2.90	0.10
ECAs Sailing	0.00	43.50	237048	228648	0.00	0.00	5448	0	3.5%	100.4%	0.00	3.00
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Idle	0	0	0		0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Ball./Debal.	0	0	0		0.00	4.55	23328	21233	0	9.0%	0.00	0.45

	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	137.60	0.00	0.00	0.00	137.60	9.49	6.5%
ECAs Sailing	0.00	141.60	0.00	0.00	141.60	9.76	6.4%
Port/ECA Maneuvering	0.00	86.26	0.00	9.93	96.19	1.46	1.5%
Port Idle	0.00	0.00	0.00	9.93	9.93	1.46	12.8%
Port Ball./Debal.	0.00	0.00	0.00	14.81	14.81	1.46	9.0%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)			DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1121.7	0.0			0.0	0.0		1121.7	0.0	74.73	2.58
ECAs Sailing	0.0	145.8			0.0	0.0		0.0	145.8	0.00	10.05
Port/ECA Maneuvering	0.0	65.4			0.0	7.5		0.0	72.9	0.00	1.11
Port Idle	0.0	0.0			0.0	3.1		0.0	3.1	0.00	0.45
Port Ball./Debal.	0.0	0.0			0.0	27.3		0.0	27.3	0.00	2.69
TOTAL PER TRC								1121.7	249.0	74.7	16.9

TOTAL PER YEAR	10,606	2,354	707	160
TOTAL PER 5 YEAR	53,031	11,772	3,533	798
TOTAL PER 10 YEAR	106,062	23,544	7,066	1,596



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.			DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3548.15	0.00			0.00	0.00		3548.15	244.78	6.5%	122.39
ECAs Sailing	0.00	474.45			0.00	0.00		474.45	32.70	6.4%	16.35
Port/ECA Maneuvering	0.00	212.78			0.00	24.49		237.27	3.61	1.5%	1.80
Port Idle	0.00	0.00			0.00	9.93		9.93	1.46	12.8%	0.73
Port Ball./Debal.	0.00	0.00			0.00	88.88		88.88	8.77	9.0%	4.38
TOTAL PER TRC								4,358.7	291.3	6.3%	145.7

TOTAL PER YEAR	41,212	2,754	6.26%	1,377
TOTAL PER 5 YEAR	206,061	13,772	6.3%	6,886
TOTAL PER 10 YEAR	412,122	27,545	6.3%	13,772

SCENARIO 1 CAPEX/OPEX/SAVINGS/ROI

Component	CAPEX	<u>OPEX (PER YEAR)</u>	<u>OPEX (PER 5 YEAR)</u>	<u>OPEX (PER 10 YEAR)</u>	<u>OPEX extra BESS Ren.</u>	<u>Total OPEX (PER YEAR)</u>	<u>Total OPEX (PER 5 YEAR)</u>	<u>Total OPEX (PER 10 YEAR)</u>
EMS & BESS (2Mwh)	850,000	3,600	18,000	36,000	400,000	129,539	647,693	1,295,386
<i>PV Panels Full Hatch Coverage</i>	1,796,000	18,210	91,050	182,100	0	18,210	91,050	182,100
<i>VAWTs (6)</i>	1,200,000	750	3,750	7,500	0	750	3,750	7,500
<i>PZ acoustic Panels</i>	140,000	1,500	7,500	15,000	0	1,500	7,500	15,000
<i>PTI/PTO (8 cycle operation)</i>	4,000,000	7,500	37,500	75,000	0	7,500	37,500	75,000
Total	7,986,000	31,560	157,800	315,600	400,000	157,499	787,493	1,574,986



PRICE Euro

	700	1200	80			
	Total VLSFO Savings €	Total LSMGO Savings €	Total EU/ets Savings € emissions mt CO2 eq.	TOTAL SAVINGS €	TOTAL OPEX COSTS €	ROI PERIOD YEARS
						12.5
TOTAL PER TRC	52,312	20,251	11,653	84,216	16,657	
TOTAL PER YEAR	494,621	191,478	110,178	796,277	157,499	
TOTAL PER 5 YEAR	2,473,103	957,392	550,890	3,981,385	787,493	
TOTAL PER 10 YEAR	4,946,205	1,914,785	1,101,780	7,962,770	1,574,986	

SCENARIO 2 PV FULL HATCH COVERAGE

INITIAL CONSUMPTION/EMISSIONS PER TRC/1 YEAR/5 YEARS/10 YEARS

<i>(EU) 2023/1805</i>	Emissions from VLSFO	Emissions from LSMGO
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206
Cf CH ₄ (gCH ₄ /gFuel)	0.00005	0.00005
Cf N ₂ O (gN ₂ O/gFuel)	0.00018	0.00018

GWP factor	CO ₂ Equivalent
CO₂	1
CH₄	28
N₂O	265

Open Sailing Days	Sea Days	ECAs Days	Sailing Port/ECA Maneuvering Days	Port Days	Idle	Port Days	Ball./Debal.
25.786		3.351	2.467	1.000		5.000	

EU port (iddle)	EU Bal/Debal
0.500	2.500

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
37.603	0.103	9.7	48.53	97.07



PER TRC	M/E Total (mt VLSFO)	M/E Total (mt LSMGO)	M/E Total Thrust Output (MWh)	DGs total Consumption (mt VLSFO)	DGs total Consumption (mt LSMGO)	DGs Total Load (MWh)	Total VLSFO (mt)	Total LSMGO (mt)	Total Power Output (MWh)
Open Sea Sailing	1162.9	0.0	6112.5	33.5	2.6	140.5	1196.5	2.6	6,253.0
ECAs Sailing	0.0	151.1	794.2	0.0	4.7	18.3	0.0	155.8	812.5
Port/ECA Maneuvering	0.0	65.4	344.0	0.0	8.6	40.3	0.0	74.0	384.2
Port Idle	0.0	0.0	0.0	0.0	3.5	16.3	0.0	3.5	16.3
Port Ball./Debal.	0.0	0.0	0.0	0.0	25	116.6	0.0	25.0	116.6
TOTAL PER TRC							1196.5	260.9	7582.6

TOTAL PER YEAR	11,614	2,532	73,602
TOTAL PER 5 YEAR	58,068	12,661	368,010
TOTAL PER 10 YEAR	116136	25323	736020



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.		Total emissions mt CO2 eq.	EU/ETS FACTOR		
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92	50%		
ECAs Sailing	0.00	491.88	0.00	15.27		507.15	50%		
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	50%		
Port Idle	0.00	0.00	0.00	11.39		11.39	50%	EU 100%	US 0%
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	50%	EU 100%	US 0%
					TOTAL PER TRC	4,633.7			
							TOTAL PER YEAR	44,978	
							TOTAL PER 5 YEAR	224,890	
							TOTAL PER 10 YEAR	449,779	

SCENARIO 2 RENEWABLE TECHNOLOGIES OUTPUT

Component		<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
<i>PV Panels Coverage</i>	<i>Full Hatch</i>	2095	2095	0	8	8
Total		2095.00	2095.00	0.00		

Saling Days per TRC	Total Saling per year	days	Total Saling days per 5 years	Total Saling days per 10 years
29.136	282.8		1414.08	2828.17
BESS RENEWALS	0.00		0.00	0.00



SCENARIO 2 REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentage from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	45.10	0.00	237048	237048	0.80	0.06	5448	3353	0.0%	38.5%	0.50	0.04
ECAs Sailing	0.00	45.10	237048	237048	0.00	0.86	5448	3353	0.0%	38.5%	0.00	0.54
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Idle	0	0	0		0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Ball./Debal.	0	0	0		0.00	4.55	23328	21233	0	9.0%	0.00	0.45



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	142.66	0.00	2.53	0.20	145.39	1.71	1.2%
ECAs Sailing	0.00	146.81	0.00	2.80	149.61	1.75	1.2%
Port/ECA Maneuvering	0.00	86.26	0.00	9.93	96.19	1.46	1.5%
Port Idle	0.00	0.00	0.00	9.93	9.93	1.46	12.8%
Port Ball./Debal.	0.00	0.00	0.00	14.81	14.81	1.46	9.0%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1162.9	0.0	20.6	1.6		1183.6	1.6	12.89	0.99
ECAs Sailing	0.0	151.1	0.0	2.9		0.0	154.0	0.00	1.80
Port/ECA Maneuvering	0.0	65.4	0.0	7.5		0.0	72.9	0.00	1.11
Port Idle	0.0	0.0	0.0	3.1		0.0	3.1	0.00	0.45
Port Ball./Debal.	0.0	0.0	0.0	22.8		0.0	22.8	0.00	2.25
TOTAL PER TRC						1183.6	254.3	12.9	6.6

TOTAL PER YEAR	11,489	2,468	125	64
TOTAL PER 5 YEAR	57,443	12,341	626	320
TOTAL PER 10 YEAR	114,885	24,682	1,251	640



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3678.50	0.00	65.26	5.17		3748.92	44.00	1.2%	22.00
ECAs Sailing	0.00	491.88	0.00	9.40		501.28	5.87	1.2%	2.94
Port/ECA Maneuvering	0.00	212.78	0.00	24.49		237.27	3.61	1.5%	1.80
Port Idle	0.00	0.00	0.00	9.93		9.93	1.46	12.8%	0.73
Port Ball./Debal.	0.00	0.00	0.00	74.07		74.07	7.31	9.0%	3.65
TOTAL PER TRC						4,571.5	62.3	1.3%	31.1

TOTAL PER YEAR	44,374	604	1.343%	302
TOTAL PER 5 YEAR	221,868	3,021	1.3%	1,511
TOTAL PER 10 YEAR	443,737	6,043	1.3%	3,021

SCENARIO 2 CAPEX/OPEX/SAVINGS/ROI

Component	<u>CAPEX</u>	<u>OPEX</u> <u>(PER</u> <u>YEAR)</u>	<u>OPEX</u> <u>(PER</u> <u>YEAR)</u> 5	<u>OPEX</u> <u>(PER</u> <u>YEAR)</u> 10	<u>OPEX</u> <u>extra</u> <u>BESS</u> <u>Ren.</u>	<u>Total</u> <u>OPEX</u> <u>(PER</u> <u>YEAR)</u>	<u>Total</u> <u>OPEX</u> <u>(PER</u> <u>YEAR)</u> 5	<u>Total</u> <u>OPEX</u> <u>(PER</u> <u>YEAR)</u> 10
1MWh EMS & BESS	435,000	1,800	9,000	18,000	0	1,800	9,000	18,000
PV Panels Full Hatch Coverage	1,796,000	18,210	91,050	182,100	0	18,210	91,050	182,100
Total	2,231,000	20,010	100,050	200,100	0	20,010	100,050	200,100



PRICE					
700 1200 80					
	Total VLSFO Savings € (mt)	Total LSMGO Savings € (mt)	Total EU/ets Savings € emissions eq. mt CO2	TOTAL SAVINGS €	TOTAL OPEX COSTS €
TOTAL PER TRC	9023.4	7917.7	2,490.1	19,431	2,061
TOTAL PER YEAR	87,587	76,855	24,170	188,612	20,010
TOTAL PER 5 YEAR	437,934	384,274	120,851	943,059	100,050
TOTAL PER 10 YEAR	875,869	768,548	241,702	1,886,118	200,100

ROI PERIOD YEARS

13.2

SCENARIO 2a PV Panels 50% Hatch Coverage

SCENARIO 2a RENEWABLE TECHNOLOGIES OUTPUT

Component		<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
<i>PV Panels Coverage</i>	<i>Full Hatch</i>	1047	1047	0	8	8
<i>Total</i>		1047.00	1047.00	0.00		

Saling Days per TRC		Total Saling days per year	Total Saling days per 5 years	Total Saling days per 10 years
29.136		282.8	1414.08	2828.17
BESS RENEWALS		0.00	0.00	0.00

2a REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentage from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	45.10	0.00	237048	237048	1.05	0.08	5448	4401	0.0%	19.2%	0.25	0.02
ECAs Sailing	0.00	45.10	237048	237048	0.00	1.13	5448	4401	0.0%	19.2%	0.00	0.27
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.28	16320	15273	0	6.4%	0.00	0.22
Port Idle	0	0	0		0.00	3.28	16320	15273	0	6.4%	0.00	0.22
Port Ball./Debal.	0	0	0		0.00	4.78	23328	22281	0	4.5%	0.00	0.22



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	142.66	0.00	3.32	0.26	146.24	0.85	0.6%
ECAs Sailing	0.00	146.81	0.00	3.68	150.49	0.88	0.6%
Port/ECA Maneuvering	0.00	86.26	0.00	10.66	96.92	0.73	0.7%
Port Idle	0.00	0.00	0.00	10.66	10.66	0.73	6.4%
Port Ball./Debal.	0.00	0.00	0.00	15.55	15.55	0.73	4.5%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1162.9	0.0	27.1	2.1		1190.0	2.1	6.44	0.50
ECAs Sailing	0.0	151.1	0.0	3.8		0.0	154.9	0.00	0.90
Port/ECA Maneuvering	0.0	65.4	0.0	8.1		0.0	73.4	0.00	0.55
Port Idle	0.0	0.0	0.0	3.3		0.0	3.3	0.00	0.22
Port Ball./Debal.	0.0	0.0	0.0	23.9		0.0	23.9	0.00	1.12
TOTAL PER TRC						1190.0	257.6	6.4	3.3

TOTAL PER YEAR	11,551	2,500	63	32
TOTAL PER 5 YEAR	57,756	12,501	313	160
TOTAL PER 10 YEAR	115,511	25,003	625	320



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3678.50	0.00	85.65	6.78		3770.93	21.99	0.6%	11.00
ECAs Sailing	0.00	491.88	0.00	12.33		504.22	2.93	0.6%	1.47
Port/ECA Maneuvering	0.00	212.78	0.00	26.30		239.07	1.80	0.7%	0.90
Port Idle	0.00	0.00	0.00	10.66		10.66	0.73	6.4%	0.37
Port Ball./Debal.	0.00	0.00	0.00	77.73		77.73	3.65	4.5%	1.83
TOTAL PER TRC						4,602.6	31.1	0.7%	15.6

TOTAL PER YEAR	44,676	302	0.671%	151
TOTAL PER 5 YEAR	223,380	1,510	0.7%	755
TOTAL PER 10 YEAR	446,760	3,020	0.7%	1,510

SCENARIO 2a CAPEX/OPEX/SAVINGS/ROI

Component	<u>CAPEX</u>	<u>OPEX (PER YEAR)</u>	<u>OPEX (PER 5 YEAR)</u>	<u>OPEX (PER 10 YEAR)</u>	<u>OPEX extra BESS Ren.</u>	<u>Total OPEX (PER YEAR)</u>	<u>Total OPEX (PER 5 YEAR)</u>	<u>Total OPEX (PER 10 YEAR)</u>
1MWh EMS & BESS	435000	1800	9000	18000	0	1800	9000	18000
PV Panels 50% Hatch Coverage	908000	9105	45525	91050	0	9105	45525	91050
Total	1343000	10905	54525	109050	0	10905	54525	109050



	PRICE				
	700	1200	80		
	Total VLSFO Savings € (mt)	Total LSMGO Savings € (mt)	Total EU/ets Savings € emissions CO2 eq. mt	TOTAL SAVINGS €	TOTAL OPEX COSTS €
TOTAL PER TRC	4509.5	3957.0	1,244.4	9,711	1,123
TOTAL PER YEAR	43,773	38,409	12,079	94,261	10,905
TOTAL PER 5 YEAR	218,863	192,045	60,397	471,305	54,525
TOTAL PER 10 YEAR	437,725	384,090	120,793	942,609	109,050

ROI PERIOD YEARS
16.1

SCENARIO 3 VAWTs (3) Collapsible

INITIAL CONSUMPTION/EMISSIONS PER TRC/1 YEAR/5 YEARS/10 YEARS

<i>(EU) 2023/1805</i>	Emissions from VLSFO	Emissions from LSMGO
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206
Cf CH ₄ (gCH ₄ /gFuel)	0.00005	0.00005
Cf N ₂ O (gN ₂ O/gFuel)	0.00018	0.00018

GWP factor	CO ₂ Equivalent
CO₂	1
CH₄	28
N₂O	265

Open Sailing Days	Sea Days	ECAs Days	Sailing Port/ECA Maneuvering Days	Port Days	Idle	Port Days	Ball./Debal.
25.786	3.351	2.467	1.000	5.000			

EU port (iddle)	EU Bal/Debal
0.500	2.500

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
37.603	0.103	9.7	48.53	97.07



PER TRC	M/E Total (mt VLSFO)	M/E Total (mt LSMGO)	M/E Total Thrust Output (MWh)	DGs total Consumption (mt VLSFO)	DGs total Consumption (mt LSMGO)	DGs Total Load (MWh)	Total VLSFO (mt)	Total LSMGO (mt)	Total Power Output (MWh)
Open Sea Sailing	1162.9	0.0	6112.5	33.5	2.6	140.5	1196.5	2.6	6,253.0
ECAs Sailing	0.0	151.1	794.2	0.0	4.7	18.3	0.0	155.8	812.5
Port/ECA Maneuvering	0.0	65.4	344.0	0.0	8.6	40.3	0.0	74.0	384.2
Port Idle	0.0	0.0	0.0	0.0	3.5	16.3	0.0	3.5	16.3
Port Ball./Debal.	0.0	0.0	0.0	0.0	25	116.6	0.0	25.0	116.6
TOTAL PER TRC							1196.5	260.9	7582.6

TOTAL PER YEAR	11,614	2,532	73,602
TOTAL PER 5 YEAR	58,068	12,661	368,010
TOTAL PER 10 YEAR	116136	25323	736020



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.		Total emissions mt CO2 eq.	EU/ETS FACTOR		
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92	50%		
ECAs Sailing	0.00	491.88	0.00	15.27		507.15	50%		
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	50%		
Port Idle	0.00	0.00	0.00	11.39		11.39	50%	EU 100%	US 0%
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	50%	EU 100%	US 0%
					TOTAL PER TRC	4,633.7			
						TOTAL PER YEAR	44,978		
						TOTAL PER 5 YEAR	224,890		
						TOTAL PER 10 YEAR	449,779		



SCENARIO 3 RENEWABLE TECHNOLOGIES OUTPUT

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
VAWTs (3)	0	98.4	0	-	24
Total	0.00	98.40	0.00		

Saling Days per TRC				
		Total Saling days per year	Total Saling days per 5 years	Total Saling days per 10 years
29.136		282.8	1414.08	2828.17
BESS RENEWALS		0.00	0.00	0.00



SCENARIO 3 REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliary s total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentag e from renewable	Auxiliary s percentag e from renewable	Total VLSF O Savings (mt)	Total LSMG O Savings (mt)
Open Sea Sailing	45.10	0.00	237048	237048	1.28	0.10	5448	5350	0.0%	1.8%	0.02	0.00
ECAs Sailing	0.00	45.10	237048	237048	0.00	1.37	5448	5350	0.0%	1.8%	0.00	0.03
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Idle	0	0	0		0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Ball./Debal.	0	0	0		0.00	5.00	23328	23328	0	0.0%	0.00	0.00



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	142.66	0.00	4.04	0.32	147.01	0.08	0.1%
ECAs Sailing	0.00	146.81	0.00	4.47	151.28	0.08	0.1%
Port/ECA Maneuvering	0.00	86.26	0.00	11.39	97.65	0.00	0.0%
Port Idle	0.00	0.00	0.00	11.39	11.39	0.00	0.0%
Port Ball./Debal.	0.00	0.00	0.00	16.28	16.28	0.00	0.0%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1162.9	0.0	32.9	2.5		1195.9	2.5	0.61	0.05
ECAs Sailing	0.0	151.1	0.0	4.6		0.0	155.7	0.00	0.08
Port/ECA Maneuvering	0.0	65.4	0.0	8.6		0.0	74.0	0.00	0.00
Port Idle	0.0	0.0	0.0	3.5		0.0	3.5	0.00	0.00
Port Ball./Debal.	0.0	0.0	0.0	25.0		0.0	25.0	0.00	0.00
TOTAL PER TRC						1195.9	260.7	0.6	0.1

TOTAL PER YEAR	11,608	2,531	6	1
TOTAL PER 5 YEAR	58,039	12,655	29	6
TOTAL PER 10 YEAR	116,078	25,310	59	13



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3678.50	0.00	104.12	8.24		3790.86	2.07	0.1%	1.03
ECAs Sailing	0.00	491.88	0.00	14.99		506.87	0.28	0.1%	0.14
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	0.00	0.0%	0.00
Port Idle	0.00	0.00	0.00	11.39		11.39	0.00	0.0%	0.00
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	0.00	0.0%	0.00
					TOTAL PER TRC	4,631.4	2.3	0.1%	1.2

TOTAL PER YEAR	44,955	23	0.1%	11
TOTAL PER 5 YEAR	224,776	114	0.1%	57
TOTAL PER 10 YEAR	449,552	227	0.1%	114



SCENARIO 3 CAPEX/OPEX/SAVINGS/ROI

Component	CAPEX	<u>OPEX</u> <u>(PER</u> <u>YEAR)</u>	<u>OPEX</u> <u>(PER 5</u> <u>YEAR)</u>	<u>OPEX</u> <u>(PER 10</u> <u>YEAR)</u>	<u>OPEX</u> <u>extra</u> <u>BESS</u> <u>Ren.</u>	<u>Total</u> <u>OPEX</u> <u>(PER</u> <u>YEAR)</u>	<u>Total</u> <u>OPEX</u> <u>(PER 5</u> <u>YEAR)</u>	<u>Total</u> <u>OPEX</u> <u>(PER 10</u> <u>YEAR)</u>
1MWh EMS & BESS	435,000	1,800	9,000	18,000	0	1,800	9,000	18,000
VAWTs (3)	675,000	3,000	15,000	30,000	0	3,000	15,000	30,000
Total	1,110,000	4,800	24,000	48,000	0	4,800	24,000	48,000

Saling Days per TRC	Total Saling days per year	Total Saling days per 5 years	Total Saling days per 10 years
29.136	282.8	1414.08	2828.17

BESS RENEWALS	0.00	0.00	0.00
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PRICE					
700 1200 80					
	Total VLSFO Savings € (mt)	Total LSMGO Savings € (mt)	Total EU/ets Savings € emissions mt CO2 eq.	TOTAL SAVINGS €	TOTAL OPEX COSTS €
TOTAL PER TRC	423.8	157.6	93.7	675	495
TOTAL PER YEAR	4,114	1,529	910	6,553	4,800
TOTAL PER 5 YEAR	20,569	7,647	4,548	32,764	24,000
TOTAL PER 10 YEAR	41,139	15,293	9,095	65,527	48,000

ROI PERIOD YEARS
633.3

SCENARIO 3a VAWTs (6) Non-Collapsible

INITIAL CONSUMPTION/EMISSIONS PER TRC/1 YEAR/5 YEARS/10 YEARS

<i>(EU) 2023/1805</i>	Emissions from VLSFO	Emissions from LSMGO
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206
Cf CH ₄ (gCH ₄ /gFuel)	0.00005	0.00005
Cf N ₂ O (gN ₂ O/gFuel)	0.00018	0.00018

GWP factor	CO ₂ Equivalent
CO₂	1
CH₄	28
N₂O	265

Open Sailing Days	Sea Days	ECAs Days	Sailing Port/ECA Maneuvering Days	Port Days	Idle	Port Days	Ball./Debal.
25.786	3.351	2.467	1.000	6.000			

EU port (iddle)	EU Bal/Debal
0.500	3.000

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
38.603	0.106	9.5	47.28	94.55



PER TRC	M/E Total (mt VLSFO)	M/E Total (mt LSMGO)	M/E Total Thrust Output (MWh)	DGs total Consumption (mt VLSFO)	DGs total Consumption (mt LSMGO)	DGs Total Load (MWh)	Total VLSFO (mt)	Total LSMGO (mt)	Total Power Output (MWh)
Open Sea Sailing	1162.9	0.0	6112.5	33.5	2.6	140.5	1196.5	2.6	6,253.0
ECAs Sailing	0.0	151.1	794.2	0.0	4.7	18.3	0.0	155.8	812.5
Port/ECA Maneuvering	0.0	65.4	344.0	0.0	8.6	40.3	0.0	74.0	384.2
Port Idle	0.0	0.0	0.0	0.0	3.5	16.3	0.0	3.5	16.3
Port Ball./Debal.	0.0	0.0	0.0	0.0	30	140.0	0.0	30.0	140.0
TOTAL PER TRC							1196.5	265.9	7606.0

TOTAL PER YEAR	11,313	2,514	71,916
TOTAL PER 5 YEAR	56,564	12,570	359,579
TOTAL PER 10 YEAR	113128	25140	719159



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.		Total emissions mt CO2 eq.	EU/ETS FACTOR		
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92	50%		
ECAs Sailing	0.00	491.88	0.00	15.27		507.15	50%		
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	50%		
Port Idle	0.00	0.00	0.00	11.39		11.39	50%	EU 100%	US 0%
Port Ball./Debal.	0.00	0.00	0.00	97.65		97.65	50%	EU 100%	US 0%
					TOTAL PER TRC	4,650.0			
					TOTAL PER YEAR	43,967			
					TOTAL PER 5 YEAR	219,833			
					TOTAL PER 10 YEAR	439,667			

SCENARIO 3a RENEWABLE TECHNOLOGIES OUTPUT

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i><u>Daily running hours (at port)</u></i>	<i><u>Daily running hours (at sea)</u></i>
VAWTs (6)	0	196.8	0	-	24
Total	0.00	196.80	0.00		

Saling Days per TRC		Total Saling days per year	Total Saling days per 5 years	Total Saling days per 10 years
29.136		275.5	1377.45	2754.91
BESS RENEWALS		0.00	0.00	0.00



SCENARIO 3a REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliary s total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentag e from renewable	Auxiliary s percentag e from renewable	Total VLSF O Savings (mt)	Total LSMG O Savings (mt)
Open Sea Sailing	45.10	0.00	237048	237048	1.25	0.10	5448	5251	0.0%	3.6%	0.05	0.00
ECAs Sailing	0.00	45.10	237048	237048	0.00	1.35	5448	5251	0.0%	3.6%	0.00	0.05
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Idle	0	0	0		0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Ball./Debal.	0	0	0		0.00	5.00	23328	23328	0	0.0%	0.00	0.00



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	142.66	0.00	3.96	0.31	146.93	0.16	0.11%
ECAs Sailing	0.00	146.81	0.00	4.39	151.20	0.16	0.11%
Port/ECA Maneuvering	0.00	86.26	0.00	11.39	97.65	0.00	0.00%
Port Idle	0.00	0.00	0.00	11.39	11.39	0.00	0.00%
Port Ball./Debal.	0.00	0.00	0.00	16.28	16.28	0.00	0.00%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1162.9	0.0	32.3	2.5		1195.3	2.5	1.21	0.09
ECAs Sailing	0.0	151.1	0.0	4.5		0.0	155.6	0.00	0.17
Port/ECA Maneuvering	0.0	65.4	0.0	8.6		0.0	74.0	0.00	0.00
Port Idle	0.0	0.0	0.0	3.5		0.0	3.5	0.00	0.00
Port Ball./Debal.	0.0	0.0	0.0	30.0		0.0	30.0	0.00	0.00
TOTAL PER TRC						1195.3	265.6	1.2	0.3

TOTAL PER YEAR	11,301	2,511	11	2
TOTAL PER 5 YEAR	56,507	12,557	57	12
TOTAL PER 10 YEAR	113,014	25,115	114	25



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3678.50	0.00	102.20	8.09		3788.79	4.13	0.11%	2.07
ECAs Sailing	0.00	491.88	0.00	14.72		506.60	0.55	0.11%	0.28
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	0.00	0.00%	0.00
Port Idle	0.00	0.00	0.00	11.39		11.39	0.00	0.00%	0.00
Port Ball./Debal.	0.00	0.00	0.00	97.65		97.65	0.00	0.00%	0.00
					TOTAL PER TRC	4,645.3	4.7	0.10%	2.3

TOTAL PER YEAR	43,922	44	0.10%	22
TOTAL PER 5 YEAR	219,612	221	0.10%	111
TOTAL PER 10 YEAR	439,224	443	0.10%	221

SCENARIO 3a CAPEX/OPEX/SAVINGS/ROI

Component	CAPEX	<u>OPEX (PER YEAR)</u>	<u>OPEX (PER 5 YEAR)</u>	<u>OPEX (PER 10 YEAR)</u>	<u>OPEX extra BESS Ren.</u>	<u>Total OPEX (PER YEAR)</u>	<u>Total OPEX (PER 5 YEAR)</u>	<u>Total OPEX (PER 10 YEAR)</u>
1MWh EMS & BESS	435,000	1,800	9,000	18,000	0	1,800	9,000	18,000
VAWTs (6)	1,200,000	750	3,750	7,500	0	750	3,750	7,500
Total	1,635,000	2,550	12,750	25,500	0	2,550	12,750	25,500



	PRICE				
	700	1200	80		
	Total VLSFO Savings € (mt)	Total LSMGO Savings € (mt)	Total EU/ets Savings € emissions mt CO2 eq.	TOTAL SAVINGS €	TOTAL OPEX COSTS €
TOTAL PER TRC	847.6	315.1	187.4	1,350	270
TOTAL PER YEAR	8,015	2,979	1,772	12,766	2,550
TOTAL PER 5 YEAR	40,073	14,897	8,860	63,830	12,750
TOTAL PER 10 YEAR	80,146	29,795	17,719	127,660	25,500

ROI PERIOD YEARS
160.0

SCENARIO 4 PIEZOACOUSTIC PANELS

INITIAL CONSUMPTION/EMISSIONS PER TRC/1 YEAR/5 YEARS/10 YEARS

<i>(EU) 2023/1805</i>	Emissions from VLSFO	Emissions from LSMGO	GWP factor	CO2 Equivalent
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206	CO₂	1
Cf CH ₄ (gCH ₄ /gFuel)	0.00005	0.00005	CH₄	28
Cf N ₂ O (gN ₂ O/gFuel)	0.00018	0.00018	N₂O	265

Open Sailing Days	Sea Days	ECAs Days	Sailing Port/ECA Maneuvering Days	Port Days	Idle	Port Days	Ball./Debal.
25.786	3.351	2.467	1.000	5.000			

EU port (iddle)	EU Bal/Debal
0.500	2.500

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
37.603	0.103	9.7	48.53	97.07



PER TRC	M/E Total (mt VLSFO)	M/E Total (mt LSMGO)	M/E Total Thrust Output (MWh)	DGs total Consumption (mt VLSFO)	DGs total Consumption (mt LSMGO)	DGs Total Load (MWh)	Total VLSFO (mt)	Total LSMGO (mt)	Total Power Output (MWh)
Open Sea Sailing	1162.9	0.0	6112.5	33.5	2.6	140.5	1196.5	2.6	6,253.0
ECAs Sailing	0.0	151.1	794.2	0.0	4.7	18.3	0.0	155.8	812.5
Port/ECA Maneuvering	0.0	65.4	344.0	0.0	8.6	40.3	0.0	74.0	384.2
Port Idle	0.0	0.0	0.0	0.0	3.5	16.3	0.0	3.5	16.3
Port Ball./Debal.	0.0	0.0	0.0	0.0	25	116.6	0.0	25.0	116.6
TOTAL PER TRC							1196.5	260.9	7582.6

TOTAL PER YEAR	11,614	2,532	73,602
TOTAL PER 5 YEAR	58,068	12,661	368,010
TOTAL PER 10 YEAR	116136	25323	736020



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.		Total emissions mt CO2 eq.	EU/ETS FACTOR		
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92	50%		
ECAs Sailing	0.00	491.88	0.00	15.27		507.15	50%		
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	50%		
Port Idle	0.00	0.00	0.00	11.39		11.39	50%	EU 100%	US 0%
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	50%	EU 100%	US 0%
					TOTAL PER TRC	4,633.7			
							TOTAL PER YEAR	44,978	
							TOTAL PER 5 YEAR	224,890	
							TOTAL PER 10 YEAR	449,779	

SCENARIO 4 RENEWABLE TECHNOLOGIES OUTPUT

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
<i>PZ Panels</i> <i>acoustic</i>	0.028	0.028	0	24	24
<i>Total</i>	0.03	0.03	0.00		



SCENARIO 4 REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentage from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	45.10	0.00	237048	237048	1.30	0.10	5448	5447.972	0.0%	0.0%	0.000007	0.000001
ECAs Sailing	0.00	45.10	237048	237048	0.00	1.40	5448	5447.972	0.0%	0.0%	0.000000	0.000007
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.50	16320	16320	0	0.0%	0.000000	0.000006
Port Idle	0	0	0		0.00	3.50	16320	16320	0	0.0%	0.000000	0.000006
Port Ball./Debal.	0	0	0		0.00	5.00	23328	23328	0	0.0%	0.000000	0.000006



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	142.66	0.00	4.11	0.33	147.09	0.00	0.0%
ECAs Sailing	0.00	146.81	0.00	4.56	151.36	0.00	0.0%
Port/ECA Maneuvering	0.00	86.26	0.00	11.39	97.65	0.00	0.0%
Port Idle	0.00	0.00	0.00	11.39	11.39	0.00	0.0%
Port Ball./Debal.	0.00	0.00	0.00	16.28	16.28	0.00	0.0%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1162.9	0.0	33.5	2.6		1196.5	2.6	0.000172	0.000013
ECAs Sailing	0.0	151.1	0.0	4.7		0.0	155.8	0.000000	0.000024
Port/ECA Maneuvering	0.0	65.4	0.0	8.6		0.0	74.0	0.000000	0.000015
Port Idle	0.0	0.0	0.0	3.5		0.0	3.5	0.000000	0.000006
Port Ball./Debal.	0.0	0.0	0.0	25.0		0.0	25.0	0.000000	0.000030
TOTAL PER TRC						1196.5	260.9	0.000172	0.000088

TOTAL PER YEAR	11,614	2,532	0.001672	0.000856
TOTAL PER 5 YEAR	58,068	12,661	0.008362	0.004280
TOTAL PER 10 YEAR	116,136	25,323	0.016723	0.008560



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92	0.00	0.000%	0.00
ECAs Sailing	0.00	491.88	0.00	15.27		507.15	0.00	0.000%	0.00
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	0.00	0.000%	0.00
Port Idle	0.00	0.00	0.00	11.39		11.39	0.00	0.000%	0.00
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	0.00	0.000%	0.00
					TOTAL PER TRC	4,633.7	0.0	0.000%	0.0

TOTAL PER YEAR	44,978	0.01	0.0000180%	0
TOTAL PER 5 YEAR	224,890	0.04	0.000%	0
TOTAL PER 10 YEAR	449,779	0.08	0.000%	0

SCENARIO 4 CAPEX/OPEX/SAVINGS/ROI

Component	<u>CAPEX</u>	<u>OPEX (PER YEAR)</u>	<u>OPEX (PER 5 YEAR)</u>	<u>OPEX (PER 10 YEAR)</u>	<u>OPEX extra BESS Ren.</u>	<u>Total OPEX (PER YEAR)</u>	<u>Total OPEX (PER 5 YEAR)</u>	<u>Total OPEX (PER 10 YEAR)</u>
<i>PZ acoustic Panels</i>	140,000	1,500	7,500	15,000	0	1,500	7,500	15,000
Total	140,000	1,500	7,500	15,000	0	1,500	7,500	15,000



PRICE					
700 1200 80					
	Total VLSFO Savings € (mt)	Total LSMGO Savings € (mt)	Total EU/ets Savings € emissions mt CO2 eq.	TOTAL SAVINGS €	TOTAL OPEX COSTS €
TOTAL PER TRC	0.1	0.1	0.0	0	155
TOTAL PER YEAR	1	1	0	3	1,500
TOTAL PER 5 YEAR	6	5	2	13	7,500
TOTAL PER 10 YEAR	12	10	3	25	15,000

ROI
PERIOD
YEARS

-93.5

SCENARIO 5 PTI/PTO SHAFT GENERATOR (8 CYCLES)

INITIAL CONSUMPTION/EMISSIONS PER TRC/1 YEAR/5 YEARS/10 YEARS

<i>(EU) 2023/1805</i>	Emissions from VLSFO	Emissions from LSMGO	GWP factor	CO2 Equivalent
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206	CO₂	1
Cf CH ₄ (gCH ₄ /gFuel)	0.00005	0.00005	CH₄	28
Cf N ₂ O (gN ₂ O/gFuel)	0.00018	0.00018	N₂O	265

Open Sailing Days	Sea Days	ECAs Days	Sailing Port/ECA Maneuvering Days	Port Days	Idle	Port Days	Ball./Debal
25.786		3.351	2.467	1.000		5.000	

EU port (iddle)	EU Bal/Debal
0.500	2.500

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
37.603	0.103	9.7	48.53	97.07



PER TRC	M/E Total (mt VLSFO)	M/E Total (mt LSMGO)	M/E Total Thrust Output (MWh)	DGs total Consumption (mt VLSFO)	DGs total Consumption (mt LSMGO)	DGs Total Load (MWh)	Total VLSFO (mt)	Total LSMGO (mt)	Total Power Output (MWh)
Open Sea Sailing	1162.9	0.0	6112.5	33.5	2.6	140.5	1196.5	2.6	6,253.0
ECAs Sailing	0.0	151.1	794.2	0.0	4.7	18.3	0.0	155.8	812.5
Port/ECA Maneuvering	0.0	65.4	344.0	0.0	8.6	40.3	0.0	74.0	384.2
Port Idle	0.0	0.0	0.0	0.0	3.5	16.3	0.0	3.5	16.3
Port Ball./Debal.	0.0	0.0	0.0	0.0	25	116.6	0.0	25.0	116.6
TOTAL PER TRC							1196.5	260.9	7582.6

TOTAL PER YEAR	11,614	2,532	73,602
TOTAL PER 5 YEAR	58,068	12,661	368,010
TOTAL PER 10 YEAR	116136	25323	736020



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.		Total emissions mt CO2 eq.	EU/ETS FACTOR		
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92	50%		
ECAs Sailing	0.00	491.88	0.00	15.27		507.15	50%		
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	50%		
Port Idle	0.00	0.00	0.00	11.39		11.39	50%	EU 100%	US 0%
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	50%	EU 100%	US 0%
					TOTAL PER TRC	4,633.7			
							TOTAL PER YEAR	44,978	
							TOTAL PER 5 YEAR	224,890	
							TOTAL PER 10 YEAR	449,779	

SCENARIO 5 RENEWABLE TECHNOLOGIES OUTPUT

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i><u>Daily running hours (at port)</u></i>	<i><u>Daily running hours (at sea)</u></i>
<i>PTI/PTO operation)</i>	(8 cycle 0	3680	8000	-	21.68
Total	0.00	3680.00	8000.00		

Saling Days per TRC	Total Saling days per year				Total Saling days per 10 years
29.136		282.8	1414.08		2828.17
BESS RENEWALS		0.32	1.62		3.23

BESS lifespan 875

SCENARIO 5 REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentage from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	43.58	0.00	237048	229048	0.42	0.03	5448	1768	3.4%	67.5%	2.40	0.07
ECAs Sailing	0.00	43.58	237048	229048	0.00	0.45	5448	1768	3.4%	67.5%	0.00	2.47
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Idle	0	0	0		0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Ball./Debal.	0	0	0		0.00	5.00	23328	23328	0	0.0%	0.00	0.00



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	137.84	0.00	1.33	0.11	139.28	7.81	5.3%
ECAs Sailing	0.00	141.85	0.00	1.48	143.33	8.03	5.3%
Port/ECA Maneuvering	0.00	86.26	0.00	11.39	97.65	0.00	0.0%
Port Idle	0.00	0.00	0.00	11.39	11.39	0.00	0.0%
Port Ball./Debal.	0.00	0.00	0.00	16.28	16.28	0.00	0.0%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1123.7	0.0	10.9	0.8		1134.6	0.8	61.89	1.74
ECAs Sailing	0.0	146.0	0.0	1.5		0.0	147.5	0.00	8.27
Port/ECA Maneuvering	0.0	65.4	0.0	8.6		0.0	74.0	0.00	0.00
Port Idle	0.0	0.0	0.0	3.5		0.0	3.5	0.00	0.00
Port Ball./Debal.	0.0	0.0	0.0	25.0		0.0	25.0	0.00	0.00
TOTAL PER TRC						1134.6	250.9	61.9	10.0

TOTAL PER YEAR	11,013	2,435	601	97
TOTAL PER 5 YEAR	55,064	12,176	3,004	486
TOTAL PER 10 YEAR	110,129	24,351	6,007	972



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3554.35	0.00	34.41	2.72		3591.49	201.44	5.3%	100.72
ECAs Sailing	0.00	475.28	0.00	4.96		480.24	26.91	5.3%	13.46
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	0.00	0.0%	0.00
Port Idle	0.00	0.00	0.00	11.39		11.39	0.00	0.0%	0.00
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	0.00	0.0%	0.00
					TOTAL PER TRC	4,405.4	228.3	4.9%	114.2

TOTAL PER YEAR	42,761	2,217	4.9%	1,108
TOTAL PER 5 YEAR	213,807	11,083	4.9%	5,541
TOTAL PER 10 YEAR	427,614	22,165	4.9%	11,083

SCENARIO 5 CAPEX/OPEX/SAVINGS/ROI

Component	<u>CAPEX</u>	<u>OPEX (PER YEAR)</u>	<u>OPEX (PER 5 YEAR)</u>	<u>OPEX (PER 10 YEAR)</u>	<u>OPEX extra BESS Ren.</u>	<u>Total OPEX (PER YEAR)</u>	<u>Total OPEX (PER 5 YEAR)</u>	<u>Total OPEX (PER 10 YEAR)</u>
2MWh EMS & BESS	850,000	3,600	18,000	36,000	400,000	132,888	664,439	1,328,878
<i>PTI/PTO (8 cycle operation)</i>	4,000,000	7,500	37,500	75,000	0	7,500	37,500	75,000
Total	4,850,000	11,100	55,500	111,000	400,000	140,388	701,939	1,403,878



	PRICE				
	700	1200	80		
	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX COSTS €
PER TRC	43,323	12,012	9,134	64,469	14,463
PER YEAR	420,525	116,597	88,660	625,782	140,388
PER 5 YEAR	2,102,624	582,985	443,302	3,128,911	701,939
PER 10 YEAR	4,205,248	1,165,970	886,604	6,257,822	1,403,878

ROI PERIOD YEARS
10.0

SCENARIO 5a PTI/PTO SHAFT GENERATOR (4 CYCLES)

SCENARIO 5a RENEWABLE TECHNOLOGIES OUTPUT

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<u>Daily running hours (at port)</u>	<u>Daily running hours (at sea)</u>
<i>PTI/PTO operation</i>	<i>(4 cycle</i> 0	1840	4000	-	10.84
Total	0.00	1840.00	4000.00		

Saling Days per TRC	Total Saling days per year				Total Saling days per 10 years
29.136		282.8	1414.08		2828.17
BESS RENEWALS		0.16	0.81		1.62

BESS lifespan 1750



SCENARIO 5a REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentage from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	44.34	0.00	237048	233048	0.86	0.07	5448	3608	1.7%	33.8%	1.20	0.03
ECAs Sailing	0.00	44.34	237048	233048	0.00	0.93	5448	3608	1.7%	33.8%	0.00	1.23
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Idle	0	0	0		0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Ball./Debal.	0	0	0		0.00	5.00	23328	23328	0	0.0%	0.00	0.00



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	140.25	0.00	2.72	0.22	143.19	3.91	2.7%
ECAs Sailing	0.00	144.33	0.00	3.02	147.35	4.02	2.7%
Port/ECA Maneuvering	0.00	86.26	0.00	11.39	97.65	0.00	0.0%
Port Idle	0.00	0.00	0.00	11.39	11.39	0.00	0.0%
Port Ball./Debal.	0.00	0.00	0.00	16.28	16.28	0.00	0.0%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1143.3	0.0	22.2	1.7		1165.5	1.7	30.95	0.87
ECAs Sailing	0.0	148.6	0.0	3.1		0.0	151.7	0.00	4.13
Port/ECA Maneuvering	0.0	65.4	0.0	8.6		0.0	74.0	0.00	0.00
Port Idle	0.0	0.0	0.0	3.5		0.0	3.5	0.00	0.00
Port Ball./Debal.	0.0	0.0	0.0	25.0		0.0	25.0	0.00	0.00
TOTAL PER TRC						1165.5	255.9	30.9	5.0

TOTAL PER YEAR	11,313	2,484	300	49
TOTAL PER 5 YEAR	56,566	12,418	1,502	243
TOTAL PER 10 YEAR	113,133	24,837	3,004	486



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3616.43	0.00	70.22	5.56		3692.21	100.72	2.7%	50.36
ECAs Sailing	0.00	483.58	0.00	10.11		493.69	13.46	2.7%	6.73
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	0.00	0.0%	0.00
Port Idle	0.00	0.00	0.00	11.39		11.39	0.00	0.0%	0.00
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	0.00	0.0%	0.00
TOTAL PER TRC						4,519.5	114.2	2.5%	57.1

TOTAL PER YEAR	43,870	1,108	2.5%	554
TOTAL PER 5 YEAR	219,348	5,541	2.5%	2,771
TOTAL PER 10 YEAR	438,697	11,083	2.5%	5,541

SCENARIO 5a CAPEX/OPEX/SAVINGS/ROI

Component	<u>CAPEX</u>	<u>OPEX</u> <u>(PER</u> <u>YEAR)</u>	<u>OPEX</u> <u>(PER</u> <u>YEAR)</u> 5	<u>OPEX</u> <u>(PER</u> <u>YEAR)</u> 10	<u>OPEX</u> extra <u>BESS Ren.</u>	<u>Total</u> <u>OPEX</u> <u>(PER</u> <u>YEAR)</u>	<u>Total</u> <u>OPEX</u> <u>(PER</u> <u>YEAR)</u> 5	<u>Total</u> <u>OPEX</u> <u>(PER</u> <u>YEAR)</u> 10
2MWh EMS & BESS	850,000	3,600	18,000	36,000	400,000	68,244	341,219	682,439
<i>PTI/PTO</i> <i>(4 cycle</i> <i>operation)</i>	4,000,000	7,500	37,500	75,000	0	7,500	37,500	75,000
<i>Total</i>	<i>4,850,000</i>	<i>11,100</i>	<i>55,500</i>	<i>111,000</i>	<i>400,000</i>	<i>75,744</i>	<i>378,719</i>	<i>757,439</i>



PRICE					
	700	1200	80		
	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX COSTS €
PER TRC	21,662	6,006	4,567	32,235	7,803
PER YEAR	210,262	58,299	44,330	312,891	75,744
PER YEAR 5	1,051,312	291,493	221,651	1,564,456	378,719
PER YEAR 10	2,102,624	582,985	443,302	3,128,911	757,439

ROI PERIOD YEARS
20.5

SCENARIO 5b PTI/PTO SHAFT GENERATOR (7.5 CYCLES)

SCENARIO 5b RENEWABLE TECHNOLOGIES OUTPUT

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i><u>Daily running hours (at port)</u></i>	<i><u>Daily running hours (at sea)</u></i>
<i>PTI/PTO operation)</i> (7.5 cycle	0	5450	6200	-	19.94
Total	0.00	5450.00	6200.00		

Saling Days per TRC	Total Saling days per year	Total Saling days per 5 years	Total Saling days per 10 years
29.136	282.8	1414.08	2828.17
BESS RENEWALS	0.32	1.62	3.23

BESS lifespan 875

SCENARIO 5b BATTERIES OPTIMIZATION

	CYCLE#	AUX POWER	THRUST	TIME
6	2760	6000		16.26
7	1230	200		1.94
8	1460			1.74

SCENARIO 5b REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliaries total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentage from renewable	Auxiliaries percentage from renewable	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	43.92	0.00	237048	230848	0.00	0.00	5448	0	2.6%	100.0%	2.48	0.10
ECAs Sailing	0.00	43.92	237048	230848	0.00	0.00	5448	0	2.6%	100.0%	0.00	2.58
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Idle	0	0	0		0.00	3.50	16320	16320	0	0.0%	0.00	0.00
Port Ball./Debal.	0	0	0		0.00	5.00	23328	23328	0	0.0%	0.00	0.00



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	138.92	0.00	0.00	0.00	138.92	8.17	5.6%
ECAs Sailing	0.00	142.97	0.00	0.00	142.97	8.40	5.5%
Port/ECA Maneuvering	0.00	86.26	0.00	11.39	97.65	0.00	0.0%
Port Idle	0.00	0.00	0.00	11.39	11.39	0.00	0.0%
Port Ball./Debal.	0.00	0.00	0.00	16.28	16.28	0.00	0.0%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1132.5	0.0	0.0	0.0		1132.5	0.0	63.94	2.58
ECAs Sailing	0.0	147.2	0.0	0.0		0.0	147.2	0.00	8.64
Port/ECA Maneuvering	0.0	65.4	0.0	8.6		0.0	74.0	0.00	0.00
Port Idle	0.0	0.0	0.0	3.5		0.0	3.5	0.00	0.00
Port Ball./Debal.	0.0	0.0	0.0	25.0		0.0	25.0	0.00	0.00
TOTAL PER TRC						1132.5	249.7	63.9	11.2

TOTAL PER YEAR	10,993	2,423	621	109
TOTAL PER 5 YEAR	54,965	12,117	3,103	545
TOTAL PER 10 YEAR	109,930	24,233	6,206	1,089



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3582.29	0.00	0.00	0.00		3582.29	210.64	5.6%	105.32
ECAs Sailing	0.00	479.02	0.00	0.00		479.02	28.13	5.5%	14.07
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	0.00	0.0%	0.00
Port Idle	0.00	0.00	0.00	11.39		11.39	0.00	0.0%	0.00
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	0.00	0.0%	0.00
					TOTAL PER TRC	4,394.9	238.8	5.2%	119.4

TOTAL PER YEAR	42,660	2,318	5.2%	1,159
TOTAL PER 5 YEAR	213,301	11,588	5.2%	5,794
TOTAL PER 10 YEAR	426,603	23,177	5.2%	11,588

SCENARIO 5b CAPEX/OPEX/SAVINGS/ROI

Component	<u>CAPEX</u>	<u>OPEX</u> <u>(PER</u> <u>YEAR)</u>	<u>OPEX</u> <u>(PER</u> 5 <u>YEAR)</u>	<u>OPEX</u> <u>(PER</u> 10 <u>YEAR)</u>	<u>OPEX</u> <u>extra BESS</u> <u>Ren.</u>	<u>Total</u> <u>OPEX</u> <u>(PER</u> <u>YEAR)</u>	<u>Total</u> <u>OPEX</u> <u>(PER</u> 5 <u>YEAR)</u>	<u>Total</u> <u>OPEX</u> <u>(PER</u> 10 <u>YEAR)</u>
2MWh EMS & BESS	850,000	3,600	18,000	36,000	400,000	132,888	664,439	1,328,878
<i>PTI/PTO</i> <i>(7.5 cycle</i> <i>operation)</i>	4,000,000	7,500	37,500	75,000	0	7,500	37,500	75,000
Total	4,850,000	11,100	55,500	111,000	400,000	140,388	701,939	1,403,878



PRICE

	700	1200	80		
	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX COSTS €
PER TRC	44,757	13,466	9,551	67,774	14,463

PER YEAR	434,439	130,710	92,707	657,856	140,388
PER 5 YEAR	2,172,196	653,551	463,534	3,289,280	701,939
PER 10 YEAR	4,344,392	1,307,101	927,067	6,578,561	1,403,878

ROI PERIOD YEARS
9.4

SCENARIO 6 PV Panels & PTI/PTO SHAFT GENERATOR (7.5 CYCLES Optimized)

INITIAL CONSUMPTION/EMISSIONS PER TRC/1 YEAR/5 YEARS/10 YEARS

<i>(EU) 2023/1805</i>	Emissions from VLSFO	Emissions from LSMGO	GWP factor	CO2 Equivalent
Cf CO ₂ (gCO ₂ /gFuel)	3.114	3.206	CO₂	1
Cf CH ₄ (gCH ₄ /gFuel)	0.00005	0.00005	CH₄	28
Cf N ₂ O (gN ₂ O/gFuel)	0.00018	0.00018	N₂O	265

Open Sea	ECAs	Sailing	Port	Idle	Port	Ball./Debal
Sailing Days	Days	Port/ECA Maneuvering Days	Days		Days	
25.786	3.351	2.467	1.000		5.000	

EU port (iddle)	EU Bal/Debal
0.500	2.500

TRC duration (days)	TRC duration (years)	Total TRCs per year	Total TRCs per 5 years	Total TRCs per 10 years
37.603	0.103	9.7	48.53	97.07



PER TRC	M/E Total (mt VLSFO)	M/E Total (mt LSMGO)	M/E Total Thrust Output (MWh)	DGs total Consumption (mt VLSFO)	DGs total Consumption (mt LSMGO)		DGs Total Load (MWh)	Total VLSFO (mt)	Total LSMGO (mt)	Total Power Output (MWh)
Open Sea Sailing	1162.9	0.0	6112.5	33.5	2.6		140.5	1196.5	2.6	6,253.0
ECAs Sailing	0.0	151.1	794.2	0.0	4.7		18.3	0.0	155.8	812.5
Port/ECA Maneuvering	0.0	65.4	344.0	0.0	8.6		40.3	0.0	74.0	384.2
Port Idle	0.0	0.0	0.0	0.0	3.5		16.3	0.0	3.5	16.3
Port Ball./Debal.	0.0	0.0	0.0	0.0	25		116.6	0.0	25.0	116.6
							TOTAL PER TRC	1196.5	260.9	7582.6
							TOTAL PER YEAR	11,614	2,532	73,602
							TOTAL PER 5 YEAR	58,068	12,661	368,010
							TOTAL PER 10 YEAR	116136	25323	736020



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.		Total emissions mt CO2 eq.	EU/ETS FACTOR		
Open Sea Sailing	3678.50	0.00	106.03	8.39		3792.92	50%		
ECAs Sailing	0.00	491.88	0.00	15.27		507.15	50%		
Port/ECA Maneuvering	0.00	212.78	0.00	28.10		240.88	50%		
Port Idle	0.00	0.00	0.00	11.39		11.39	50%	EU 100%	US 0%
Port Ball./Debal.	0.00	0.00	0.00	81.38		81.38	50%	EU 100%	US 0%
					TOTAL PER TRC	4,633.7			
							TOTAL PER YEAR	44,978	
							TOTAL PER 5 YEAR	224,890	
							TOTAL PER 10 YEAR	449,779	

SCENARIO 6 RENEWABLE TECHNOLOGIES OUTPUT

Component	<i>Estimated Auxiliary Power (at port) (KWh/day)</i>	<i>Estimated Auxiliary Power (at sea) (KWh/day)</i>	<i>Estimated Thrust Power (at sea) (KWh/day)</i>	<i>Daily running hours (at port)</i>	<i>Daily running hours (at sea)</i>
<i>PV Panels Full Hatch Coverage</i>	2095	2095	0	8	8
<i>PTI/PTO (7.5 cycle operation)</i>	0	3353	8001	-	20.35
Total	2095.00	5448.00	8001.00		

Saling Days per TRC	Total Saling days per year	Total Saling days per 5 years	Total Saling days per 10 years
29.136	282.8	1414.08	2828.17
BESS RENEWALS	0.32	1.62	3.23
BESS lifespan	875		

SCENARIO 6 BATTERIES OPTIMIZATION

	Auxiliaries load	PV Panels Surpluss	PTO CHARGE	PTI DISCHARGE	Time
	227		920		1.74
	227			1000	0.97
	227		920		1.74
	227			1000	0.97
	227		920		1.74
	227			1000	0.97
	227		920		1.74
PV Oper	227	35		1235	1.235
PV Oper	227	35	920		1.25
PV Oper	227	35		1235	1.235
PV Oper	227	35	920		1.25
PV Oper	227	35		1235	1.235
PV Oper	227	50			
PV Oper	227	35	920		1.25
PV Oper	227	19		992	0.99
	227		920		1.74
	227			304	3.945
	227				
	227				
	227				
	227				
	227				
	227				
	227				
	227				

SCENARIO 6 REDUCED CONSUMPTION/EMISSIONS

	M/E daily reduced consumption (mt VLSFO)	M/E daily reduced consumption (mt Lsmgo)	Total. Thrust Output (kWh)	M/E Total. Reduced Output (kWh)	DGs daily Reduced Consumption (mt VLSFO)	DGs daily reduced Consumption (mt MGO)	Auxiliary s total Load (kWh)	DGs total reduced Load (kWh)	Thrust percentag e from renewable	Auxiliary s percentag e from renewable	Total VLSF O Savings (mt)	Total LSMG O Savings (mt)
Open Sea Sailing	43.58	0.00	237048	229047	0.00	0.00	5448	0	3.4%	100.0%	2.82	0.10
ECAs Sailing	0.00	43.58	237048	229047	0.00	0.00	5448	0	3.4%	100.0%	0.00	2.92
Port/ECA Maneuvering	0	26.5	139440	139440	0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Idle	0	0	0		0.00	3.05	16320	14225	0	12.8%	0.00	0.45
Port Ball./Debal.	0	0	0		0.00	4.55	23328	21233	0	9.0%	0.00	0.45



	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs daily VLSFO total emissions mt CO2 eq.	DGs daily LSMGO emissions mt CO2 eq.	Total emissions mt CO2 eq.	Total Reduction of emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.
Open Sea Sailing	137.84	0.00	0.00	0.00	137.84	9.25	6.3%
ECAs Sailing	0.00	141.85	0.00	0.00	141.85	9.51	6.3%
Port/ECA Maneuvering	0.00	86.26	0.00	9.93	96.19	1.46	1.5%
Port Idle	0.00	0.00	0.00	9.93	9.93	1.46	12.8%
Port Ball./Debal.	0.00	0.00	0.00	14.81	14.81	1.46	9.0%



PER TRC	M/E Total Reduced (mt VLSFO)	M/E Total Reduced (mt LSMGO)	DGs total Consumption Reduced (mt VLSFO)	DGs total Consumption Reduced (mt LSMGO)		Total VLSFO (mt)	Total LSMGO (mt)	Total VLSFO Savings (mt)	Total LSMGO Savings (mt)
Open Sea Sailing	1123.7	0.0	0.0	0.0		1123.7	0.0	72.77	2.58
ECAs Sailing	0.0	146.0	0.0	0.0		0.0	146.0	0.00	9.79
Port/ECA Maneuvering	0.0	65.4	0.0	7.5		0.0	72.9	0.00	1.11
Port Idle	0.0	0.0	0.0	3.1		0.0	3.1	0.00	0.45
Port Ball./Debal.	0.0	0.0	0.0	22.8		0.0	22.8	0.00	2.25
TOTAL PER TRC						1123.7	244.7	72.8	16.2

TOTAL PER YEAR	10,907	2,375	706	157
TOTAL PER 5 YEAR	54,536	11,876	3,532	785
TOTAL PER 10 YEAR	109,073	23,753	7,064	1,570



PER TRC	M/E daily VLSFO total emissions mt CO2 eq.	M/E daily LSMGO emissions mt CO2 eq.	DGs VLSFO total emissions mt CO2 eq.	DGs LSMGO total emissions mt CO2 eq.		Total Reduced emissions mt CO2 eq.	Total Reduction emissions mt CO2 eq.	Total Reduction % emissions mt CO2 eq.	EU/ETS Savings x 50%
Open Sea Sailing	3554.34	0.00	0.00	0.00		3554.34	238.58	6.3%	119.29
ECAs Sailing	0.00	475.28	0.00	0.00		475.28	31.87	6.3%	15.94
Port/ECA Maneuvering	0.00	212.78	0.00	24.49		237.27	3.61	1.5%	1.80
Port Idle	0.00	0.00	0.00	9.93		9.93	1.46	12.8%	0.73
Port Ball./Debal.	0.00	0.00	0.00	74.07		74.07	7.31	9.0%	3.65
TOTAL PER TRC						4,350.9	282.8	6.1%	141.4

TOTAL PER YEAR	42,233	2,745	6.1%	1,373
TOTAL PER 5 YEAR	211,163	13,727	6.1%	6,863
TOTAL PER 10 YEAR	422,326	27,454	6.1%	13,727

SCENARIO 6 CAPEX/OPEX/SAVINGS/ROI

Component	<u>CAPEX</u>	<u>OPEX (PER YEAR)</u>	<u>OPEX (PER 5 YEAR)</u>	<u>OPEX (PER 10 YEAR)</u>	<u>OPEX extra BESS Ren.</u>	<u>Total OPEX (PER YEAR)</u>	<u>Total OPEX (PER 5 YEAR)</u>	<u>Total OPEX (PER 10 YEAR)</u>
2MWh EMS & BESS	850,000	3,600	18,000	36,000	400,000	132,888	664,439	1,328,878
<i>PV Panels Full Hatch Coverage</i>	1,796,000	18,210	91,050	182,100	0	18,210	91,050	182,100
<i>PTI/PTO (7.5 cycle operation)</i>	4,000,000	7,500	37,500	75,000	0	7,500	37,500	75,000
Total	6,646,000	29,310	146,550	293,100	400,000	158,598	792,989	1,585,978



	PRICE				
	700	1200	80		
	Total VLSFO Savings €	Total LSMGO Savings €	Total EUAs Savings €	TOTAL SAVINGS €	TOTAL OPEX COSTS €
PER TRC	50,942	19,407	11,313	81,662	16,339
PER YEAR	494,474	188,377	109,815	792,666	158,598
PER YEAR 5	2,472,370	941,885	549,075	3,963,329	792,989
PER YEAR 10	4,944,739	1,883,769	1,098,150	7,926,658	1,585,978

ROI PERIOD YEARS
10.5