Economic Operation of Ships using Electric Propulsion, Cogeneration Units, Renewable Energy Sources and Energy Storage

Technical University of Crete
School of Electrical and Computer Engineering

Tsarknias Stergios

Examination Committee
Kanellos Fotios, Associate Professor ECE TUC (supervisor)
Tsekouras George, Associate Professor EEE UNIWA
Staurakakis George, Professor ECE TUC

February 2024

Thanks

I would like to thank my thesis supervisor, Professor Kanellos Fotios, for the time he dedicated and the guidance he provided towards the completion of this thesis.
Most importantly , I would like to thank my friends and family, thanks to whom I had the energy, the disposition and the motivation to progress and complete my studies.

Contents

List of Figures

Objective of Thesis

The objective of the thesis is to plan the operation of a ship with electric propulsion during a voyage, in order to achieve the lowest possible operating cost. This is achieved by setting the power level of the system's power plants for minimizing fuel consumption while meeting the ship's needs and constraints. Also, this work aims to identify the advantages of the ship with electric propulsion over the conventional and to evaluate the practices and the utility of the individual elements (storage unit, renewable energy sources, cogeneration) of the system.

Abstract

Ships are a driving force in the transport of people and, above all, goods. 80% of commodities are transported by sea, making ships the "bridge" between producing and consuming countries. Millions of commercial voyages a year carry about 11 billion tons of goods, and passenger voyages carry tens of millions of people. It is therefore imperative that these much-needed transfers are handled as efficiently as possible. Efficiency is interwoven with electronic systems for scheduling and determining how the system's power plants operate. The shift towards electrification could not fail to affect the shipping sector as well, but in a different way from that of automobiles. Because ships need to sail for up to weeks without docking at a port, it is not economically and practically viable to support their needs solely by an energy storage systems with today's advances in the storage industry. But electric propulsion offers greater degrees of freedom and the potential for greater fuel efficiency, which can allow power plants to run optimally and more cheaply. In this thesis, the optimization of a conventional ship with a cogeneration unit in terms of power plants' operation during the voyage is firstly studied. The "weaknesses" of the conventional propulsion system are identified and a new system with electric-propulsion, i.e. the propeller is rotated by electric motors, is counter-proposed. In addition, an energy storage unit with batteries and an electricity production unit using photovoltaics are introduced into the system. Finally, various travel scenarios are studied and a comparison is made between the conventional and the electric powered ship, but also between the practices used in these scenarios.

Resume

This thesis deals with the operation of a ship with electric propulsion, cogeneration units, photovoltaic cells and an energy storage unit in the most economical way possible during a voyage.

Initially, the conventional energy system of ships is formed, which is still used today, based on the scientific publication: «Intertemporal optimization of synthesis, design and operation of integrated energy systems of ships: General method and application on a system with Diesel main engines». It describes three branches of needs encountered during a voyage: 1. Propulsion power: is the mechanical power required by the system to propel the ship. 2. Electric power which is used for the auxiliary functions of the ship: lighting, loading and unloading systems, power supply for communication and navigation systems, security systems and monitoring the proper operation of the ship through sensors. In addition, air conditioning and cooling needs are covered for the comfort of passengers. 3. Thermal power to provide heating and hot water.

Via the cogeneration system, the hot exhaust gases of the propulsion engines are exploited. The exhaust gases come into contact with pipes containing water and create steam which is used for heating or to produce additional mechanical work like a combined cycle unit.

When converting the conventional system to an electric propulsion system, the series hybrid system was chosen where the diesel engines that drove the propeller are used to generate electrical power. Now, the blades are rotated by electric motors. Uncoupling the engines from the propeller allows them to vary their revolutions per minute (rpm) to cover the required load in an optimal way in terms of fuel consumption. Also, since electric power is now required for propulsion, but also with the introduction of the storage unit and photovoltaics, greater degrees of freedom are given to the system in choosing the sources from which the needs will be met, allowing the power

plants to operate close to their optimal operating point for a longer period of time.

The optimum operating points are then identified in sampled scenarios depending on the propulsion, electrical and thermal power requirements for the two ship types.

Finally, a comparison is made between a conventional and an electric powered ship for the same travel scenarios, but also between the different scenarios for the same ship types.

Notation

AES: All Electric Ship
HRSG: Heat Recovery Steam Generator
PMSG: Permanent Magnet Synchronous Generator
SFOC: Specific Fuel Operation Consumption
RES: Renewable Energy Sources
ME: Main Engines
DG: Diesel Generators
CCP: Combined Cycle Plant
AB: Auxiliary Boilers
P: Pressure
T: Temperature
h: enthalpy
s: entropy
x: steam quality

Keywords

Conventional Ship All Electric Ship Electric Propulsion Energy efficiency Cogeneration Energy Storage Hybrid Energy System Slow Steaming

Chapter 1

Necessity of more energy efficient ships

The need for ships with high energy efficiency stems from many important reasons. First, cost savings is a major advantage. These vessels consume less fuel per unit of cargo carried, offering lower operating costs for ship owners and their operators. In addition, improved efficiency can lead to reduced wear and tear on the ship's engines and systems, resulting in lower maintenance costs throughout the life of the vessel. Highly energy efficient ships also contribute to energy security. Their dependence on fossil fuels is reduced, contributing to the conservation of finite energy resources. In addition, they contribute to long-term sustainability by adapting themselves to the changing energy landscape, as the world transitions to alternative energy sources, energy efficient ships are able to incorporate these new technologies. Chartering such vessels also offers a significant competitive advantage in the market. Customers and partners increasingly value practices that respect the environment, and energy-efficient ships can attract environmentally conscious customers and partners. Their use demonstrates a commitment to sustainability and responsible business practices, enhancing the reputation and image of ship-owning companies. Thus, ships with high energy efficiency offer not only financial benefits but also added value to the company that uses them.

Chapter 2

Ship Energy Systems

The term "ship energy system" generally refers to the complex set of mechanisms and technologies responsible for providing power and energy to various components and systems on a ship. Ships require energy for propulsion, navigation, communication, lighting, heating, hotel services and other onboard systems. There are many approaches as to how these needs are met, leading to different vessel types [6].

2.1 Conventional Vessel

A conventional ship power system includes a main propulsion system, which usually consists of diesel engines, and auxiliary systems such as generators, pumps, and air conditioning and heating units. The main propulsion system converts the fuel into mechanical energy to turn the ship's propellers, the auxiliary systems generate electricity to power various systems and equipment, while the heating needs are covered by diesel-powered boilers. Fuel for the propulsion system and the diesel generator is usually stored in the ship's tanks and supplied to the power plants as they are needed. Electricity for essential operations and amenity services is generated by generators powered by the main propulsion system or auxiliary engines. Heating needs are covered from boilers operating on diesel.

- Diesel engines (Main Engines – Diesel engines) propel the ship.
- Diesel generators (Diesel Generators -DG) supply the system with electricity.

- Steam boilers (Auxiliary Boilers - AB) cover thermal needs by heating water.

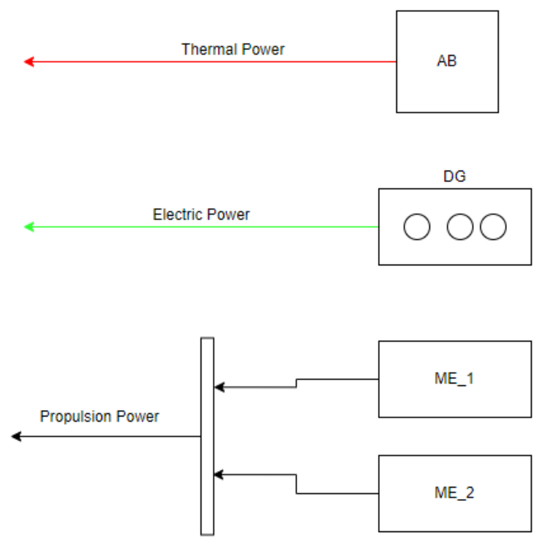


Figure 2.1: Conventional Energy System

2.2 Description of the Conventional System used

The development of the system that later became the electric propulsion ship was based on the scientific publication: "Intertemporal optimization of synthesis, design and operation of integrated energy systems of ships: General method and application on a system with Diesel main engines" [13]. In this work, the dimensioning of the technical characteristics of the ship's units is studied, based on its energy needs and fuel costs. The arrangement used is two main engines which take over the propulsion. The element that differentiates this system from the conventional ship is the exploitation of the thermal power of the exhaust gases (red dotted lines) produced by the main engines during their operation. Because the heat of these exhaust gases is able to heat-up water and create superheated steam (blue dotted lines), it is clear that with the a Heat Recovery Steam Generator (HRSG) system the exhaust thermal power can be harnessed either to cover a heat load, or by expanding the steam in a turbine, for the production of mechanical and/or electrical work like a Combined Cycle Plant (CCP). From now on, when reference is made to a conventional ship, the specific one will be implied.

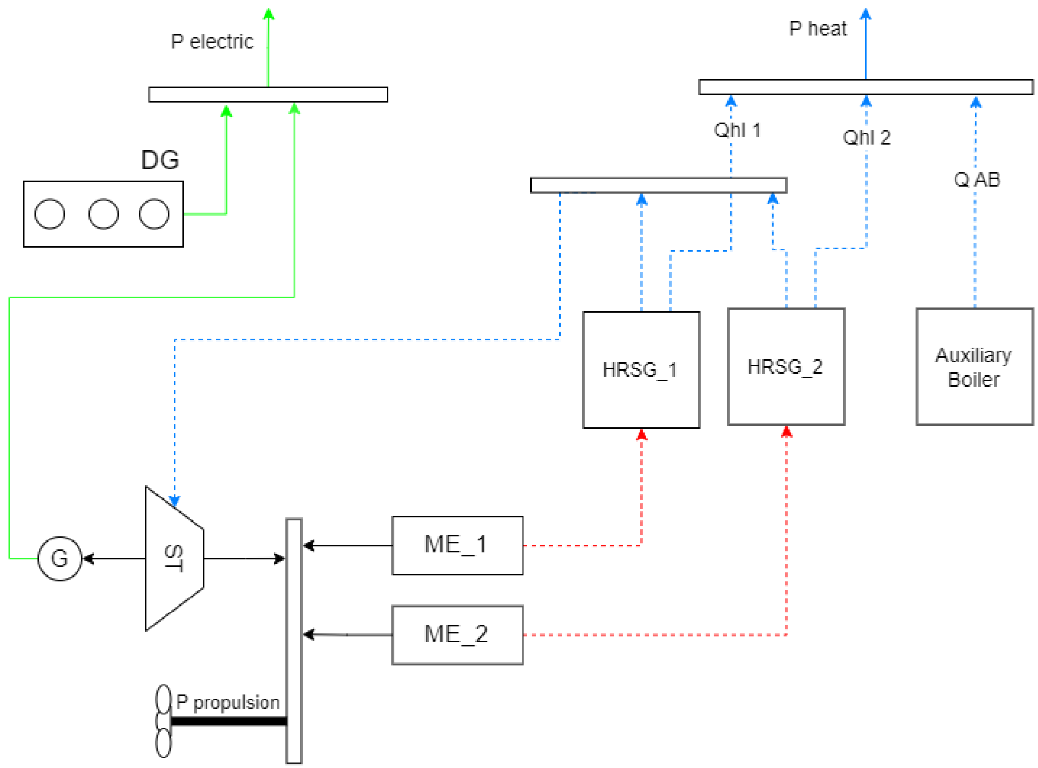


Figure 2.2: Superconfiguration of the energy system

2.3 Weaknesses of the conventional ship

In a conventional ship because it is strictly defined what kind of power each engine covers, the system is more "rigid" in terms of the operating point of the engines because there are not many alternative ways to cover the loads and also at least two power plants must be running at any time which leads to increased pollution and costs. The diesel generator for example should run almost always when there are electrical demands. This creates two problems: firstly the power plants are likely in many scenarios to operate far from their optimum point and secondly there is an issue of reliability. If e.g. if the diesel generator is damaged then the ship will depend only on the electric power of the cogeneration to perform basic functions such as communication, navigation, operation of the safety systems and sensors of the ship. This power is of the order of 1-1.5 MW, so definitely hotel services will be suspended. Also, because the main engines are attached to the propeller, they are forced to run at the specific rpm the propeller is rotating at, which means that in many scenarios their rpm are not optimal for producing the mechanical power required.

2.4 All Electric Ship (AES)

The all-electric ship has gathered the interest of the shipping community because of the increasingly strict limitations of the pollutants produced due to climate change. Also, the electrical parts have the ability to be automated more easily, which makes it possible, with appropriate optimization, to significantly reduce operating costs. More specifically, propulsion is carried out by electric motors which are powered by large-scale storage units. Diesel engines and generators are absent while all electrical needs are covered by batteries, supercapacitors and/or hydrogen cells (fuel shells) which are installed on board, with appropriate use of power electronics.

Advantages

- Zero pollution during the voyage, so the environment of major ports is not degraded and there is no penalty for the companies operating the ships.
- The electric motor presents a very high torque in its wide range of operation as shown on Fig. 2.3, even at low speeds, making maneuvers within the ports easier.
- Ability to schedule operation and thus great scope for optimization and automation of processes during the journey, leading to lower operating costs of the overall system and less involvement of the human factor.

- Ability to absorb the charging energy of the batteries from clean forms of energy (RES, hydrogen, etc.) so that the environmental footprint of their operation is negligible.

- Lower noise pollution: Electric motors tend to produce less noise than traditional internal combustion engines, which can help reduce noise pollution in ports and other coastal areas.

- Lower maintenance costs: Electric propulsion systems have fewer moving parts than traditional systems, which can lead to lower maintenance costs.

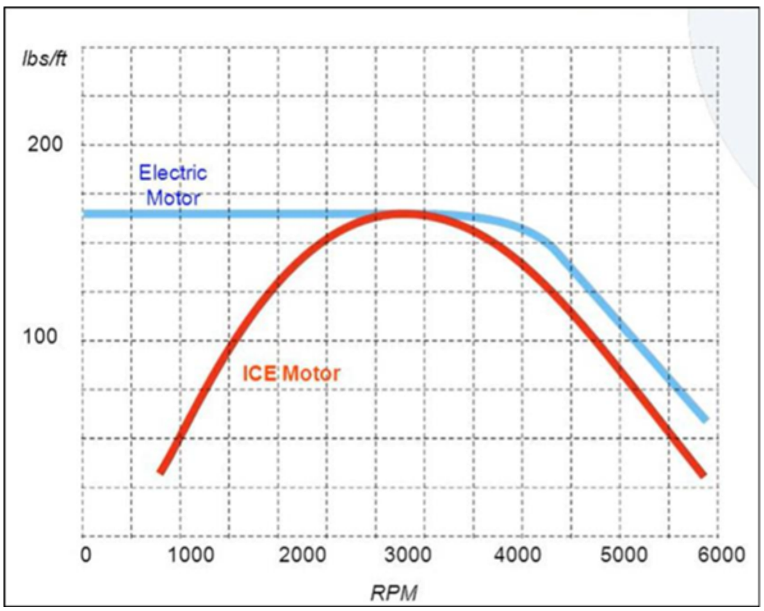


Figure 2.3: Torque – rpm graph for internal combustion and electric motor

Disadvantages

- Cargo ships or cruise ships cannot cover long journeys relying only on energy from batteries, as their needs are in the range of hundreds of megawatt hours (MWh).

- The cost of storage, although it has been reduced to a tenth due to the great research and development taking place in recent years, remains quite high as an investment, and the finite lithium deposits which is a key component of modern batteries does not allow the mass development of AES.

- Inserting battery packs on a large scale requires a lot of space while their weight is not negligible.
- When such big storage units are required, the environmental footprint of the construction of those units should also be taken into account.
- The availability of charging infrastructure may be limited in some areas, which can make it difficult to operate in these areas for ships using large storage units.
- The refueling time, i.e. charging their storage unit, is much longer than the refueling time of conventional ships, which affects the distance that can be covered in days of travel.

RES integrated in the ship

To aid in their operation, all-electric ships incorporate Renewable Energy Sources to generate power during the voyage or when docked. Many technologies can be used such as solar, wind and hydroelectric. Photovoltaic panels are used in this thesis due to their reduced complexity, ease of installation and lack of mechanical parts leading to less maintenance needs. With technological progress, the density of the cells in the photovoltaic panels has increased, but the power of the panels in relation to the available space on the ship for their placement can cover a small percentage of the ship's energy needs.

Investigation

It is assumed that the available space for placing panels is 2,000 square meters (2000 m^2). The most efficient panels of the year 2023 are 450 Watt and have dimensions $1722 \cdot 1134 \cdot 30$ mm. Thus, they cover an area of $1.722 \text{ m} \cdot 1.134 \text{ m} = 1.953\text{m}^2$.

The area is rounded to 2m^2 for reasons of practicality and ease of installation and maintenance. The number of panels that can be installed is 1,000. (2,000 m^2 / 2 m^2) The peak power (maximum possible power output under ideal conditions) is 1,000 panels $\cdot$ 450 W = 450 kW

The peak power is reached in about 10% of the operating time, so in the remaining 90% the generated power is less than 450 kW. Especially at night the generated power is essentially 0.

Overall, while fully electric ships have many potential benefits, they have not yet been widely adopted in the shipping industry due to the challenges discussed above and the costs associated with the storage technology. However, as technology advances, battery costs decrease and charging infrastructure improves, it is certain that AES will become more common in the future.

2.5 Hybrid Energy Systems

The term "hybrid" refers to the combination of conventional Diesel engines and generators with the All Electric Ship system discussed above. The use of fuel (Diesel) or Natural Gas as energy sources reduces the required size of the batteries and enables its application in systems with greater energy requirements. The storage units are charged either by the diesel engines with the interposition of generators to convert the mechanical work into electric with the appropriate use of power electronics, or by the ship's Renewable Energy Sources, or by energy sources on land, when it docks in the port. Conventional engines can either directly contribute to propulsion in parallel with the electric engines (Parallel Hybrid Propulsion System), or be connected in series with generators to produce electric power (Series Hybrid Propulsion System).

2.5.1 Parallel Hybrid System

In ships with a hybrid parallel propulsion system, the propeller is driven by two types of engines. Conventional Internal Combustion Engines and Electric Engines. This arrangement allows the system to take advantage of the positive features of the two approaches depending on the needs of the system at any given time.

The parallel propulsion system includes the positive elements of the all-electric ship (lower fuel consumption, reduced exhaust gases, less noise during operation) and with the introduction of the Internal Combustion Engine the load that the battery must cover is reduced, increasing the autonomy and the range of the trips it can accomplish.

But having the storage system serve the propulsion of the electric motor and the other loads, there are still negative elements of the All Electric Ship mentioned above. The hybrid parallel system will be able to be a transitional stage from the conventional to the all-electric ship, as the storage unit required is smaller and the internal combustion engine provides reliability in case of emergencies (e.g. bad weather that will force the ship to stay at sea longer than planned and more propulsive power will be required).

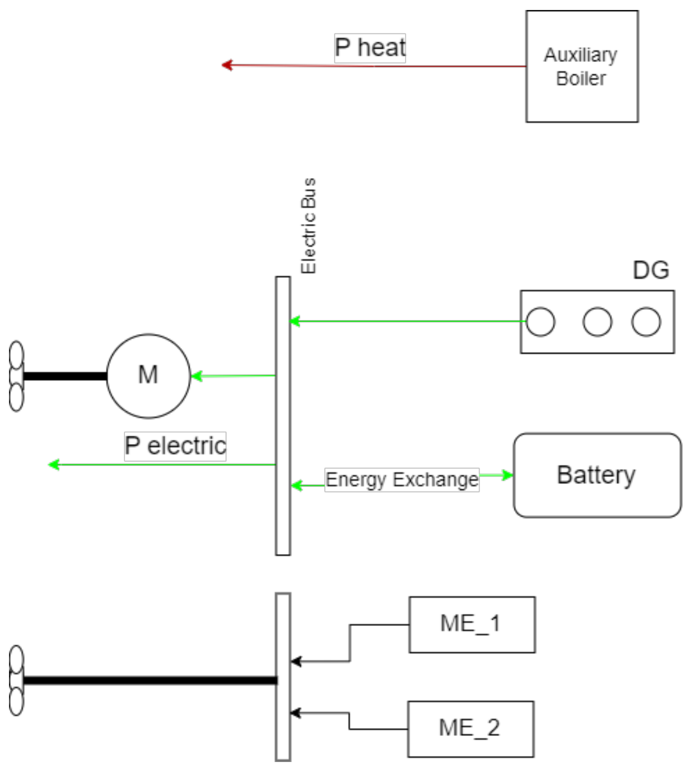


Figure 2.4: Parallel Hybrid Energy System

2.5.2 Series Hybrid Energy System

A series hybrid propulsion system, also known as a range-extending hybrid system, is a type of hybrid propulsion system in which the internal combustion engine is not directly connected to the drivetrain. Instead, it is used to generate electricity, towards a bus which distributes this energy between the electric motor for propulsion and the auxiliary loads.

This architecture allows more flexibility in powertrain design, as the internal combustion engine can be optimized for electricity generation and the electric motor can be optimized for propulsion. Because the internal combustion engine does not need to be connected to the drivetrain, it can be smaller and more efficient allowing better arrangement of the engine room.

The **advantages** of series hybrid systems include:

- Improved fuel efficiency: The internal combustion engine can operate at its most efficient point, which is usually at a lower rpm than required for propulsion.
- Reduced emissions: The internal combustion engine only produces electricity and does not directly power the vehicle, which reduces emissions.
- Lower mechanical stress: Since the internal combustion engine is not directly connected to the propeller shaft, it can operate in more efficient conditions.

The **disadvantages** include:

- Higher cost: Series hybrid propulsion systems can be more expensive than traditional or parallel hybrid systems because they require more components (generators attached to each diesel engine and more power electronics).
- Limited electric range: The battery in a series hybrid vehicle is usually smaller than the fuel tank, so the vessel cannot cover great distances on electric power alone.
- Dependence on fossil fuels: although hybrid technology improves fuel efficiency, it still depends on fossil fuels as the primary source of energy for the internal combustion engines.

The hybrid series system was chosen because it keeps up with current data of technological progress of the storage systems, thus, there is less dependence on them. Also, if no engine is directly connected to the propeller shaft, it is possible to operate all engines at variable speeds, making the system more efficient in terms of fuel consumption, as will be analyzed later.

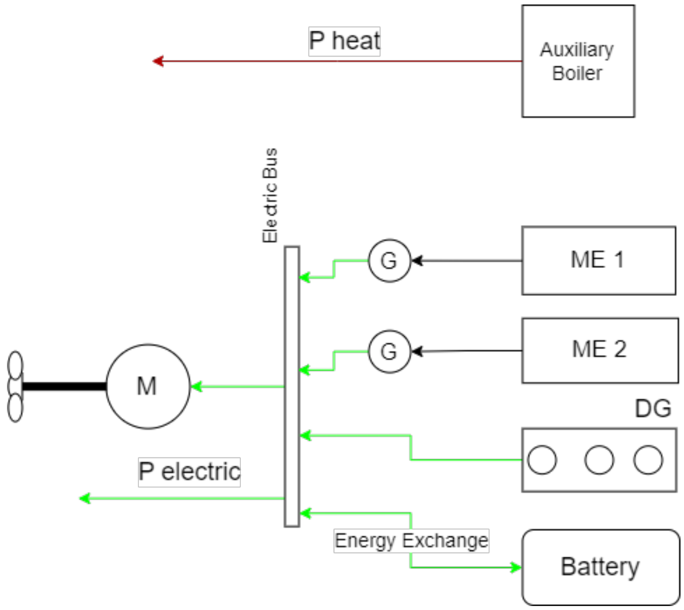


Figure 2.5: Series Hybrid Energy System

2.6 Conversion of the conventional into a ship with electric propulsion

For the conversion of the ship described above according to the Paper [13] to an electric propulsion ship the mechanical work of the main engines is not used directly for propulsion. Instead, it is used to rotate the rotor of generators to produce electrical power. So, the main engines along with the generators that are imported are now considered as electrical power generating elements of the new system. Propulsion takes place through electric motor(s) which are able to utilize not only the energy of the engine-generators, but also the energy of the battery, photovoltaics and diesel generator. In addition, the electrical power from the main engines can be used to cover auxiliary electrical needs. Thus, greater degrees of freedom are provided to the system, which allows its components to operate closer to their most efficient point. Now, the propulsion needs and electrical needs of the conventional ship form one type of needs (electrical only) for the electric propulsion ship. Finally, the surplus thermal power produced by the exhaust gases after covering the thermal needs, produces exclusively electrical power since the propulsion also utilizes electrical work.

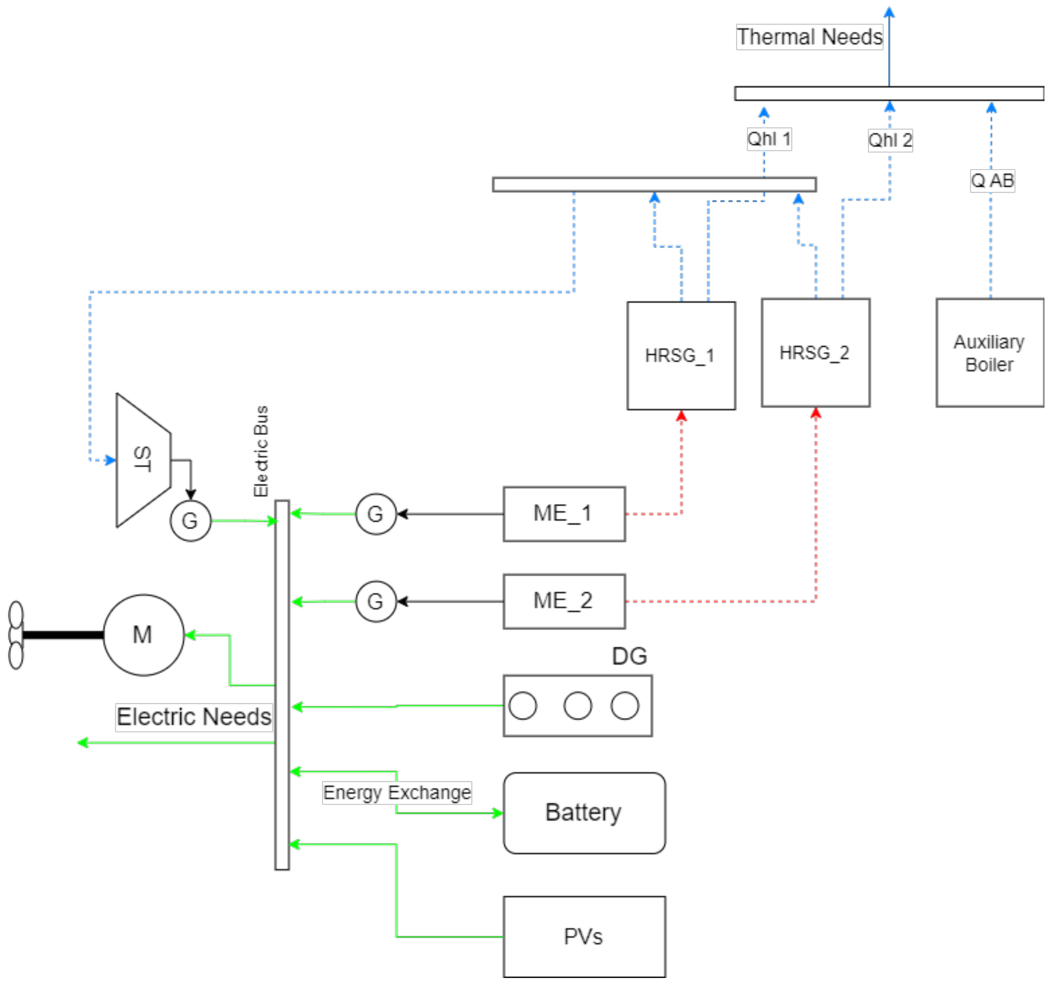


Figure 2.6: Series Hybrid Energy System with Cogeneration

2.7 Power Electronics required to operate such a ship

Until recently, constant speed generators were the only technology available. Operation at constant speeds, however, pushes the engines to work inefficiently. The rotor revolutions determine the frequency of the power produced. It should therefore be possible to operate the main engines at variable speeds and the electrical power produced to have the frequency required by the loads. This is achieved by inserting a DC bus[3, 9]. The actual AC output of the generator is converted through some solid state rectifiers to DC. The direct current can, with additional power electronics, take on the characteristics required by the various loads for their operation. The motor speed can now be varied without affecting the output frequency of the inverter and the motor operates at an optimum point to produce the power required at that time. Engine life is increased, noise levels are reduced and fuel economy is optimized. Advances in power electronics have made the entire conversion process extremely efficient, with the overall system of generators, power electronics and electric motor achieving over 90% efficiency.

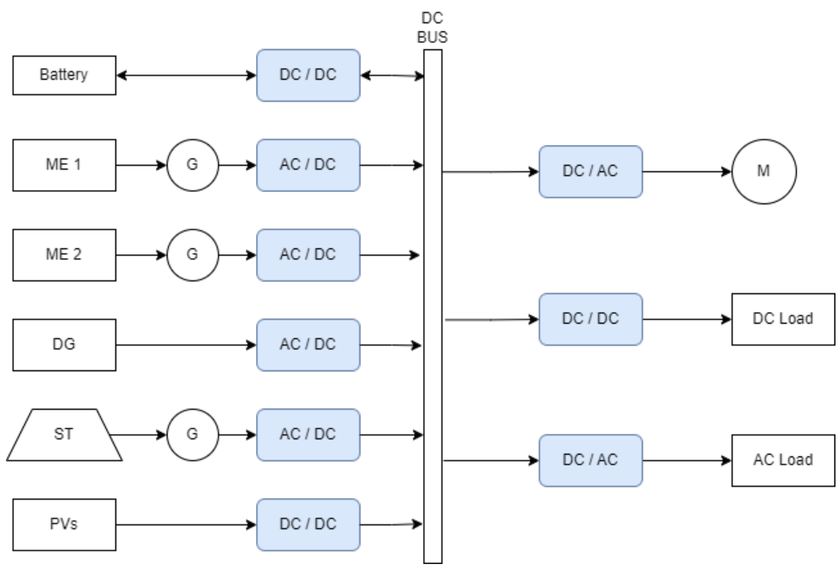


Figure 2.7: Power Electronics coupling with System Components and Loads

Chapter 3

Cogeneration

Cogeneration is defined as the exploitation of the waste heat produced during engine operation for heating and other purposes. In this particular study, this is achieved through a heat and exhaust gas recovery system for steam production, known as a Heat Recovery Steam Generator (HRSG). To comprehend how the cogeneration system works, some basic knowledge of thermodynamics is required, and this is analyzed below.

3.1 Thermodynamics

In order to understand the following sections, it is appropriate to give some definitions of thermodynamic phenomena.

3.1.1 Definitions

Fluid: A substance is characterized as such when it can flow, i.e. it is in a liquid or gaseous state.

Enthalpy (H) : Enthalpy describes the energy contained in a fluid, therefore its unit of measurement is kJ. Equation:

$$H = U + P \cdot V \tag{3.1}$$

where H is the enthalpy symbol, U is the internal energy of the fluid (kJ), P is the pressure (Pascal) and V is the volume (m^3).

Specific enthalpy (h): The addition of the term "specific" means that the quantities in the equation are measured relative to some other quantity. In this case they are measured in terms of the mass of the fluid.

$$h = u + P \cdot v \tag{3.2}$$

where h is the specific enthalpy (kJ/kg), u is the specific internal energy (kJ/kg), P is the pressure (Pa - Pascal) and v is the specific volume (m^3/kg).

Entropy (s): Entropy measures disorder at the molecular level or molecular randomness. In solid elements the entropy is smaller as the molecular "lattices" are immutable and the movement of the molecules is usually limited only to their vibration. In liquids, because their shape is not specific, the position of the molecules is not as strictly defined as in solids. The entropy of liquids is greater than that of solids. Gasses have the highest entropy as their shape is irregular, their volume changes and the bonds between molecules are looser, so they have a lot of freedom to move in space (Great Randomness).

Isentropic: without change in entropy.

Isobaric: without change in pressure.

Saturated Liquid: Liquid which with heat intake at constant pressure changes to a gaseous state.

Saturated Gas: Gas which by removal of heat at constant pressure changes to a liquid state.

3.1.2 Temperature – Entropy Diagram (T-s)

Below is the T-s diagram (temperature-entropy)(Fig.3.1), which illustrates the behavior of water during its heating. A "bell" is formed (continuous line) on which saturated liquid exists to the left of the "critical point" (e.g. point B) and saturated gas exists to the right of the "critical point" (e.g. point C).

Outside the bell and to the left of the critical point is unsaturated liquid and outside the bell and to the right of the critical point is unsaturated vapor.

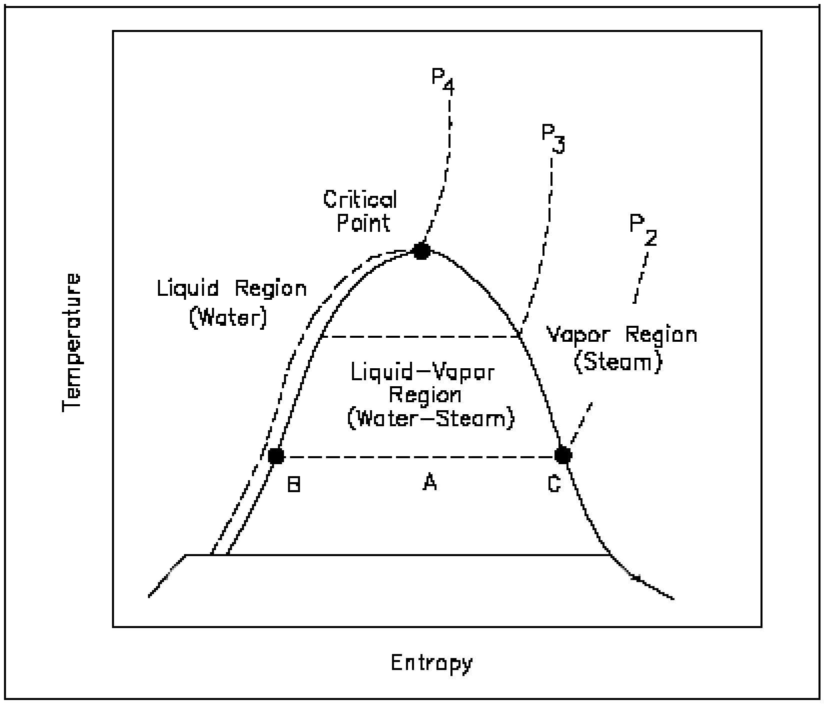


Figure 3.1: T-s Diagram for Water

As mentioned above in point B, the container contains saturated liquid. With the addition of heat, a transition is made gradually from point B to point C, where finally there is only saturated steam. Until the transition from point B to point C (dashed horizontal line) takes place in the container, saturated liquid and saturated gas coexist (e.g. point A inside the "bell"). The ratio of the mass of vapor in relation to the total mass of fluid is called steam quality.

3.1.3 Steam quality

Steam quality measures the ratio of the steam mass compared to the total liquid and steam mass and is symbolized with x.

Steam Quality:

$$x = \frac{m_{gas}}{m_{overall}} = \frac{m_{gas}}{m_{liquid} + m_{gas}} \tag{3.3}$$

where m is the mass

It is evident from the equation that quality x takes values from 0 to 1.

The above concept is only defined and meaningful within the "bell" (where water and steam coexist). The closer to point B, the more saturated liquid is present relative to vapor, so the quality takes lower values. The closer to point C, the more saturated gas is present in relation to liquid, so the quality takes on higher values. At point B the quality is 0 and at point C it is 1.

3.2 Water as a medium for the conversion of thermal power into mechanical power

Water is commonly used as a medium for converting heat into mechanical energy due to its unique properties and abundance. The process involves using heat to produce steam, which is then used to drive turbines and produce mechanical work. To begin with, water has a high specific heat capacity, which means that it can absorb and store a significant amount of heat energy without experiencing a significant increase in its temperature. This property allows it to efficiently transfer heat from a source to a steam generator or boiler. In addition, it has a large latent heat of vaporization, which means that it requires a significant amount of energy to change from liquid to gaseous state. This property allows water to absorb a large amount of heat when it evaporates as steam, maximizing the energy transfer during the conversion process. It is also abundant and widely available, making it a cost-effective choice for heat-to-mechanical energy conversion systems. Its accessibility makes it a practical choice for large-scale power generation. Water is non-toxic and environmentally friendly, making it a safe and sustainable medium for energy conversion. It does not contribute to air pollution or emit harmful greenhouse gases when used as working fluid. Water has a wide range of temperatures and pressures in which it can exist in both liquid and gaseous states, making it adaptable to various power generation systems. It can withstand the high temperatures required for efficient energy conversion without reaching critical points or causing equipment damage. Finally, water-based steam cycles, such as the Rankine cycle, have been extensively studied and optimized for power generation by allowing the efficient extraction of energy from heat sources and have been applied in various industries, including thermal power plants and cogeneration systems such as the one that is studied in the present work.

Overall, water possesses a combination of physical and chemical properties that make it an ideal medium for converting heat into mechanical energy. Its high heat capacity, latent heat of vaporization, abundance, safety and adaptability contribute to its widespread use in power generation systems.

3.3 Ideal Rankine Cycle

The Rankine cycle is a thermodynamic cycle commonly used in steam power plants to convert heat energy into mechanical work. The cycle consists of four main processes: isentropic compression, isobaric heat addition, isentropic expansion, and isobaric heat rejection. In the Rankine cycle, a working fluid (usually water) undergoes these processes in a closed-loop system, with the goal of maximizing the efficiency of energy conversion. Steam turbines are often employed to extract mechanical work from the cycle, making it a fundamental concept in the design and operation of steam power plants.

Four components are used in the Rankine cycle [1]. The compressor, the boiler, the turbine and the condenser. Each is used to transition from one state of the Rankine cycle to the next.

The Rankine cycle consists of four reversible stages which are described by the figure 3.2:

1. Isentropic Compression: Water is in state 1 as a saturated liquid and is compressed without changing its entropy to a pressure suitable for boiler operation (point 2).

2. Isobaric Heat Uptake: The compressed saturated liquid is heated at constant pressure until it reaches the superheated vapor state. (Transition 2-3)

3. Isentropic Expansion: Superheated steam is isentropically detonated in a turbine and mechanical work is produced. (Transition 3-4)

4. Isobaric Heat Rejection: Heat is expelled to the environment while the steam condenses at constant pressure and turns into water. (Transition 4-1)

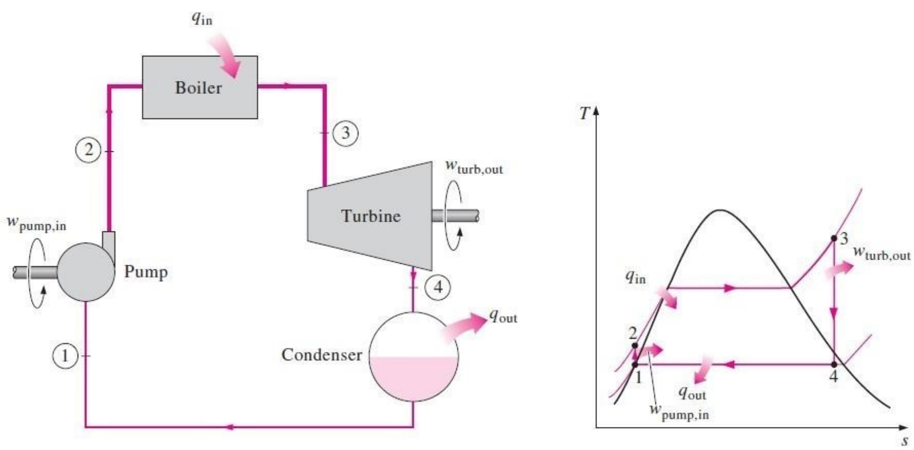


Figure 3.2: Ideal Rankine Cycle

3.4 Deviation between Ideal and Actual Rankine Cycle

The ideal Rankine cycle is reversible. Thus, in each transition, if the opposite path is followed (heat removal instead of absorption) the cycle returns to the previous state, meaning no losses occur.

Ideal Rankine Cycle Components	Heat	Work
Boiler feed Pump $W_{\text{pump-in}}$	$q = 0$	$W_{pump-in} = h_2' - h_1, or, W_{pump-in} = V(P_2' - P_1)$
Boiler	$q_{in} = (h_3' - h_2')$	$W = 0$
Turbine	$q = 0$	$W_{turbine-out} = (h_3' - h_4')$
Condenser	$q_{out} = (h_4' - h_1')$	$W = 0$

The real Rankine cycle has, as can be seen in the cycle with dotted lines in Fig.3.3 some non-reversibilities exist in work intake (1-2) and work output

(3-4). These pressure losses are due to fluid friction causing pressure loss and heat and steam losses. If the opposite course is followed, one ends up in a situation different from the previous one because the friction and heat losses cannot be regained.

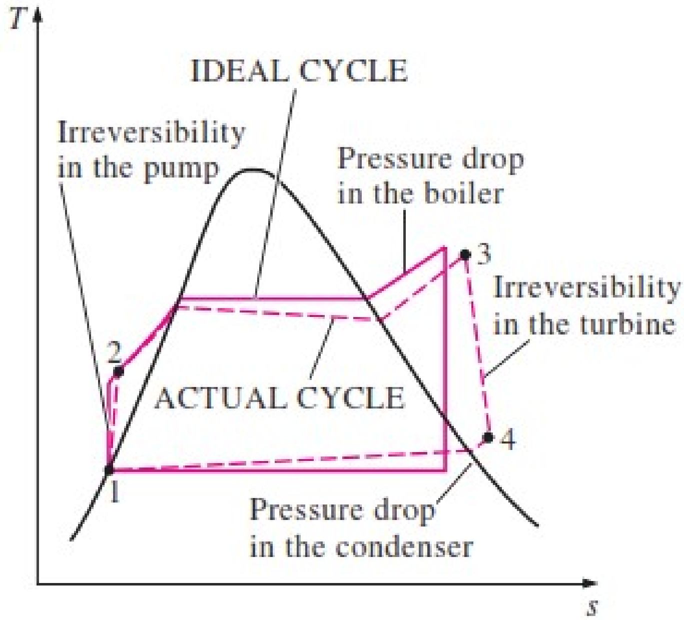


Figure 3.3: Ideal and Actual Rankine Cycle

Actual Rankine Cycle Components	Heat	Work
Boiler feed Pump $W_{pump\text{-}in}$	$q = 0$	$W_{pump-in} = (h_2 - h_1), or, W_{pump-in} = V(P_2 - P_1)$
Boiler	$q_{in} = (h_3 - h_2)$	$W = 0$
Turbine	$q = 0$	$W_{turbine-out} = (h_3 - h_4)$
Condenser	$q_{out} = (h_4 - h_1)$	$W = 0$

The table above shows that the difference in pressure drop between states

3 and 4 is smaller in the non-ideal cycle which yields less energy delivered to the turbine than the ideal one.

3.5 Assumptions made while studying the Rankine cycle of the cogeneration system

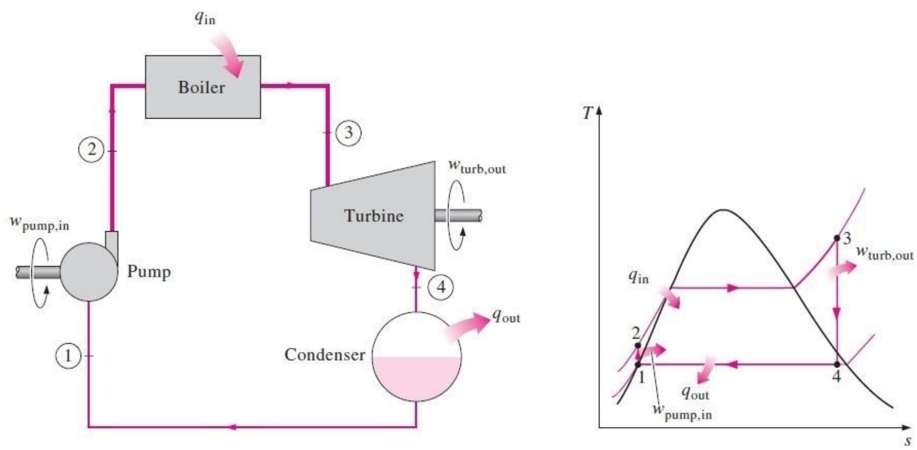


Figure 3.4: Ideal Rankine Cycle

In this particular thesis some assumptions are made based on the application of the Rankine cycle in real conditions:

- The power required by the pump to compress water from the 1^{st} stage to the 2^{nd}, constitutes 5% of the power transferred to the turbine.
- Because expanding in real conditions is not isentropic but entropy increases, point 4 is further to the right, so it is likely to be somewhere to the right of the bell, where the enthalpy h_4 increases with increasing entropy. So the enthalpy drop is less than that in the ideal Rankine cycle. The difference is calculated at 15% for this and the resulting turbine power is multiplied by a factor of 0.85
- Pressure after expansion: $P_4 = 0.1$ bar = 10000 Pascal (1 bar = 100000 Pascal).

- The temperature of the exhaust gases when they are released into the atmosphere is 130°C.

The mechanical power attributed to the turbine [1] is defined by the formula :

$$P_{ST} = m_s \cdot (h_3 - h_4) \tag{3.4}$$

The symbol m_s describes the mass flow of steam in kg/s while the subtraction h_3-h_4 symbolizes the difference in the energy (enthalpy) of the steam before and after expansion, i.e. it symbolizes the energy transferred from the steam to the turbine per unit mass.

If the pressure and temperature at point 3 (before expansion) are known then the enthalpy (h_3) and the entropy (s_3) at this point through the Refprop (3.7) application are calculated and since the transition 3-4 is considered isentropic, the entropy at point 4 is defined ($s_3 = s_4$).

Inside the "bell" the entropy of the mixture [1] is calculated as :

$$s_3 = s_4 = x_4 \cdot s_{ss} + (1 - x_4) \cdot s_{sl} \tag{3.5}$$

(considered pressure P_4 =0.1 bar).

s_{sl}*:entropy of saturated liquid at 0.1 bar=0.64920 kJ/(kg·K)*
s_{ss}*:entropy of saturated steam at 0.1 bar=8.1488 kJ/(kg·K)*

The steam quality after steam expansion (x_4) is calculated from the above equation.

The entropy after expansion [1] is calculated as:

$$h_4 = x_4 \cdot h_{ss\ at\ 0.1bar} + (1 - x_4) \cdot h_{sl\ at\ 0.1bar} \tag{3.6}$$

$h_{sl\ at\ 0.1bar}$*=191.84 kJ/kg :enthalpy of saturated liquid at pressure P=0.1 bar*
$h_{ss\ at\ 0.1bar}$*=2583.9 kJ/kg :enthalpy of saturated steam at pressure P=0.1 bar*

(The above are calculated by RefProp which gives the thermodynamic properties of saturated liquid/vapor at 0.1 bar.)

3.6 Calculation of enthalpy and entropy on the saturation curve

When the studied point is exactly on the saturation curve, then the knowledge of both pressure and temperature is not needed to determine the thermodynamic properties of water, but only one of them. Because it is in a saturated state, the temperature-pressure relationship is one-to-one, so for a given temperature value of the fluid there is only one pressure value for which the fluid is saturated and vice versa. Therefore, knowing that the fluid is saturated and one of the pressure or temperature values is also calculated.

As water is either in a saturated liquid state or a saturated gas state, the program returns two enthalpy values and two entropy values: one for a saturated liquid and one for a saturated gas. Both saturated fluid states (liquids and gases) have the same pressure and temperature.

3.7 The Refprop Tool

The Refprop program has many functionalities for studying the thermodynamic properties of a variety of elements. In this particular study it is used for the calculation of the thermodynamic properties of water/steam (enthalpy, entropy) based on pressure and temperature data entered by the user. In addition, it presents the curves that describe the behavior of fluids, and specifically for this work, water at various pressure values.

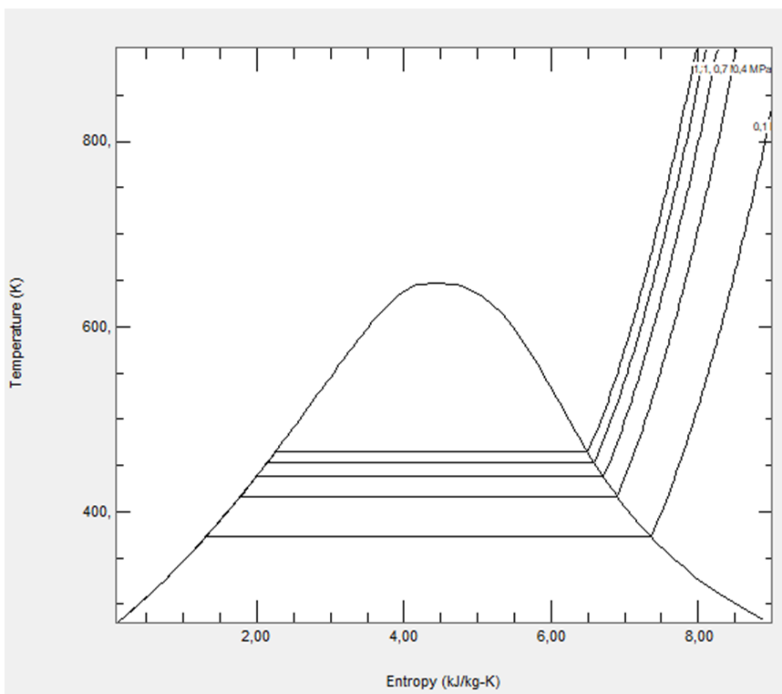


Figure 3.5: Water T-s Diagram on Refprop

3.8 Heat Recovery Steam Generator –HRSG

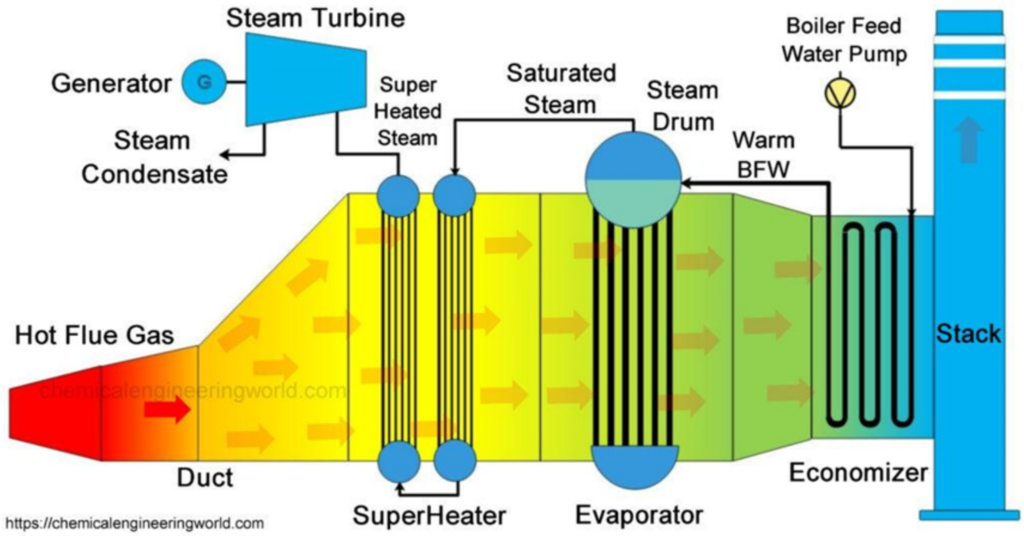


Figure 3.6: HRSG map

The Heat Recovery Steam Generator is a system that exploits the heat of the exhaust gases to produce high pressure and high temperature steam. It plays the role of the boiler mentioned in the Rankine cycle. The process inside the HRSG is divided into four (4) stages. First, the water is compressed by a pump and heated to saturation. This happens inside the economizer. Then the saturated liquid is transferred to the Evaporator where with additional heat supply the saturated liquid is converted into saturated steam. The steam is then introduced into the superheater and its temperature rises rapidly. The compressed, superheated steam is blown into the turbine which it sets in motion and mechanical work is produced.

The exhaust fumes have a very high temperature (295-370 °C) when entering the Heat Recovery Steam Generator and after each stage some of its heat is transferred to the water/steam. For this reason and when they are introduced they meet the superheater tubes, where very high temperatures are required for the steam to superheat. After the heat exchange the temperature of the exhaust fumes have decreased but is enough to cause the saturated water to boil and turn into steam. The exhaust gases are then passed between the economizer tubes to saturate the water. At their exit from the HRSG their temperature is about 130 °C. As can be seen from the figure, the course of exhaust gases and water/steam is opposite, due to the increasing thermal needs towards the final stages of conversion of water into superheated steam.

After the vapor is detonated, heat is released to the environment and the vapor through the condenser is converted back into liquid to repeat the operating cycle.

Chapter 4

Energy System Graphs, Components and Behavior

4.1 Propulsion Power

In ships, as in other means of transport, there is a direct dependence between the speed of movement and the power required for propulsion.. This relation is shown below:

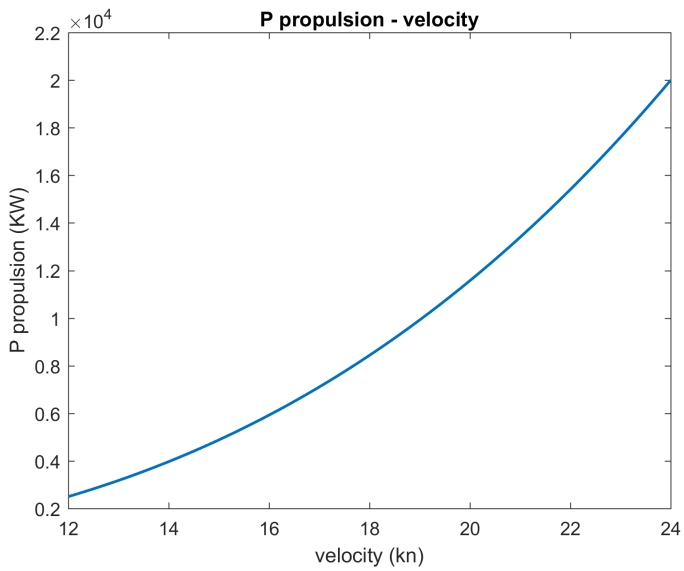


Figure 4.1: Propulsion Power -velocity graph

Firstly, it appears that the relation is exponential and follows the cubic law, which describes that moving the ship at twice the speed requires eight times the energy (12 knots requires 2.5 MW, while 24 knots requires 20 MW). This occurs because the opposing force that the ship has to overcome is related to the vessel's speed exponentially, as will be analyzed in the next subsection. Furthermore, it is evident that by converting knots to km/h, multiplying by the factor 1.852, the ship's speed is in the range of 22.20 km/h to 44.5 km/h. The travel speed range includes lower cruising speeds and higher speeds.

4.1.1 Ship Drag

Ship drag is the total force opposing the forward motion of the ship at constant speed in calm water. Alternatively, the force required to tow a ship in calm water at a constant speed. In order to achieve forward motion, the thrust of the vessel must overcome the total resistance. The latter of the ship consists of air resistance and hydrodynamic resistance. The hydrodynamic resistance is divided into losses due to friction of the ship with the medium (water) and losses due to the generation of waves during the displacement of water.

According to the scientific publication "Numerical study on the hydrodynamic drag force of a container ship model" [4], the resistance encountered by the ship is given by the formula:

$$R = 1/2 \cdot \rho \cdot C \cdot A \cdot V^2 \tag{4.1}$$

Where:

- C – The resistance coefficient
- ρ – The density of the medium (water)
- A – Wetted Surface area – surface area that is in contact with the medium
- V – The vessel speed

The above equation explains that the resistance encountered by the ship from the water while sailing is exponentially proportional to its speed of movement, the construction characteristics of the vessel and the medium in which it moves.

4.1.2 Propulsion-Velocity relation

In the same paper the power required for movement at a constant speed V is defined as:

$$P = R \cdot V = 1/2 \cdot \rho \cdot C \cdot A \cdot V^2 \cdot V = 1/2 \cdot \rho \cdot C \cdot A \cdot V^3 = k \cdot V^3 \qquad (4.2)$$

Where k constant determined by the characteristics of the ship and the medium.

4.1.3 Effects of non-uniformities of the movement speed (spikes)

If the movement speed is uneven, i.e. periods of high and low movement speed alternate continuously, due to the exponential relationship between movement speed and propulsive power the total propulsive load is greater than moving at an average speed.

Example:

Suppose that a distance of 18 nautical miles must be covered in one hour. Two scenarios are studied:

In the 1$^{\text{st}}$, the ship is moving steadily at a speed of 18 knots.

In the 2$^{\text{nd}}$, the ship moves at a speed of 22 knots for the first half-hour and 14 knots for the second half-hour.

For the first scenario the required energy is 8.438 kWh In the second scenario the energy needed is $15,410 \cdot 0.5 + 3,970 \cdot 0.5 = 9,960$ kWh much more than the first When it moves at high speed the energy per velocity knot is very high and due to the exponentiality, when it then moves at low speed it cannot make up for the high speed power of the first half hour.

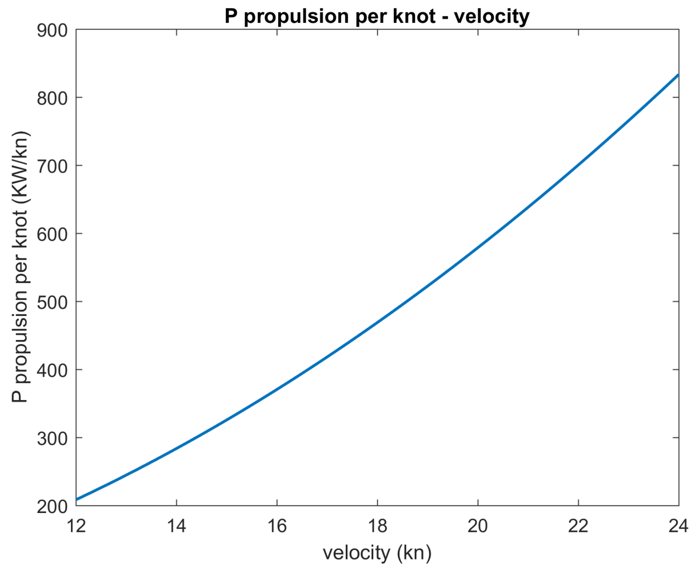


Figure 4.2: Propulsion power per knot/h - velocity graph

4.2 Ship with electric propulsion and fuel efficiency

In conventional ships, the revolutions per minute-rpm of the engines are determined by the nominal operating point of the engine and the propeller, so usually the required load is covered in a non-optimal way as the revolutions affect the fuel consumption. In the diagram below it can be seen that covering the same load but with different operating speeds leads to different fuel consumption.

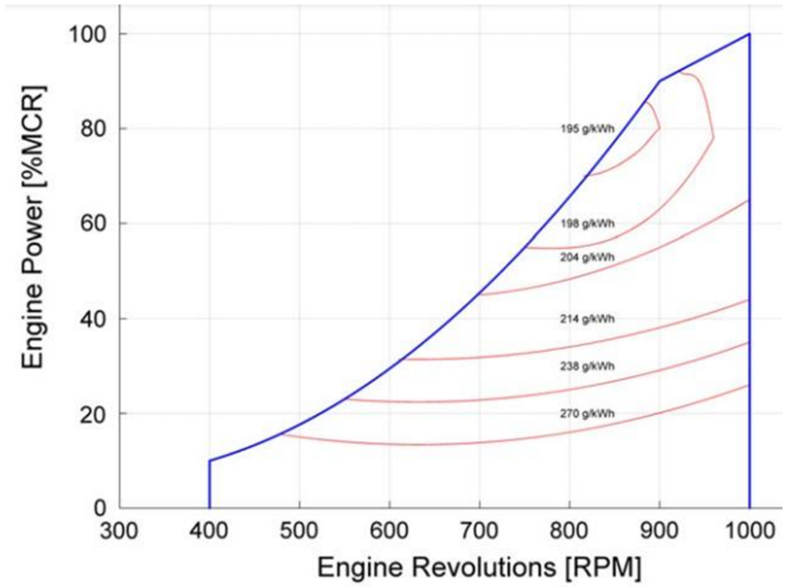


Figure 4.3: Engine SFOC for varying load and rpm

Higher loads cannot be covered with low rpm because engine revolutions are proportional to the power output.

Load Factor is defined as the percentage of the engine's nominal (maximum-MCR) operating power. Thus, if a machine with a nominal power of 10 MW produces 5 MW, it operates with a load factor of 50%.

In the electric propulsion ship, the operating revolutions of the engines are independent of the revolutions of the propeller as the generator, the appropriate power electronics and the electric motor intervene. This allows the engines to adjust their revs to meet the load in the most fuel-efficient way [9].

It is therefore possible, based on the diagram above, to determine the optimal operating point for each power value, i.e. the optimal operating speeds to cover the requested load with the minimum possible fuel consumption.

In the scientific publications [7, 8, 9], the change in specific fuel consumption curves between constant and variable speed operation is described as shown in Fig. 4.4:

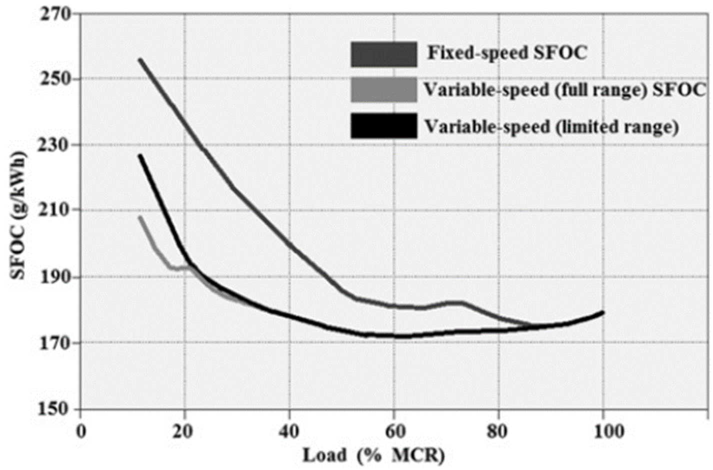


Figure 4.4: SFOC curve for fixed and variable speed operation

Changing the SFOC curve that has been used for the conventional ship, compared to the uncoupled from the propeller operation where rpm can be optimized for minimal fuel consumption and take values across the permitted operating range, the specific consumption curve for variable revolutions per minute compared to the original is shown below:

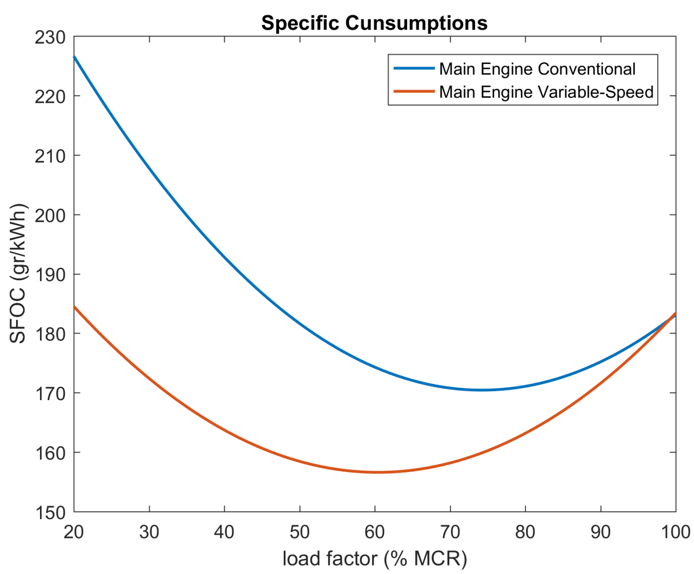


Figure 4.5: Conventional and Variable rpm SFOC

It is observed that initially the deviation is large and as the load increases the two curves converge. The fact that justifies this phenomenon is that smaller loads are optimally covered at lower operating speeds by the variable speed motor. As the load increases, so do the RPMs because they are in part proportional to the power output. Thus, the operating point converges to the nominal. Eventually they end up at the same operating point for rated load.

4.3 Exhaust Gasses Thermal Power Curve

To increase the efficiency of the system, the exhaust gases resulting from the combustion of Diesel are passed between pipes containing deionized water. As the water is heated, it turns into steam which acquires high temperature and pressure, i.e. it has enough energy stored in it (Transition 2-3). This energy will dissipate into a turbine which is set in motion by Transition (3-4). The energy deposited depends on the pressure and temperature of the steam before and after it "passes" through the turbine. The greater the difference in these two stages, the greater the mechanical energy of the turbine.

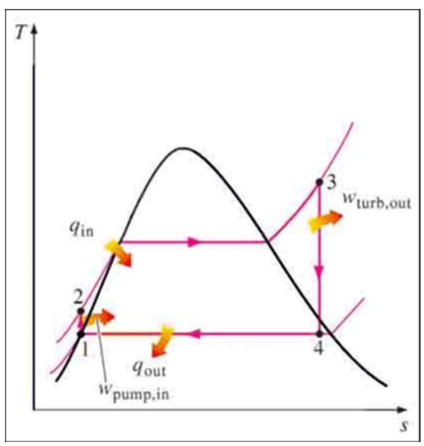


Figure 4.6: Ideal Rankine Cycle

It is important to study the engines in terms of the exhaust gases produced so that the benefit obtained depending on the point of operation can be determined.

The chemical equation of diesel combustion is as follows:

$$C_{13}H_{28} + 20\ O_2 \rightarrow 13\ CO_2 + 14\ H_2O$$

ΔH <0 (Exothermic)
Exothermic: the chemical reaction in which energy is released in the form of light and/or heat.

The thermal power of exhaust gases depends on two factors: their temperature and their quantity. This thermal power is calculated by the simple formula:

$$Q_g = m_g \cdot T_g \cdot c_{pg} \tag{4.3}$$

Where $c_{pg} = 1.06\ kJ/(kg \cdot\ ^{\circ}C)$ constant
T_g Exhaust gas temperature ($^{\circ}C$)
m_g the exhaust gas mass flow (kg/s)

To calculate the thermal power attributed to water-steam, the above formula is converted into:

$$Q_{w-s} = m_g \cdot (T_{g\ in} - T_{g\ out}) \cdot c_{pg} \tag{4.4}$$

Where $T_{g\ in}$ the inlet temperature of the exhaust gas to the cogeneration system and Tg out their temperature of exit from it.
The exit temperature is set to the value $T_{g\ out}$= 130 °C based on real data.

The mass flow of the exhaust gases is given by the equation:

$$m_g = (a_1 \cdot MCR_{ME}^3 + b_1 \cdot MCR_{ME}^2 + c_1 \cdot MCR + d_1) \cdot (e_1 \cdot fl_{ME}^3 + f_1 \cdot fl_{ME}^2 + g_1 \cdot fl_{ME} + h_1) \tag{4.5}$$

Where MCR_{ME} is the main engines' nominal power - Maximum Continuous Rating (constant) and fl_{ME} the engines' load factor and a_1,b_1,c_1,d_1,e_1,f_1,g_1,h_1 are coefficients based on the engines' characteristics.

The graph of the above equation is illustrated below:

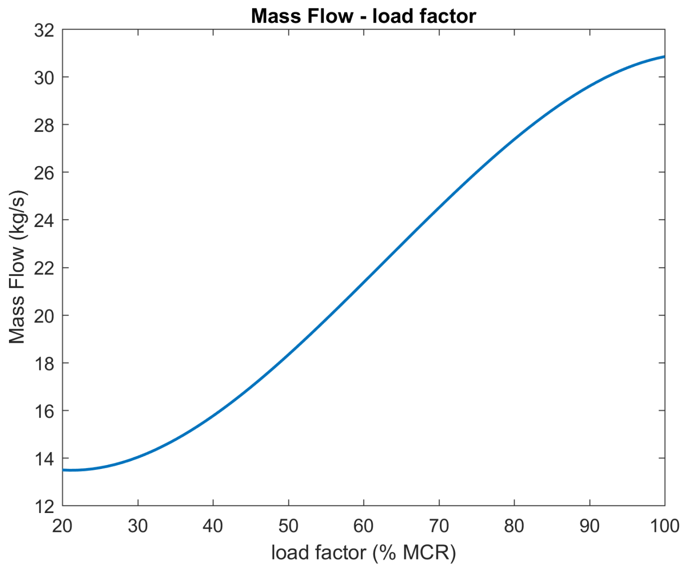


Figure 4.7: Exhaust gasses mass flow - load factor graph

The curve follows this path because higher loads require a greater volume of air-fuel mixture to burn in the engine. Therefore, according to the chemical combustion equation, a greater volume of reactants (diesel and air) results in greater energy and volume of products, leading to an increased exhaust mass flow.

The temperature of the exhaust gases resulting from the combustion ($T_{g\ in}$) is expressed by the equation:

$$T_g = (a_2 + b_2 \cdot MCR_{ME} + c_2/MCR_{ME}^2) \cdot (d_2 \cdot fl_{ME}^3 + e_2 \cdot fl_{ME}^2 + f_2 \cdot fl_{ME} + g_2) \tag{4.6}$$

The temperature is related to the engine's load factor, as shown below:

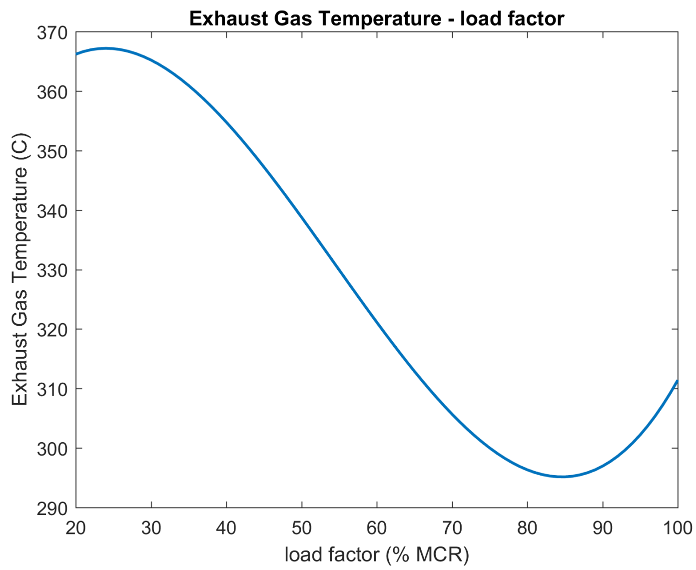


Figure 4.8: Exhaust gasses mass flow - load factor graph

The graph follows this path for two reasons:

Improved combustion efficiency: Higher loads can lead to better combustion efficiency. When a motor is operating at a higher load factor, it tends to operate closer to its optimum operating conditions. This optimized combustion process results in more complete and efficient combustion of the fuel, reducing the formation of unburned fuel or partially burned products that can contribute to a higher exhaust gas temperature.

Increased air/fuel mixture: When the load on the engine increases, it requires more power to meet it. To meet this demand, the engine injects more fuel into the combustion chamber, resulting in a richer air/fuel mixture. A richer mixture contains more fuel and less air, which can lower the temperature required for combustion and therefore lower the exhaust gas temperature.

The thermal power transmitted in the pipes containing water-steam is the reduction in the power of the combustion products from their entry into the cogeneration system to their exit from it. The thermal power transferred to the medium is given by the formula:

$$Q_{w-s} = m_g \cdot (T_{g\ in} - T_{g\ out}) \cdot c_{pg} \tag{4.7}$$

$Q_{w\text{-}s}$ the thermal power attributed to water-steam, $T_{g\ in}$ the exhaust gases temperature when entering and $T_{g\ out}$=130°C temperature when exiting the HRSG. c_{pg}=1.06 kJ/(kg·°C) constant.

The two curves presented previously are essentially multiplied and create the graph 4.9

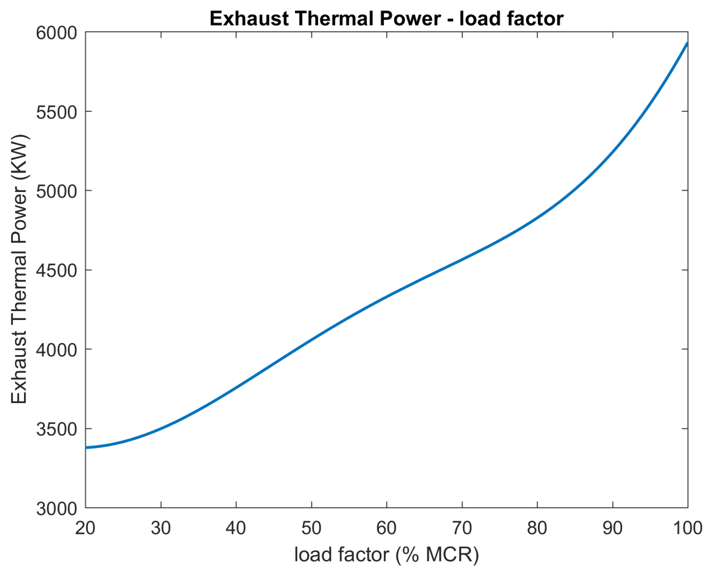


Figure 4.9: Exhaust gasses thermal power - load factor graph

Because the increase in mass flow is greater than the decrease in flue gasses temperature along the previous curves, the thermal power of the flue gases is a strictly increasing equation.

4.4 HRSG Operating Point

During the optimization, the pressure and temperature of the steam before expansion in the turbine were defined as input variables. It was observed that the optimizer arrived at the same values regardless of the scenario being studied. There is a reason, thus, for studying the behavior of those variables.

An upper pressure limit of 15 bar (due to the construction materials of the superheater) and an upper temperature limit of the temperature of the exhaust gases were set, as these heat the steam and it would be unreasonable to assume that the temperature of the steam can exceed the temperature of the exhaust gases.

When studying the results of the code, the pressure was set by the optimizer to the maximum possible (15 bar) and similarly the temperature was given the maximum possible value (temperature equal to that of the exhaust gases).These values gave the maximum power to the turbine and the reason is explained by the graphs below.
The study is based on two factors: pressure and temperature.

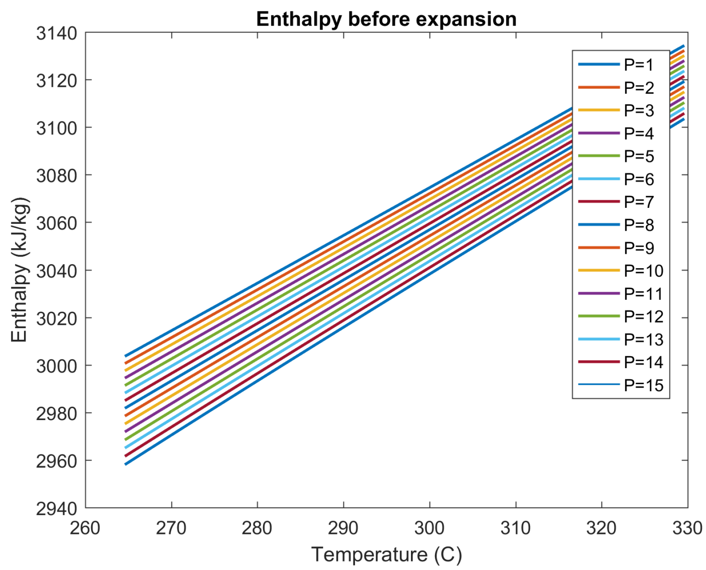


Figure 4.10: Enthalpy before expansion - Temperature graph for varying pressure

Enthalpy is proportional to temperature because steam molecules move more vigorously as they absorb heat, i.e. their internal energy increases.

The lower the pressure-the higher the enthalpy (stored energy of the steam) at the point before expansion for a given temperature.

The energy deposited in the turbine as mentioned above is equal to the change in energy (enthalpy) of the steam.

The steam is assumed to have a pressure of 0.1 bar after expansion (from actual operating data of cogeneration systems on ships)

After expansion there is a mixture of water and steam. The quality of the mixture determines the enthalpy after expansion. Steam has a distinctly higher enthalpy than water, so the more steam that remains after expansion in the turbine, the more energy is left unused by the turbine. The steam quality graph after expansion versus pre-expansion pressure and temperature:

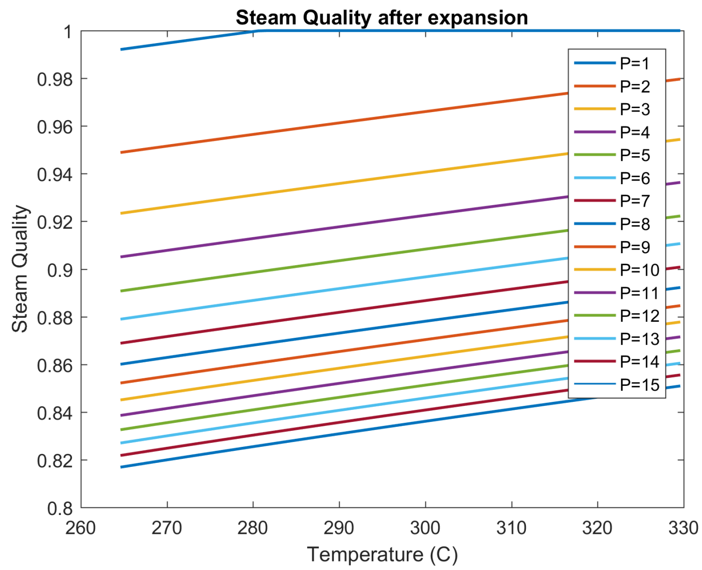


Figure 4.11: Steam Quality after expansion - Temperature for varying pressure before expansion

The higher pressure the steam has before expansion, it ends up in a state of lower steam quality after expansion (where pressure P= 0.1 bar). Lower steam quality means less energy after expansion.

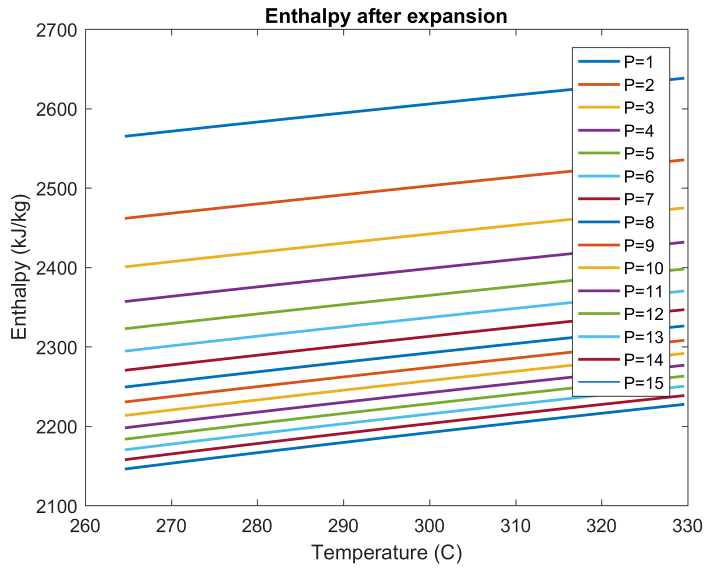


Figure 4.12: Enthalpy after expansion - Temperature for varying pressure

The greater the energy difference before and after expansion the more energy is transferred to the turbine.

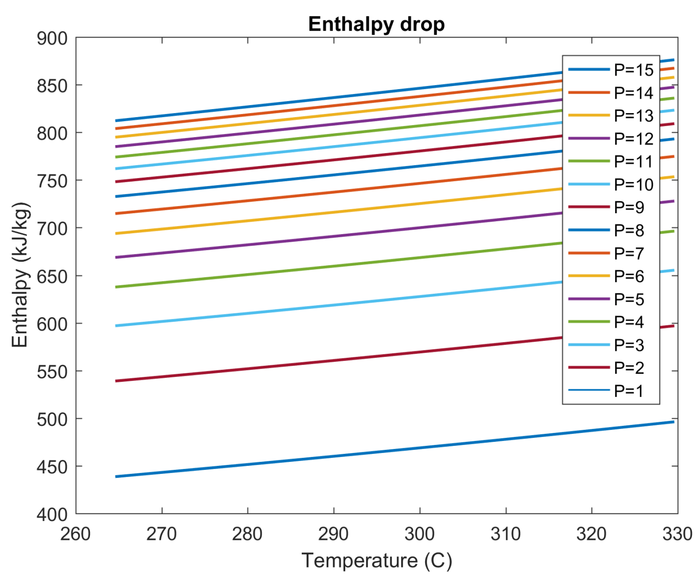


Figure 4.13: Enthalpy drop - Temperature for varying pressure

For pressure P= 15 bar the enthalpy change is the maximum at all temperature values. Also the enthalpy change is proportional to the temperature. For this reason the optimizer prefers the maximum value of pressure and temperature.

Now these two variables are not determined by the algorithm in order to lighten the optimization burden. Instead, the pressure takes the maximum possible value as input and the temperature is set to a value that depends on the exhaust gas temperature with a coefficient that represents the thermal losses on the surfaces of the cogeneration system ($T_{s\,3} = 90\%\ T_{g\,in}$).

4.5 Slow Steaming

The graph 4.2 explains why the slow steaming [15] method is preferred when the ship is travelling. As mentioned above, the cube law implies that a ship moving at half the speed needs 1/8 of the energy for propulsion. It is therefore economically beneficial for ships to move at low speeds in order to save propulsion energy and,therefore, money.on fuel.

When a ship takes advantage of slow steaming, it reduces its movement speed to the range of 12 to 19 knots. This can sometimes mean almost half the speed of the normal 20 to 24 knots. The reduction in speed results in a reduction in the required power, therefore in consumption and ultimately in the cost spent on fuel. As mentioned, there are mainly economic, environmental and performance-related benefits. For shipping companies to remain profitable when fuel prices rise and when recessions occur, slow steaming becomes more of a necessity than a choice. However, this decision is also taken by companies to become environmentally responsible. Environmental benefits are associated with using less fuel. For example, when a ship reduces its speed by 10%, engine power is reduced by almost 30%. Less power required means less fuel. When less fuel is used, fewer emissions are produced and released into the environment. The end result is less pollution and contribution to the global issue of climate change. With increasing pressure on all industries to reduce carbon dioxide emissions, the implementation of slow steaming is practically becoming a requirement. Fortunately, it provides an efficient way for shipping companies to save more money by using less energy. There are also performance benefits as a ship will become more reliable and efficient when practising slow steaming regularly.

4.6 System Constraints

The following constraints exist based on system design:

Conventional:

- The main engines and steam turbine must cover the propulsive power.
- The steam turbine generator and diesel generators must meet the electrical needs. (Diesel generators supplement the required electrical power)
- The Heat Recovery Steam Generator and the boilers cover the thermal needs. (Boilers supplement the required thermal power)

Electric:

- The main engines-generators, diesel generator, turbine-generator must cover the total electrical load. (Electric propulsion and auxiliary services. PV and battery power are considered as loads)
- The Heat Recovery Steam Generator and the boilers cover the thermal needs. (Boilers supplement the required thermal power)

The following operating constraints exist:

- The temperature of the steam before expansion inside the HRSG cannot exceed the temperature of the exhaust gases of the main engine because it is heated by the latter.
- The entropy of the steam before expansion cannot be greater than the value 8.1488 (kJ/(kg °C)) which is the entropy of the mixture after expansion for a pressure of 0.1 bar and steam quality x=1. An isentropic e is considered.
- The steam pressure cannot exceed 15 bar,due to the construction materials of the superheater.
- The energy that is stored at any moment in the battery should be between the E_{max} and E_{min} values, where E_{min} = 10% of E_{max}.
- The equation of fuel consumption of the diesel generator is valid for a load factor between the values 20%-100%

- The main engines are oversized for reasons of less mechanical stress during their operation and reliability in adverse weather conditions. Thus, under normal conditions the load factor does not exceed 67%, while the equations are not valid for a load factor lower than 20%.

4.7 Ship Power Systems Parameters

Electric Power Plants Parameters

	ME 1	ME 2	DG
Nominal Power (MW)	15	15	5
Permissible operating limits (% Nom. Power)	20% - 67%	20% - 67%	20% - 100%
Start-up/shut-down costs	160 / 160 (€)	160 / 160 (€)	55 / 55 (€)

Energy Storage Parameters

Energy Capacity (MWh)	10	SOC range(%)	10 - 100
Max. charge/Discharge power (MW)	3/3	Charge/Discharge efficiency (%)	95/95

Nominal Speed (kn)	24	Simulation Step Dt (h)	0.5
c_{pg}	1.06 kJ/(kg ·°C)		

start-up/shut down cost equal to 20% of power plants' nominal hourly fuel consumption cost

Chapter 5

Description of the System Components

5.1 Storage Units

Over the past ten years, research and development (R&D) efforts in battery technology have significantly affected both their cost and performance. R&D has led to significant reductions in battery manufacturing costs, making them more affordable for a variety of applications, including electric vehicles (EVs) and grid energy storage. In addition, advances in energy density have enabled greater driving range for EVs, more efficient portable electronic devices, and increased energy storage capacity for grid applications. Also, battery life has been extended in various applications, reducing replacement frequency and overall costs. Fast charging technologies developed through research have reduced charging times, improving the ease of use and practicality of large storage units. These developments, which are due to research and development, have contributed to the widespread adoption of batteries and their dynamic potential in many fields.

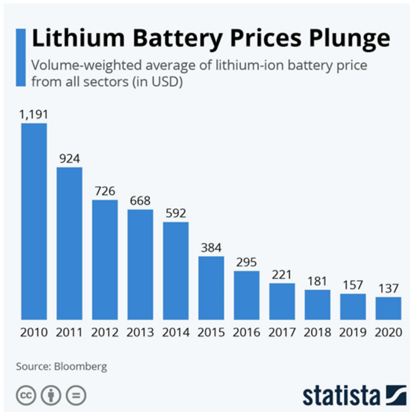


Figure 5.1: Li-ion batteries price over time

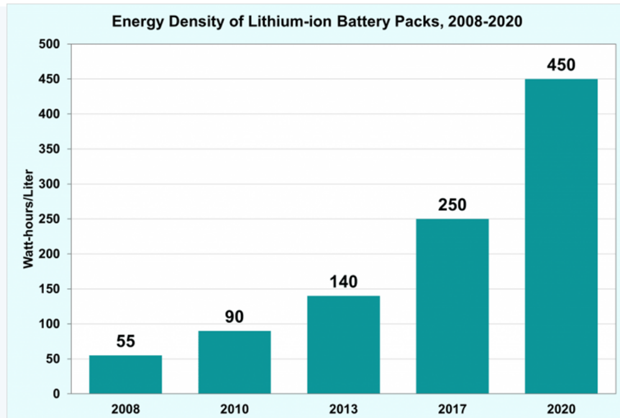


Figure 5.2: Li -ion batteries energy density over time

Energy density refers to the amount of energy that can be stored per volume unit of batteries. Higher energy density results in less volume and weight of the storage unit.

5.2 Storage units using Lithium Batteries

5.2.1 Principle of Operation

Lithium-ion batteries work by moving lithium ions between the positive and negative electrodes during discharge and charge cycles. During discharge, ions flow from the positive electrode (cathode) to the negative electrode (anode), creating a flow of electrons that provides energy to power a device. During charging, the process is reversed and lithium ions flow back to the positive electrode. This movement of ions is facilitated by an electrolyte, which allows ion transport, and the use of a spacer that prevents direct electrical contact between the electrodes.

5.2.2 Advantages of lithium-ion batteries

Lithium-ion batteries have the highest charge density of any comparable system. This means they can provide a lot of energy without being too heavy. This happens for two reasons. First, lithium is the most electropositive element.

Electropositivity is a measure of how easily an element can give up electrons to produce positive ions. In other words, it is a measure of how easily an element can produce energy. Lithium loses electrons very easily. This means that a lot of energy can easily be produced. It is also the lightest of all metals making lithium batteries the most suitable for applications in the transportation industry, placing as little burden on the ship as possible.

5.2.3 Battery Facilities on Land

The largest battery facility in the US is Vistra Moss Landing, in Monterey County, California, which can sustain 400 megawatts (MW) of discharge power for four hours. In the energy sector, this means it has a capacity of 1,600 megawatt hours (MWh) or 1.6 Gigawatt hours (GWh)

5.2.4 The utility of storage during ship operation

The storage unit allows the system's productive elements to operate closer to their optimum operating point as they can store or offset the difference between the power produced and the requested power. Batteries also offer the advantage of responding instantly to rapid load changes, while diesel engines will need to rev accordingly. This adjustment of the revolutions takes some time due to the mechanical inertia of the rotor. The system does not make use of cold ironing, i.e. charging the battery in ports. The storage unit is charged from the energy system's power plants.

5.2.5 Difficulties in the adoption of large-scale electric ships

Drawing from the negatives of the all-electric ships it is clear that despite the great progress the technology is not yet mature enough to support the use of batteries in commercial or cruise ships. The problem initially lies in battery technology. The storage system should support the operation of the ship for consecutive days or even weeks without the possibility of charging. In this case, a storage unit of the order of gigawatt-hours (GWh) is required. According to the above graphs of the development of energy density and energy requirements, it is estimated that 1,000 cubic meters of batteries are needed for storage capacity of 500 MWh in order to sail autonomously for 40-50 hours. The weight, moreover, cannot be neglected as the volume of

1,000,000 liters of batteries with a weight of 2.5 kg/l burdens the ship with 2,500 tons, the same order of magnitude as weight of the rest of the ship. The center of gravity of the ship is affected making it more unstable and much more power is required to move.

The cost of storage remains extremely high. In the period from 2010 to 2020, due to increased research and development on batteries, the cost decreased tenfold. In the last 3 years there has been a slight increase due to the increased inflation and the instabilities brought by the corona virus period. Even with the progress that has been made, the investment cost remains quite high. A 0.5 GWh (= 500,000 kWh) installation costs 500,000 $\cdot$ 140 = \$70 million dollars.

5.3 Principle of Operation of Photovoltaic panels

Photovoltaics, often simply referred to as solar cells or solar panels, harness the power of sunlight to produce electricity. These remarkable devices have revolutionized the way clean and sustainable energy is produced. The semiconductor material inside the cell absorbs the sun's photons, leading to the release of electrons from their normal positions within the material. These freed electrons are free to carry electricity. To produce an electric current, the electrons must flow in the same direction. This is achieved by using two types of silicon. The silicon layer exposed to the sun is doped with phosphorus atoms, which has one more electron than silicon in its outer shell (5), while the side not in contact with the sun is doped with boron atoms, which has one less electron (3).

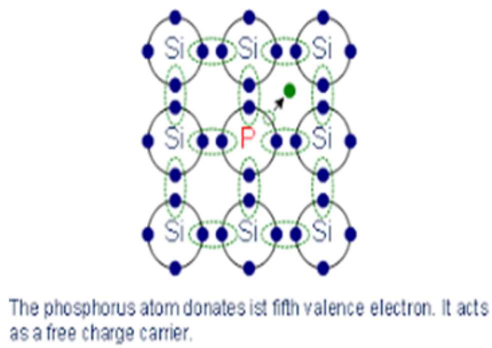


Figure 5.3: n-junction chemical bonds

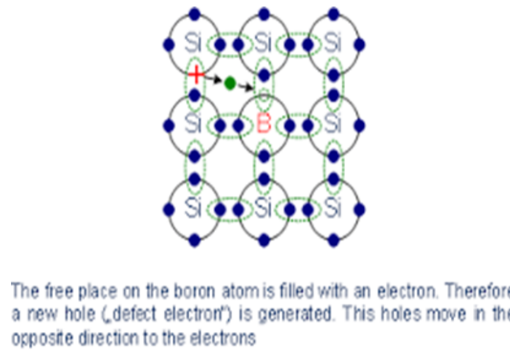


Figure 5.4: p-junction chemical bonds

The resulting compound of adulterated semiconductors works like a battery: the layer with a surplus of electrons becomes the negative pole (n) and the side with a deficit of electrons becomes the positive pole (p). An electric field is created at the junction between the two layers. When electrons are excited by photons, they are drawn by the electric field to the n-side, while holes are drawn to the p-side. Electrons and holes are directed to electrical contacts applied to both sides, before flowing to the external circuit in the form of electricity. Thus direct current is produced. An anti-reflective coating is added to the top of the cell to minimize photon loss due to surface reflection.

The electrical power produced by the system, or peak power, is a percentage of the incoming solar energy. The maximum theoretical efficiency of a photovoltaic cell is about 33%. This is referred to as the Shockley-Queisser limit.

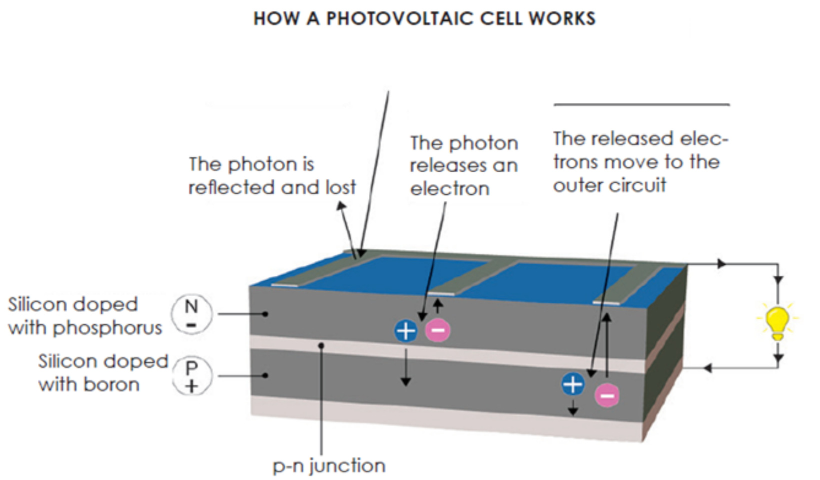


Figure 5.5: Photovoltaic cell cross-section and operation

5.3.1 Photovoltaic system used

In the previous study while discussing the electric ship (Section 2.4), an area of 2000 m^2 was considered fitting photovoltaic panels of total power 450 kW. To maximize output,the panels should face the sun beams vertically. In order to achieve that,for Greece which has latitude of 35° north, the panels in fields are placed in an angle of 35° facing towards the south. But in a ship which is always changing direction, placing the panels in a angle would not be effective because their orientation is constantly changing along with the sailing direction. This is the reason they are placed parallel to the deck (0°) when no sun tracking is used, not achieving maximum output in places with latitude different than 0, but always producing power regardless of the ship's course.

Since the photovoltaics power output depends on the weather and not on the system, they are considered as negative loads, meaning that their production is subtracted from the total energy load and the system covers the result.

The solar irradiance graph [11] is illustrated below:

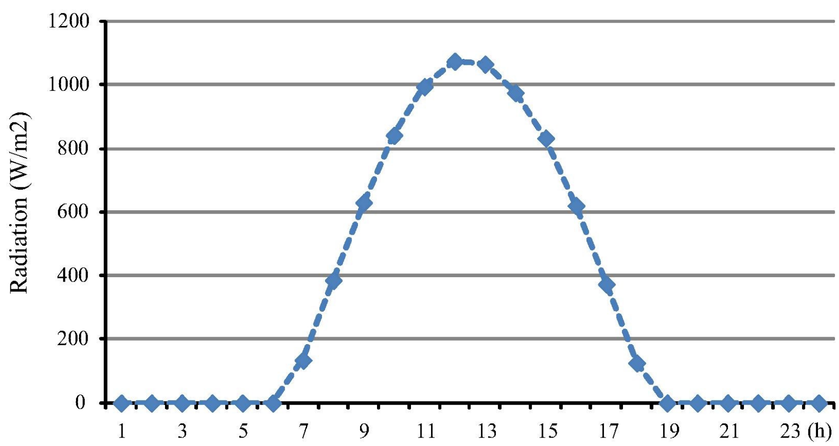


Figure 5.6: Solar Radiation during the day

Based on the graph 5.6 the energy yield of the photovoltaic unit will be calculated. A conversion efficiency of 17% is assumed.

5.4 Generator Type Selected

For this specific application, permanent magnet generators have been chosen, similarly to the scientific publication "Coordinated Control of the Hybrid Electric Ship Power-Based Batteries/Supercapacitors/Variable Speed Diesel Generator (Permanent Magnet Synchronous Generators -PMSG)" [2], which are suitable for variable speed operation due to several key advantages [3]:

1. High efficiency: PMSGs tend to have higher efficiency over a wide range of speeds and loads compared to other types of generators. This means they can efficiently convert mechanical energy into electrical energy even at different speeds.

2. Enhanced control: PMSGs offer precise and reliable speed control, which makes them ideal for applications where variable speed is required, such as wind turbines and hybrid electric systems. The speed can be adjusted to optimize performance and adapt to varying load conditions.

3. Reduced size and weight: PMSG generators often have a more compact and lightweight design compared to other types of generators, making them suitable for mobile or space-constrained applications.

4. Minimal maintenance: As there are no rotor windings, slip rings or brushes in PMSGs, they have a simpler construction with fewer wear-prone parts, resulting in lower maintenance requirements and greater reliability.

5.5 Advantages of a ship with electric propulsion

- The ship with electric propulsion apart from the advantages analyzed above offers greater reliability precisely because the electrical power required for propulsion and electrical needs can be produced from many and different sources, so the impartial operation of the ship is ensured even in the event of failure of some of them.

- Because the main engines are not constantly operating at their rated point, their mechanical stress is less, leading to less operating noise and a longer service life.

- As nuisance and pollution margins become more and more stringent, especially when navigating near residential areas (ports), hybrid ships can be put into All Electric Ship mode where electrical power is provided exclusively by RES and the battery for a short period of time so that they are able to approach all ports regardless of the severity of environmental restrictions.

5.6 System Equations

Propulsion Power – Velocity equation:

$$P(t) = 0.00144676 \cdot v^3(t) \tag{5.1}$$

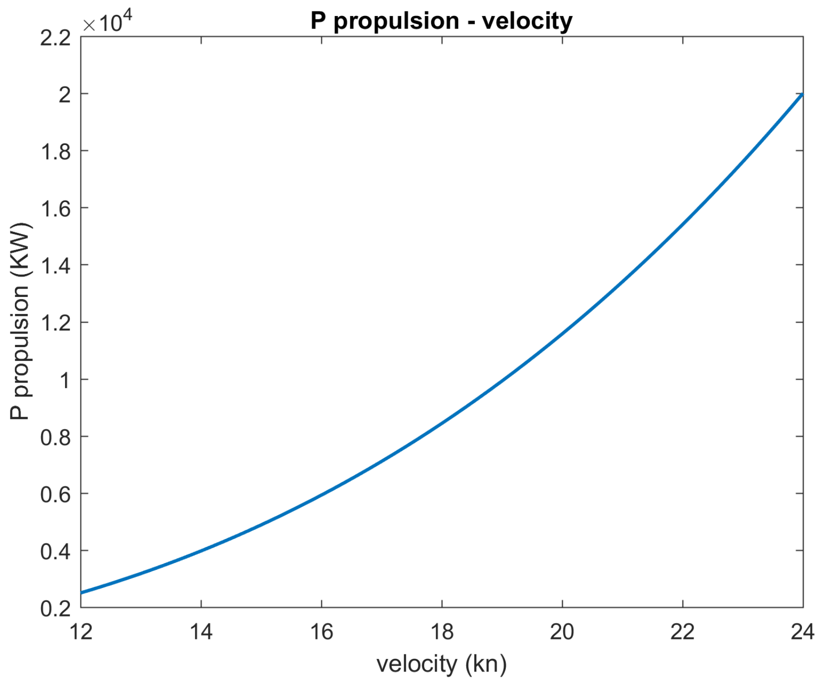


Figure 5.7: Propulsion Power-velocity graph

Main Engines Load:

Conventional

$$P_{ME\,conv}(t) = P_{PROP\,total}(t) \cdot \lambda_{ME\,conv}(t), 0 < \lambda_{ME\,conv}(t) < 1 \tag{5.2}$$

$$P_{ME1\,conv}(t) = P_{ME\,conv}(t) \cdot \mathrm{Perc}_{ME1\,conv}(t), 0 < \mathrm{Perc}_{ME1\,conv}(t) < 1 \tag{5.3}$$

$$P_{ME2\,conv}(t) = P_{ME\,conv}(t) \cdot (1 - \mathrm{Perc}_{ME1\,conv}(t)), 0 < \mathrm{Perc}_{ME1\,conv}(t) < 1 \tag{5.4}$$

Electric Propulsion

$$P_{ME\ el}(t) = P_{EL\ total}(t) \cdot \lambda_{ME\ el}(t), 0 < \lambda_{ME\ el}(t) < 1 \tag{5.5}$$

$$P_{ME1\ el}(t) = P_{ME\ el}(t) \cdot \mathrm{Perc}_{ME1\ el}(t), 0 < \mathrm{Perc}_{ME1\ el}(t) < 1 \tag{5.6}$$

$$P_{ME2\ el}(t) = P_{ME\ el}(t) \cdot (1 - \mathrm{Perc}_{ME1\ el}(t)), 0 < \mathrm{Perc}_{ME1\ el}(t) < 1 \tag{5.7}$$

Power Plants Load Factor:

$$\mathrm{fl}_k(t) = \frac{P_k(t)}{\mathrm{MCR}_k} \cdot 100, k = \mathrm{ME1,\ ME2,\ DG} \tag{5.8}$$

Power Plants Specific Fuel Oil Consumption (gr/kWh):

$$SFOC_{\mathrm{ME\ 1,conv}}(t) = 0.01910 \cdot fl_{ME\ 1}(t)^2 - 2.8357 \cdot fl_{ME\ 1}(t) + 275.68 \tag{5.9}$$

$$SFOC_{\mathrm{ME\ 2,conv}}(t) = 0.01967 \cdot fl_{ME\ 2}(t)^2 - 2.9208 \cdot fl_{ME\ 2}(t) + 283.95 \tag{5.10}$$

$$SFOC_{\mathrm{ME\ 1,el}}(t) = 0.01710 \cdot fl_{\mathrm{ME\ 1,el}}(t)^2 - 2.066 \cdot fl_{\mathrm{ME\ 1,el}}(t) + 217.39 \tag{5.11}$$

$$SFOC_{\mathrm{ME\ 2,el}}(t) = 0.01761 \cdot fl_{\mathrm{ME\ 2,el}}(t)^2 - 2.128 \cdot fl_{\mathrm{ME\ 2,el}}(t) + 223.91 \tag{5.12}$$

$$\begin{aligned} SFOC_{DG}(t) = {} & a + b\ln(MCR_{DG}) + c\ln(fl_{DG}(t)) + d\ln^2(MCR_{DG}) \\ & + e\ln^2(fl_{DG}(t)) + f\ln(MCR_{DG})\ln(fl_{DG}(t)) \\ & + g\ln^3(MCR_{DG}) + h\ln^3(fl_{DG}(t)) \\ & + i\ln(MCR_{DG})\ln^2(fl_{DG}(t)) \\ & + j\ln^2(MCR_{DG})\ln(fl_{DG}(t)), \quad a,b,c,d,e,f,g,h,i,j \text{ constants} \end{aligned} \tag{5.13}$$

Battery power level:

$$E(t_i) = P(t_i) \cdot Dt + P(t_{i-1}) \cdot Dt + \cdots + P(t_1) \cdot Dt + E0, \tag{5.14}$$

$-3(MW) < P(t_i) < 3(MW),\ i = 1, 2, 3, 4, 5 \ldots,\ t_1 = 0.5, t_2 = 1, t_3 = 1.5 \ldots$

Where Dt the simulation time step, E0 the initial state of charge of the battery.

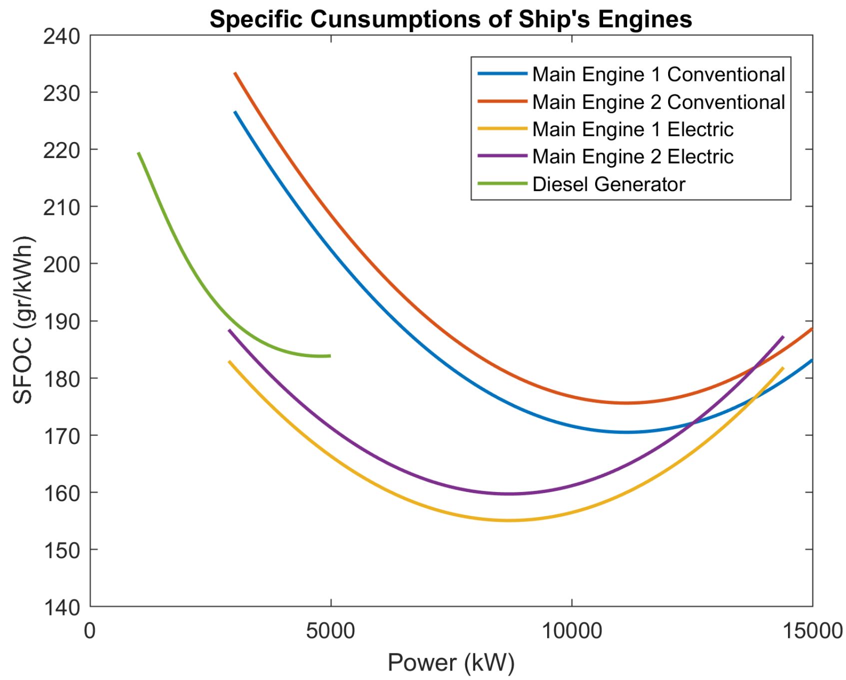


Figure 5.8: SFOC of All Power Plants

The Main Engines have different power output ranges in Conventional and Hybrid energy systems because in the latter, electric power is produced and there are losses in the generators.

The second Main Engine is 3% more expensive than the first in each energy system.

Chapter 6

Method of Resolution

The **optimization variable is the total travel cost** which consists of the total cost for fuel and the power plants opening/closing costs. The system requirements are divided into three categories: propulsion, electricity, heating. To better approximate real conditions where requirements change over time, the system modeling is divided into half hours (time-slots). The optimizer initially had seven (7) input variables for each time-slot: The speed of the ship (v(t)), the percentage of coverage of the propulsion needs (conventional) or the total electrical power (electric) from the main engines ($\lambda_{ME}(t)$), the percentage of coverage of the heating needs by the HRSG ($\lambda_{Q}(t)$), the steam pressure ($P_3(t)$) and temperature ($T_3(t)$) before expansion, and the percentage of power distribution to be covered by the main engines in 1^{st} ($Perc_{ME1}(t)$) and the 2^{nd} ($1-Perc_{ME1}(t)$) and the charging/discharging power of the battery ($P_{bat}(t)$) only in the electric-propulsion ship).

As discussed earlier, the algorithm preferred the maximum vapor pressure and temperature values. Thus, the pressure is always set to the maximum value (15 bar), while the temperature of the steam before expansion is set as 90% of the flue gas temperature to simulate also the heat losses on the pipe surfaces. So variables P_3 and T_3 are predefined.

The optimizer preferred to first cover the thermal power needs from the cogeneration steam and, if there was excess, to contribute to cover electricity or propulsion. This choice was made because when steam is used to rotate the turbine, its thermal power cannot be utilized to the maximum, as it maintains a relatively high temperature after expanding. Whereas, when used for heating needs the temperature of the heated spaces or water is much lower than that of the cogeneration water, so its usefulness is greater in this application. So variable λ_Q is always 100%

The remaining input variables are:
Conventional System Input Variables

- Velocity (v(t)) - the ship's speed in knots.
- The percentage of the propulsion power covered by the main engines ($\lambda_{ME\ conv}(t)$). It is not always 100% because mechanical power can be produced by the Combined Cycle Plant.
- The percentage of power distribution to be covered by the main engines in the 1^{st} ($Perc_{ME1\ conv}(t)$) and the 2^{nd} ($1-Perc_{ME1\ conv}(t)$) (only when both operate).
- The power plants layout (ME 1,ME 2 - which ones are open and which ones are closed).

Hybrid System Input Variables

- Velocity (v(t)) - the ship's speed in knots.
- The battery charging/discharging power ($P_{bat}(t)$).
- The percentage of the total electric power covered by the main engines ($\lambda_{ME\ el}(t)$). Total electric power is the sum of the power electric motors need for propulsion, the power battery needs (or provides - in this case the battery power is subtracted from the needs) and power for auxiliary operations, minus the photovoltaic power.
- The percentage of power distribution to be covered by the main engines in the 1^{st} ($Perc_{ME1\ el}(t)$) and the 2^{nd} ($1-Perc_{ME1\ el}(t)$) (only when both operate).
- The power plants layout (ME 1,ME 2,DG - which ones are open and which ones are closed).

The optimization takes place in 2 stages: Firstly the optimizer is setting the values of velocity and, in the electric propulsion ship, the battery power. Based on velocity the propulsion power is calculated. The power needs are known and must be distributed between the system's power plants (via variables $\lambda_{ME}(t)$, $Perc_{ME1}(t)$) . The variables $\lambda_{ME}(t)$, $Perc_{ME1}(t)$ and power plants' layout are determined in a second stage based on a sampled table of combinations of propulsion power, electricity and thermal power described below.

6.1 Creating a table with exhaustive method

In order to create a table of samples, the value range of the requirements (propulsion power, electrical power, thermal requirements) was studied and an appropriate investigation step was taken so that the execution time of the program does not exceed the interval of a few hours and the density of the samples is sufficient so that all possible power values are studied. Exhaustive scenarios of combinations of propulsion, electrical and thermal requirements were considered and for each engine layout and the optimal values of input variables were determined (The percentage of coverage of the propulsion needs (conventional) or percentage of coverage of the total electrical needs (electric) by the main engines and the distribution of the power to be covered by the main engines in the 1^{st} and the 2^{nd}). Thus, there is a grid with samples in the space.

Because in the **conventional** ship the requirements are of three kinds, (propulsion (mechanical), electrical, and thermal),a three-dimensional grid should therefore be created to represent the possible combinations of the three power types. This 3D matrix would make linear combination quite complex and running the exhaustive program to generate the mesh very time consuming. An approach was taken to simplify the way the system is explored. It is assumed that the thermal requirements are a constant percentage of the electrical requirements.

$$Thermal\ Power = Electric\ Power \cdot constant\ coefficient\ (coefficient < 1)$$

In this study it was assumed that the coefficient has a value of 0.24 or 24%

Thus, knowing the electrical power, the thermal power is also calculated with a one-to-one correspondence. So thermal power does not add a new dimension to the grid (since for every electrical power value there is a thermal value). The grid is now two-dimensional: One dimension is propulsion power and the other is electrical power.

The propulsion power is covered by the main engines and the mechanical power of the cogeneration, the electrical power is covered by the diesel generator and the electrical power of the CCP and the thermal needs are covered by the boiler and the thermal power of the cogeneration.

For each combination of propulsion and electricity, three scenarios are studied shown in the table below:

	ME 1	ME 2
1st	1	0
2nd	0	1
3rd	1	1

1 open / 0 closed

The arguments change in small steps. These are the rate of coverage of propulsion needs ($\lambda_{ME,conv}(t)$) by the main engines and the share of the power to be covered by the main engines in 1st ($Perc_{ME1,conv}(t)$) and the 2nd (1- $Perc_{ME1,conv}(t)$) (for scenarios where both operate). Finally, the layout of the power plants and the values of the variables that result in the lowest cost are stored.

In the **ship with electric propulsion**, the propulsion power is translated into the electrical power needed by the electric motor divided by the efficiency rating of the engine. It is then added to the electrical requirements of the rest of the ship's systems. The total electrical power is covered by the main engines, the diesel generator, the electrical power of the CCP and the thermal power is covered by the boiler and the thermal power of the cogeneration.

For each combination of electricity and heating, seven scenarios are studied shown in the table below:

	ME 1	ME 2	DG
1st	1	0	0
2nd	0	1	0
3rd	0	0	1
4th	1	0	1
5th	0	1	1
6th	1	1	0
7th	1	1	1

1 open / 0 closed

The arguments are the coverage percentage of the total electrical needs ($\lambda_{ME,el}(t)$) by the main engines and the share of the power to be covered by the main engines in 1st ($Perc_{ME1,el}(t)$) and the 2nd (1-$Perc_{ME1,el}(t)$) (for scenarios where both operate). Finally, the layout of the power plants and the values of the arguments that result in the lowest cost are stored.

The combination of propulsion and electric power for the conventional and electric and thermal power samples for the electric ship creates a grid of two-dimensional space.

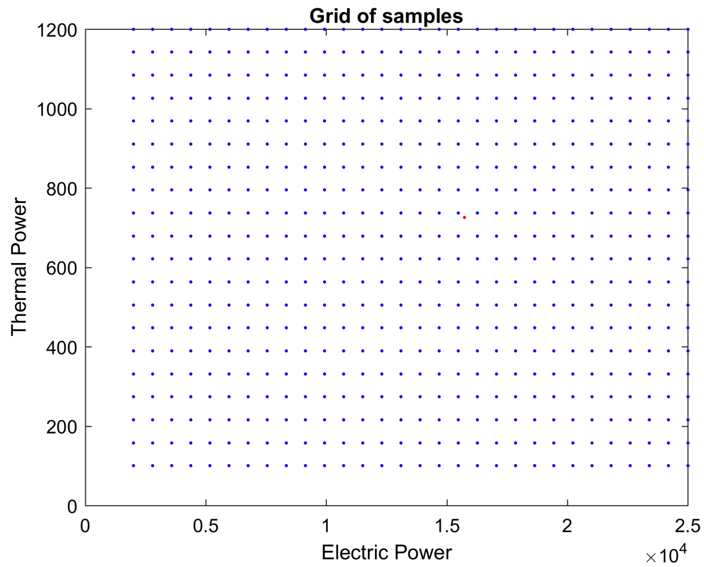


Figure 6.1: Grid of samples for electric propulsion

During optimization, intermediate values are obtained in the samples. These values are approximated with the linear interpolation technique. The closest samples to the resulting values are determined and through a linear interpolation according to the distance from each sample, the values of the input variables are calculated.

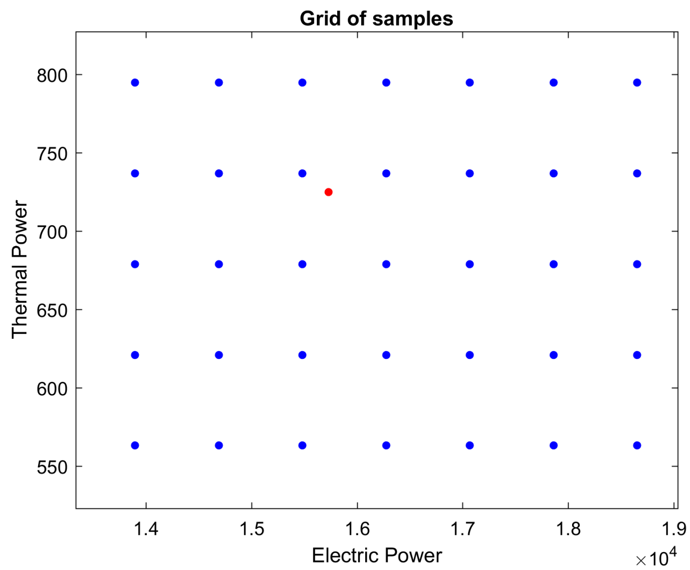


Figure 6.2: Grid of samples (zoomed in)

It appears that the resulting point (red dot) is enclosed by a square of 4 samples each time. Depending on its distance from every one of these four samples, the weighting factor is obtained, which is inversely proportional to the distance and determines how much the input variables each sample affect the resulting input values.

6.2 The Matlab tool

The thesis was implemented in the Matlab environment as the specific tool had been studied and used in a number of courses of the School of Electrical and Computer Engineering of the Technical University of Crete. It is one of the most suitable for solving problems of finding a minimum, since the whole system is represented by equations. It provides many tools for studying the system and representing the results.

6.2.1 Optimization in Matlab

The equations presented above were imported into Matlab. The optimizer must find the values of the input variables for which the cost of the trip is minimized while the constraints are met. To achieve this, Matlab's Particle Swarm Optimization (PSO) function was used. In other words, particles are created with various values as input variables in the range of restrictions and depending on the results obtained, the values of the particles change and are directed towards the result that has given the minimum value. Also, when a constraint on the result is not met, a penalty is imposed (a large value multiplied by the final result) which is proportional to how far the solution is outside the constraints.

6.2.2 Penalty Function

In optimization, a penalty function is used to handle constraints that are not easy to incorporate into the objective function. Constraints in optimization problems often take the form of inequalities or equalities that limit the feasible region of the problem. A penalty function is added to the objective function to create an augmented objective function. The value of the penalty function is set to increase as the constraint is more severely violated. This means that the optimization process will be guided towards solutions that satisfy the constraints and discourage solutions that violate them.In this solution a linear penalty function was chosen because the constraints are described with linear equations or inequalities and because of the ease of implementation. The penalty is introduced to the algorithm output as shown below:

$$Output = Original\ Objective\ Function \cdot (1 + Penalty\ Term)$$

When the penalty term is zero, the algorithm output reduces to the original objective function, maintaining its original form. As the penalty term increases, the impact on the regularized objective function output also increases accordingly. The penalty should always have a positive value because it is a minimization problem and negative values would produce negative algorithm output, encouraging the optimizer to violate the constraints. For that reason the penalty is enclosed in absolute value bars.

6.3 Graphical explanation of optimization

The process that is followed in order to determine the optimal operation of the energy systems during the voyage is shown in Diagrams 6.3 and 6.4.

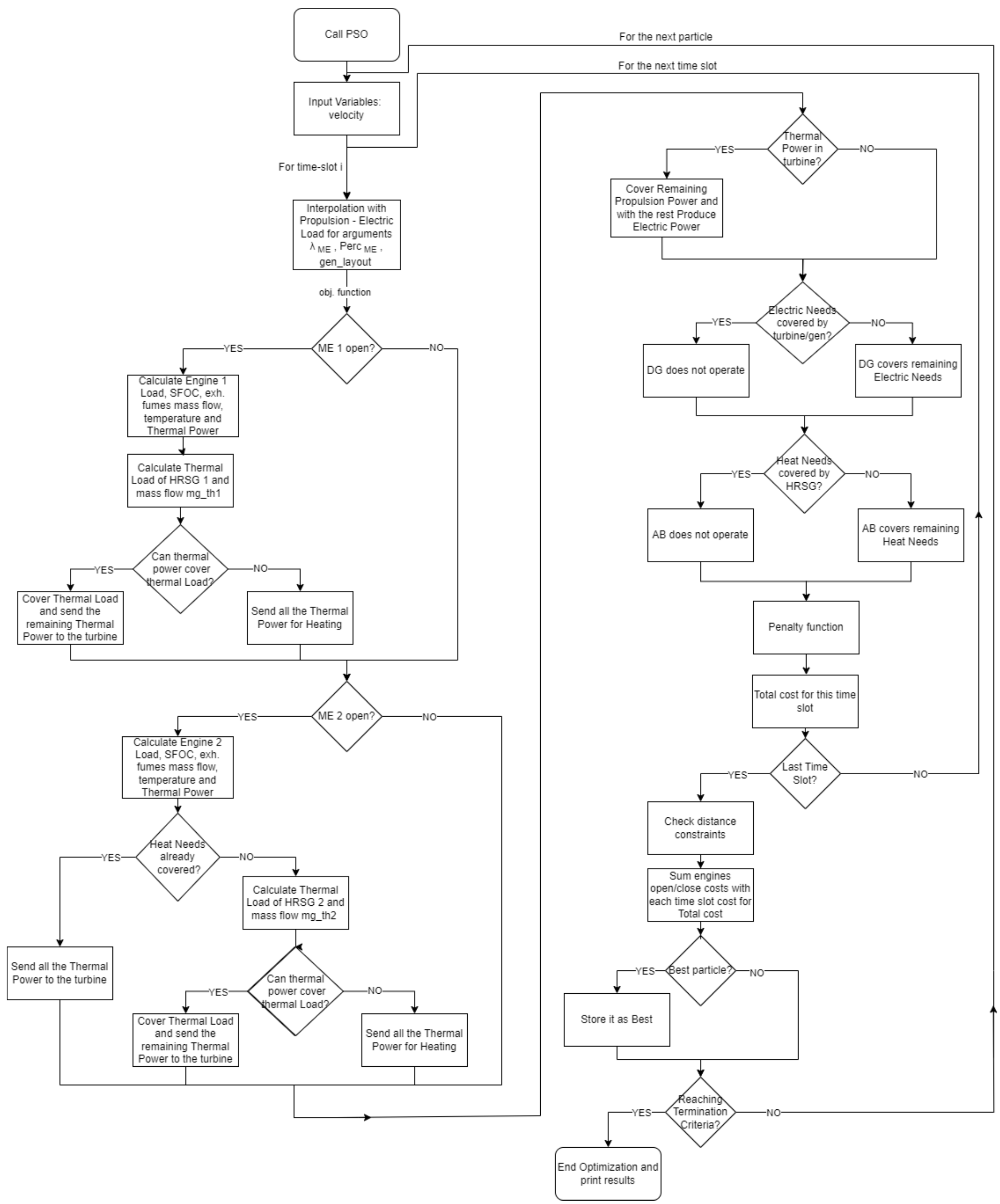


Figure 6.3: Conventional Energy System Block Diagram

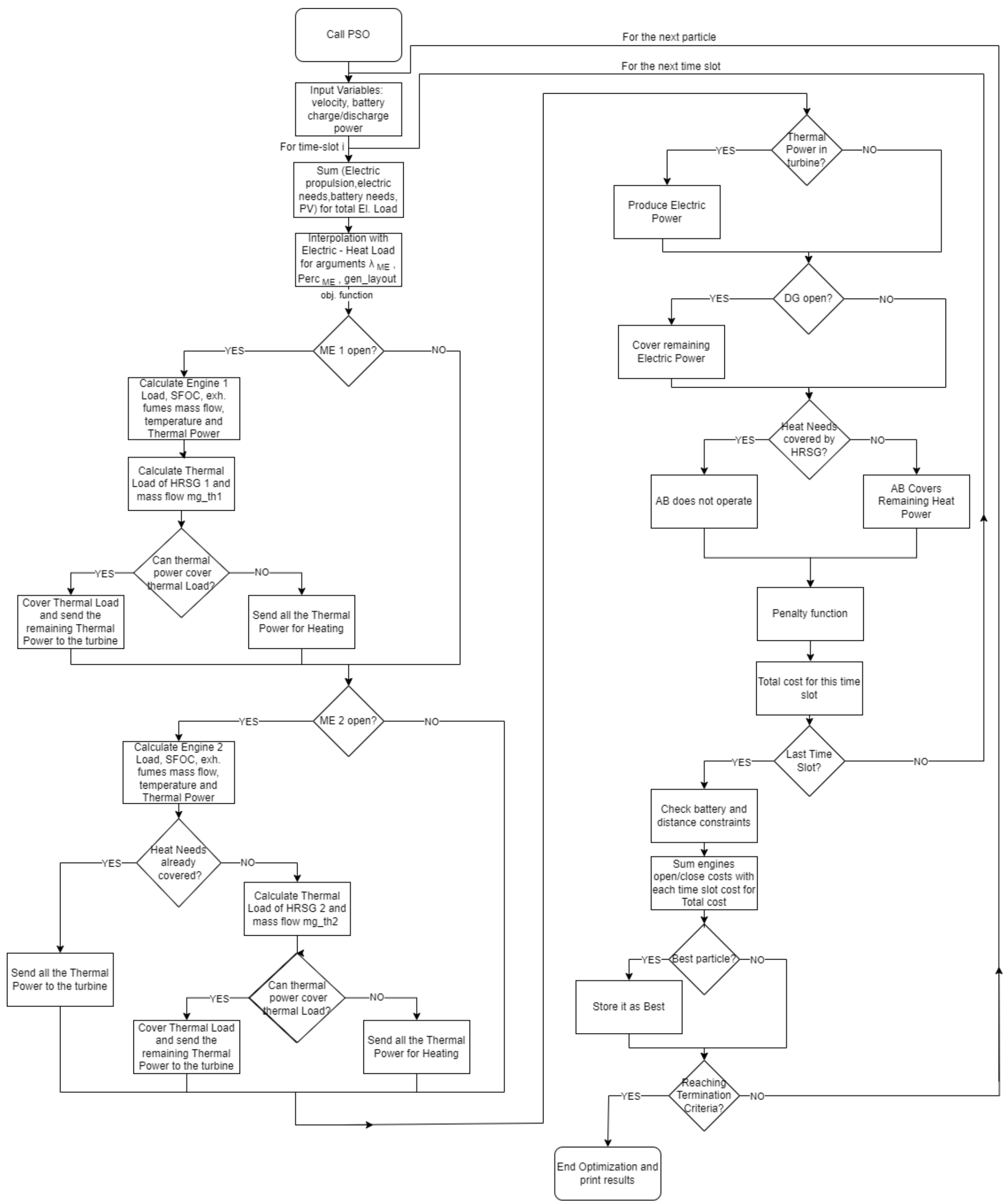


Figure 6.4: Hybrid Energy System Block Diagram

6.4 Mathematical explanation of optimization

The mathematical calculation taking place inside during the optimization is described below:

6.4.1 Conventional Ship

Firstly,the optimizer inputs the values of velocity (v) for each time slot.

Now examining each time-slot t, based on velocity and with the equation:

$$P_{prop\,total}(t) = 0.00144676 \cdot v^3(t) \tag{6.1}$$

the propulsion power needed is calculated.

Electric and heat needs are predefined. Electric needs are divided by the efficiency of the power electronics (99%) to calculate the the electric power that must be produced.

$$Electric\ Load(t) = Electric\ Needs(t)/0.99 \tag{6.2}$$

Based on Propulsion and Electric Load and with the use of interpolation, the input variables $\lambda_{\mathrm{ME,conv}}(\mathrm{t})$, $\mathrm{Perc}_{\mathrm{ME1,conv}}(\mathrm{t})$ and the power plants layout are calculated.

The propulsion power that the main engines must cover is :

$$P_{prop\,ME}(t) = P_{prop\,total}(t) \cdot \lambda_{ME,conv}(t) \quad (kW) \tag{6.3}$$

The propulsion power of Main Engine 1 is:

$$P_{prop\,ME\,1}(t) = P_{prop\,ME}(t) \cdot Perc_{ME\,1,conv}(t) \quad (kW) \tag{6.4}$$

The propulsion power of Main Engine 2 is:

$$P_{prop\,ME\,2}(t) = P_{prop\,ME}(t) \cdot (1 - Perc_{ME\,1,conv}(t)) \quad (kW) \tag{6.5}$$

If the 1st engine is closed, $\text{Perc}_{\text{ME1,conv}}(\text{t})$ is 0 and if the 2nd engine is closed $\text{Perc}_{\text{ME1,conv}}(\text{t})$ is 1.

The load factor of the Main Engines is :

$$fl_{ME\,1}(t) = P_{prop\,ME\,1}(t)/MCR_{ME\,1} \cdot 100 \tag{6.6}$$

$$fl_{ME\,2}(t) = P_{prop\,ME\,2}(t)/MCR_{ME\,2} \cdot 100 \tag{6.7}$$

Where $\text{MCR}_{\text{ME 1}} = \text{MCR}_{\text{ME 2}} =$ 15,000 kW is the Main Engines nominal power output.

Based on the load factor, the specific fuel consumption of the engines is calculated.

$$SFOC_{\text{ME 1,conv}}(t) = 0.01910 \cdot fl_{ME\,1}(t)^2 - 2.8357 \cdot fl_{ME\,1}(t) + 275.68 \quad (g/kWh) \tag{6.8}$$

$$SFOC_{\text{ME 2,conv}}(t) = 0.01967 \cdot fl_{ME\,2}(t)^2 - 2.9208 \cdot fl_{ME\,2}(t) + 283.95 \quad (g/kWh) \tag{6.9}$$

The above results are divided by 1000 to be converted to kg/kWh.

The mass flow of exhaust fumes is:

$$m_{g\,k}(t) = (a_1 \cdot MCR^3_{ME\,k} + b_1 \cdot MCR^2_{ME\,k} + c_1 \cdot MCR_{ME\,k} + d_1) \cdot \cdot (e_1 \cdot fl^3_{ME\,k}(t) + f_1 \cdot fl^2_{ME\,k}(t) + g_1 \cdot fl_{ME\,k}(t) + h_1) \quad (kg/s),\ k = 1, 2 \tag{6.10}$$

The temperature of exhaust fumes is:

$$T_{g\,k}(t) = (a_2 + b_2 \cdot MCR_{ME\,k} + c_2/MCR^2_{ME\,k}) \cdot \cdot (d_2 \cdot fl^3_{ME\,k}(t) + e_2 \cdot fl^2_{ME\,k}(t) + f_2 \cdot fl_{ME\,k}(t) + g_2) \quad (^\circ C),\ k = 1, 2 \tag{6.11}$$

The first HRSG tries to cover the thermal needs if the Main Engine 1 operates

$$Q_{HRSG\,thermal\,1}(t) = P_{heat}(t) \tag{6.12}$$

. The equal mass flow required for thermal needs is:

$$m_{g\,th1}(t) = \frac{P_{heat}(t)}{(T_{g\,1}(t) - T_{g\,out}) \cdot c_{pg}} (kg/s) \tag{6.13}$$

c_{pg}=1.06 kJ/(kg · °C) is the specific heat capacity of exhaust fumes.

If the exhaust fumes are not enough to cover thermal needs ($m_{g\ th\ 1}$>$m_{g\ 1}$), then their exploitable thermal power is calculated:

$$Q_{HRSG\ thermal\ 1}(t) = m_{g\ 1}(t) \cdot (T_{g\ 1}(t) - T_{g\ out}) \cdot c_{pg} \quad (kW) \tag{6.14}$$

Where $T_{g\ out}$=130 °C is the exhaust fumes exit temperature from the HRSG.

If the exhaust fumes are enough to cover thermal needs then the excess mass flow to be used for producing steam to be expanded in the turbine is calculated:

$$m_{w\ 1}(t) = m_{g\ 1}(t) - m_{g\ th1}(t) \quad (kg/s) \tag{6.15}$$

The steam temperature before expansion is considered to be:

$$T_{s\ 1}(t) = T_{g\ 1}(t) \cdot 90\% \quad (°C) \tag{6.16}$$

The steam pressure P_s before expansion is 15 bar as analyzed earlier.

Using T_s and P_s the enthalpy of steam before expansion (h_3) is calculated . The steam mass flow heading to the turbine is:

$$m_{s\ 1}(t) = \frac{m_{w\ 1}(t) \cdot (T_{g\ 1}(t) - T_{g\ out} \cdot c_{pg}}{h_3(t) - h_{in}} \quad (kg/s) \tag{6.17}$$

Where h_{in}=191.81 (kJ/kg) is the enthalpy of saturated liquid after condensation at 0.1 bar.

For the second HRSG the power for heating is:

$$Q_{HRSG\ thermal\ 2}(t) = P_{heat}(t) - Q_{HRSG\ thermal\ 1}(t) \quad (kW) \tag{6.18}$$

If the heat needs are covered from the HRSG of the 1st Main Engine the power for heating to be covered by HRSG 2 is 0.

The exhaust fumes mass flow required for heating is:

$$m_{g\ th2}(t) = \frac{Q_{HRSG\ thermal\ 2}(t)}{(T_{g\ 2}(t) - T_{g\ out}) \cdot c_{pg}} \quad (kg/s) \tag{6.19}$$

If the exhaust fumes are not enough to cover thermal needs ($m_{g\ th\ 2} > m_{g\ 2}$), then their exploitable thermal power is calculated:

$$Q_{HRSG\ thermal\ 2}(t) = m_{g\ 2}(t) \cdot (T_{g\ 2}(t) - T_{g\ out}) \cdot c_{pg} \quad (kW) \tag{6.20}$$

If the exhaust fumes are enough to cover thermal needs then the excess mass flow to be used for producing steam to be expanded in the turbine is calculated:

$$m_{w\ 2}(t) = m_{g\ 2}(t) - m_{g\ th2}(t) \quad (kg/s) \tag{6.21}$$

The steam mass flow heading to the turbine is:

$$m_{s\ 2}(t) = \frac{m_{w\ 2}(t) \cdot (T_{g\ 2}(t) - T_{g\ out}) \cdot c_{pg}}{h_3(t) - h_{in}} \quad (kg/s) \tag{6.22}$$

Using T_s and P_s the enropy of steam before expansion (s_3) is calculated. Because expansion is considered isentropic, entropy after expansion (s_4) is equal to entropy before expansion (s_3).

The steam quality after expansion is:

$$x_4(t) = \frac{s_4(t) - s_{sl}}{s_{ss} - s_{sl}} \tag{6.23}$$

Where s_{sl}=0.64920 (kJ/(kg·K)) is the entropy of saturated liquid at pressure after expansion (P_4=0.1 bar) and s_{ss}=8.1488 (kJ/(kg·K)) is the entropy of saturated steam at P_4.

The enthalpy of water/steam after expansion (h_4) is:

$$h_4(t) = x_4(t) \cdot h_{ss} + (1 - x_4(t)) \cdot h_{sl} \quad (kJ/kg) \tag{6.24}$$

Where h_{sl}=191.84 (kJ/kg) is the enthalpy of saturated liquid at P_4=0.1 bar and h_{ss}=2583.9 (kJ/kg) is the enthalpy of saturated steam at P_4.

The power produced in the steam turbine is given by the equation:

$$P_{ST}(t) = (m_{s\ 1}(t) + m_{s\ 2}(t)) \cdot (h_3(t) - h_4(t)) \cdot 0.95 \cdot 0.85 \quad (kW) \tag{6.25}$$

Where the power of the pump accounts for 5% of the produced power and the losses in fluid friction account for 15% of the remaining power. That is why the result is multiplied with 0.95 and 0.85 respectively.

The turbine power utilized for propulsion is:

$$P_{ST\,prop}(t) = P_{prop\,total}(t) - P_{prop\,ME}(t) \quad (kW) \tag{6.26}$$

The remaining turbine power is used for electricity:

$$P_{ST\,el}(t) = (P_{ST}(t) - P_{ST\,prop}(t)) \cdot n_G \quad (kW) \tag{6.27}$$

Where n_G=0.95 is the efficiency of the generator

The load of the Diesel Generator is:

$$P_{DG}(t) = Electric\ Load(t) - P_{ST\,el}(t) \quad (kW) \tag{6.28}$$

Its Load Factor is:

$$fl_{DG}(t) = P_{DG}(t)/MCR_{DG} \cdot 100 \tag{6.29}$$

Where MCR_{DG}=5000 kW is the Diesel Generator nominal power output.

The latter's Specific Fuel Oil Consumption is:

$$\begin{aligned} SFOC_{DG}(t) = {} & a + b\ln(MCR_{DG}) + c\ln(fl_{DG}(t)) + d\ln^2(MCR_{DG}) \\ & + e\ln^2(fl_{DG}(t)) + f\ln(MCR_{DG})\ln(fl_{DG}(t)) \\ & + g\ln^3(MCR_{DG}) + h\ln^3(fl_{DG}(t)) \\ & + i\ln(MCR_{DG})\ln^2(fl_{DG}(t)) \\ & + j\ln^2(MCR_{DG})\ln(fl_{DG}(t)), \quad (g/kwh) \end{aligned} \tag{6.30}$$

Where a,b,c,d,e,f,g,h,i,j are constants. The result is divided by 1000 to be converted to kg/kWh.

The Auxiliary Boiler power is:

$$P_{AB}(t) = P_{heat}(t) - (Q_{HRSG\,thermal\,1}(t) + Q_{HRSG\,thermal\,2}(t)) \quad (kW) \tag{6.31}$$

Its Fuel Consumption is:

$$FC_{AB}(t) = P_{AB}(t)/(LHV_{fuel} \cdot n_{AB}) \quad (kg/s) \tag{6.32}$$

Where LHV_{fuel}=42,700(kJ/kg) is the fuel lower heating value and n_{AB}=0.9 is the boiler efficiency. The result is multiplied by 3,600 to convert it to kg/h.

At this point the **Penalty Function** is called which is analyzed in the next section and the *Total Penalty* for time slot t is calculated.

The fuel cost for time-slot t is:

$$\begin{aligned} tsFC(t) = [&Dt \cdot P_{prop\ ME\ 1}(t) \cdot SFOC_{\mathrm{ME\ 1,conv}}(t) \cdot diesel\ cost \\ &+ Dt \cdot P_{prop\ ME\ 2}(t) \cdot SFOC_{\mathrm{ME\ 2,conv}}(t) \cdot diesel\ cost \\ &+ Dt \cdot P_{DG}(t) \cdot SFOC_{DG}(t) \cdot diesel\ cost \\ &+ Dt \cdot FC_{AB}(t) \cdot diesel\ cost] \cdot (1 + Total\ Penalty(t)) \qquad (€) \end{aligned} \tag{6.33}$$

Where Dt=0.5 h is the time slot duration and diesel cost is 0.8 €/kg.

After the fuel cost for all time slots is determined, the power plants opening and closing costs ($oc_{\mathrm{ME\ 1}}$,$oc_{\mathrm{ME\ 2}}$,oc_{DG}) are calculated based on how many times each power plant opens or closes.

Afterwards the distance constraints are checked (*Penalty 9*).

Finally the total travel cost is:

$$\begin{aligned} \textbf{Total Cost} = &(sum(tsFC) + oc_{ME\ 1} + oc_{ME\ 2} + oc_{DG}) \cdot \\ &\cdot (1 + Penalty\ 9) \quad (€) \end{aligned} \tag{6.34}$$

6.4.2 Conventional Ship Penalty Equations

If some constraints are not met, then a penalty, which is the multiplication of a large coefficient with the amount of violation, is imposed in order to lead to the optimizer in solutions which respect constraints. In the following equations a penalty factor of 100 is imposed.

The penalty for not covering propulsion power is:

$$Penalty\ 1(t) = |[P_{prop\,total}(t) - (P_{prop\,ME\,1}(t) + P_{prop\,ME\,2}(t) + P_{ST\,prop}(t))] \cdot 100| \tag{6.35}$$

If the Power Plants' load factor is higher than the maximum permitted value, a penalty is imposed:

$$Penalty\ 2(t) = |(fl_{ME\,1}(t) - 67) \cdot 100| \tag{6.36}$$

$$Penalty\ 3(t) = |(fl_{ME\,2}(t) - 67) \cdot 100| \tag{6.37}$$

$$Penalty\ 4(t) = |(fl_{DG}(t) - 100) \cdot 100| \tag{6.38}$$

If the Power Plants' load factor is lower than the minimum permitted value, a penalty is imposed:

$$Penalty\ 5(t) = |(20 - fl_{ME\,1}(t)) \cdot 100| \tag{6.39}$$

$$Penalty\ 6(t) = |(20 - fl_{ME\,2}(t)) \cdot 100| \tag{6.40}$$

$$Penalty\ 7(t) = |(20 - fl_{DG}(t)) \cdot 100| \tag{6.41}$$

In order for the simplify the problem, the steam after expansion must be inside the saturation curve thus, its entropy must be lower than that of the saturated steam [8.1488 (kJ/(kg · K))]. If the entropy is higher than this value a penalty is imposed:

$$Penalty\ 8(t) = |(s_4(t) - 8.1488) \cdot 100| \tag{6.42}$$

The total Penalty is:

$$\begin{aligned} Total\ Penalty(t) = {} & Penalty\ 1(t) + Penalty\ 2(t) + Penalty\ 3(t) \\ & + Penalty\ 4(t) + Penalty\ 5(t) + Penalty\ 6(t) \\ & + Penalty\ 7(t) + Penalty\ 8(t) \end{aligned} \tag{6.43}$$

When all time slots are examined, **a second penalty function** checks if the travel distance is covered.

If the distance is not covered a penalty is imposed:

$$Penalty\ 9 = |(travel\ distance - sum(v) \cdot Dt) \cdot 100| \tag{6.44}$$

6.4.3 Electric Propulsion Ship

Firstly,the optimizer inputs the values of velocity (v) and battery charge/discharge power (P_b) for each time slot.

Now examining each time-slot t, based on velocity and with the equation:

$$P_{prop\ total}(t) = 0.00144676 \cdot v^3(t) \tag{6.45}$$

the propulsion power needed is calculated.
In order to calculate the electric energy the motors need for propulsion the propulsion power is divided by their efficiency:

$$P_{prop\ total\ el}(t) = P_{prop\ total}(t)/m_{eff} \tag{6.46}$$

Where m_{eff}=0.96.

If the battery charges the system provides this power, which is given by the equation:

$$P_{battery}(t) = P_{bat}(t)/Bat_{\text{charge eff}} \quad \geq 0 \quad (kW) \tag{6.47}$$

If the battery discharges the system receives power:

$$P_{battery}(t) = P_{bat}(t) \cdot Bat_{\text{discharge eff}} \quad < 0 \quad (kW) \tag{6.48}$$

Where both $Bat_{\text{charge eff}}$ and $Bat_{\text{discharge eff}}$ are 0.95 . Electric and heat auxiliary needs are predefined. The total Electric Load is:

$$ElectricLoad(t) = \frac{P_{prop\ total\ el}(t) + P_{battery}(t) + P_{electric}(t)}{PE_{\ eff}} - PV(t) \tag{6.49}$$

Where P_{electric} are the auxiliary electric needs ,PV is the power produced by Photovoltaics and PE_{eff}=0.99 the efficiency of Power Electronics.

Based on Electric Load and Thermal Load and with the use of interpolation, the input variables $\lambda_{\text{ME,el}}$(t), $\text{Perc}_{\text{ME1,el}}$(t) and the power plants layout are calculated.

The electric power that the main engines must cover is :

$$P_{el\ ME}(t) = ElectricLoad(t) \cdot \lambda_{ME,el}(t) \quad (kW) \tag{6.50}$$

The mechanical power to produce the electric electric power that the main engines must cover is :

$$P_{ME}(t) = P_{el\ ME}(t)/Gen_{\ eff} \quad (kW) \tag{6.51}$$

Where Gen $_{\text{eff}}$=0.96 .

The propulsion power of Main Engine 1 is:

$$P_{ME\ 1}(t) = P_{ME}(t) \cdot Perc_{ME\ 1,el}(t) \quad (kW) \tag{6.52}$$

The propulsion power of Main Engine 2 is:

$$P_{ME\ 2}(t) = P_{ME}(t) \cdot (1 - Perc_{ME\ 1,el}(t)) \quad (kW) \tag{6.53}$$

If the 1$^{\text{st}}$ engine is closed, $\text{Perc}_{\text{ME1,el}}$(t) is 0 and if the 2$^{\text{nd}}$ engine is closed $\text{Perc}_{\text{ME1,el}}$(t) is 1.

The load factor of the Main Engines is :

$$fl_{ME\ 1}(t) = P_{ME\ 1}(t)/MCR_{ME\ 1} \cdot 100 \tag{6.54}$$

$$fl_{ME\ 2}(t) = P_{ME\ 2}(t)/MCR_{ME\ 2} \cdot 100 \tag{6.55}$$

Where $\text{MCR}_{\text{ME 1}}$ = $\text{MCR}_{\text{ME 2}}$= 15,000 kW is the Main Engines nominal power output.

Based on the load factor, the specific fuel consumption of the engines is calculated.

$$SFOC_{\text{ME 1,el}}(t) = 0.01710 \cdot fl_{\text{ME 1,el}}(t)^2 - 2.066 \cdot fl_{\text{ME 1,el}}(t) + 217.39 \quad (g/kWh) \tag{6.56}$$

$$SFOC_{\text{ME 2,el}}(t) = 0.01761 \cdot fl_{\text{ME 2,el}}(t)^2 - 2.128 \cdot fl_{\text{ME 2,el}}(t) + 223.91 \quad (g/kWh) \tag{6.57}$$

The above results are divided by 1000 to be converted to kg/kWh.

The mass flow of exhaust fumes is:

$$m_{g\ k}(t) = (a_1 \cdot MCR^3_{ME\ k} + b_1 \cdot MCR^2_{ME\ k} + c_1 \cdot MCR_{ME\ k} + d_1) \cdot \\ \cdot (e_1 \cdot fl^3_{ME\ k}(t) + f_1 \cdot fl^2_{ME\ k}(t) + g_1 \cdot fl_{ME\ k}(t) + h_1) \quad (kg/s),\ k = 1,2 \tag{6.58}$$

The temperature of exhaust fumes is:

$$T_{g\,k}(t) = (a_2 + b_2 \cdot MCR_{ME\,k} + c_2/MCR^2_{ME\,k})\cdot$$
$$\cdot\,(d_2 \cdot fl^3_{ME\,k}(t) + e_2 \cdot fl^2_{ME\,k}(t) + f_2 \cdot fl_{ME\,k}(t) + g_2) \quad (^{\circ}C),\ k = 1,2 \tag{6.59}$$

The first HRSG tries to cover the thermal needs if the Main Engine 1 operates

$$Q_{HRSG\,thermal\,1}(t) = P_{heat}(t) \tag{6.60}$$

. The equal mass flow required for thermal needs is:

$$m_{g\,th1}(t) = \frac{P_{heat}(t)}{(T_{g\,1}(t) - T_{g\,out}) \cdot c_{pg}}(kg/s) \tag{6.61}$$

c_{pg}=1.06 kJ/(kg · °C) is the specific heat capacity of exhaust fumes.
If the exhaust fumes are not enough to cover thermal needs ($m_{g\ th\ 1}$>$m_{g\ 1}$), then their exploitable thermal power is calculated:

$$Q_{HRSG\,thermal\,1}(t) = m_{g\,1}(t) \cdot (T_{g\,1}(t) - T_{g\,out}) \cdot c_{pg} \quad (kW) \tag{6.62}$$

Where $T_{g\ out}$=130 °C is the exhaust fumes exit temperature from the HRSG.

If the exhaust fumes are enough to cover thermal needs then the excess mass flow to be used for producing steam to be expanded in the turbine is calculated:

$$m_{w\,1}(t) = m_{g\,1}(t) - m_{g\,th1}(t) \quad (kg/s) \tag{6.63}$$

The steam temperature before expansion is considered to be:

$$T_{s\,1}(t) = T_{g\,1}(t) \cdot 90\% \quad (^{\circ}C) \tag{6.64}$$

The steam pressure P_s before expansion is 15 bar as analyzed earlier.

Using T_s and P_s the enthalpy of steam before expansion (h_3) is calculated .
The steam mass flow heading to the turbine is:

$$m_{s\,1}(t) = \frac{m_{w\,1}(t) \cdot (T_{g\,1}(t) - T_{g\,out} \cdot c_{pg}}{h_3(t) - h_{in}} \quad (kg/s) \tag{6.65}$$

Where h_{in}=191.81 (kJ/kg) is the enthalpy of saturated liquid after condensation at 0.1 bar.

For the second HRSG the power for heating is:

$$Q_{HRSG\ thermal\ 2}(t) = P_{heat}(t) - Q_{HRSG\ thermal\ 1}(t) \quad (kW) \tag{6.66}$$

If the heat needs are covered from the HRSG of the 1^{st} Main Engine the power for heating to be covered by HRSG 2 is 0.

The exhaust fumes mass flow required for heating is:

$$m_{g\ th2}(t) = \frac{Q_{HRSG\ thermal\ 2}(t)}{(T_{g\ 2}(t) - T_{g\ out}) \cdot c_{pg}} \quad (kg/s) \tag{6.67}$$

If the exhaust fumes are not enough to cover thermal needs ($m_{g\ th\ 2} > m_{g\ 2}$), then their exploitable thermal power is calculated:

$$Q_{HRSG\ thermal\ 2}(t) = m_{g\ 2}(t) \cdot (T_{g\ 2}(t) - T_{g\ out}) \cdot c_{pg} \quad (kW) \tag{6.68}$$

If the exhaust fumes are enough to cover thermal needs then the excess mass flow to be used for producing steam to be expanded in the turbine is calculated:

$$m_{w\ 2}(t) = m_{g\ 2}(t) - m_{g\ th2}(t) \quad (kg/s) \tag{6.69}$$

The steam mass flow heading to the turbine is:

$$m_{s\ 2}(t) = \frac{m_{w\ 2}(t) \cdot (T_{g\ 2}(t) - T_{g\ out}) \cdot c_{pg}}{h_3(t) - h_{in}} \quad (kg/s) \tag{6.70}$$

Using T_s and P_s the enropy of steam before expansion (s_3) is calculated. Because expansion is considered isentropic, entropy after expansion (s_4) is equal to entropy before expansion (s_3).

The steam quality after expansion is:

$$x_4(t) = \frac{s_4(t) - s_{sl}}{s_{ss} - s_{sl}} \tag{6.71}$$

Where s_{sl}=0.64920 (kJ/(kg·K)) is the entropy of saturated liquid at pressure after expansion (P_4=0.1 bar) and s_{ss}=8.1488 (kJ/(kg·K)) is the entropy of saturated steam at P_4.

The enthalpy of water/steam after expansion (h_4) is:

$$h_4(t) = x_4(t) \cdot h_{ss} + (1 - x_4(t)) \cdot h_{sl} \quad (kJ/kg) \tag{6.72}$$

Where h_{sl}=191.84 (kJ/kg) is the enthalpy of saturated liquid at P_4=0.1 bar and h_{ss}=2583.9 (kJ/kg) is the enthalpy of saturated steam at P_4.

The power produced in the steam turbine is given by the equation:

$$P_{ST}(t) = (m_{s\,1}(t) + m_{s\,2}(t)) \cdot (h_3(t) - h_4(t)) \cdot 0.95 \cdot 0.85 \quad (kW) \tag{6.73}$$

Where the power of the pump accounts for 5% of the produced power and the losses in fluid friction account for 15% of the remaining power. That is why the result is multiplied with 0.95 and 0.85 respectively.

All the turbine power is used for electricity production:

$$P_{ST\,el}(t) = P_{ST}(t) \cdot n_G \quad (kW) \tag{6.74}$$

Where n_G=0.95 is the efficiency of the generator

The load of the Diesel Generator is:

$$P_{DG}(t) = Electric\ Load(t) - [(P_{ME\,1}(t) + P_{ME\,2}(t)) \cdot \text{Gen}_{\text{eff}} + P_{ST\,el}(t)] \quad (kW) \tag{6.75}$$

Its Load Factor is:

$$fl_{DG}(t) = P_{DG}(t)/MCR_{DG} \cdot 100 \tag{6.76}$$

Where MCR_{DG}=5000 kW is the Diesel Generator nominal power output.

The latter's Specific Fuel Oil Consumption is:

$$\begin{aligned} SFOC_{DG}(t) = {} & a + b\ln(MCR_{DG}) + c\ln(fl_{DG}(t)) + d\ln^2(MCR_{DG}) \\ & + e\ln^2(fl_{DG}(t)) + f\ln(MCR_{DG})\ln(fl_{DG}(t)) \\ & + g\ln^3(MCR_{DG}) + h\ln^3(fl_{DG}(t)) \\ & + i\ln(MCR_{DG})\ln^2(fl_{DG}(t)) \\ & + j\ln^2(MCR_{DG})\ln(fl_{DG}(t)), \quad (g/kWh) \end{aligned} \tag{6.77}$$

Where a,b,c,d,e,f,g,h,i,j are constants.The result is divided by 1000 to be converted to kg/kWh.

The Auxiliary Boiler power is:

$$P_{AB}(t) = P_{heat}(t) - (Q_{HRSG\ thermal\ 1}(t) + Q_{HRSG\ thermal\ 2}(t)) \quad (kW) \quad (6.78)$$

Its Fuel Consumption is:

$$FC_{AB}(t) = P_{AB}(t)/(LHV_{fuel} \cdot n_{AB}) \quad (kg/s) \quad (6.79)$$

Where LHV_{fuel}=42,700(kJ/kg) is the fuel lower heating value and n_{AB}=0.9 is the boiler efficiency. The result is multiplied by 3,600 to convert it to kg/h.

At this point the **Penalty Function** is called which is analyzed in the next section and the *Total Penalty* for time slot t is calculated.

The fuel cost for time-slot t is:

$$\begin{aligned} tsFC(t) = [&Dt \cdot P_{ME\ 1}(t) \cdot SFOC_{\mathrm{ME\ 1,el}}(t) \cdot diesel\ cost \\ &+ Dt \cdot P_{ME\ 2}(t) \cdot SFOC_{\mathrm{ME\ 2,el}}(t) \cdot diesel\ cost \\ &+ Dt \cdot P_{DG}(t) \cdot SFOC_{DG}(t) \cdot diesel\ cost \\ &+ Dt \cdot FC_{AB}(t) \cdot diesel\ cost] \cdot (1 + Total\ Penalty(t)) \quad (€) \end{aligned} \quad (6.80)$$

Where Dt=0.5 h is the time slot duration and diesel cost is 0.8 €/kg.

After the fuel cost for all time slots is determined, the power plants opening and closing costs ($oc_{\mathrm{ME\ 1}}$,$oc_{\mathrm{ME\ 2}}$,oc_{DG}) are calculated based on how many times each power plant opens or closes.

Afterwards the distance and battery constraints are checked (*Penalty 9*,*Penalty 10*, *Penalty 11*)

Finally the total travel cost is:

$$\begin{aligned} \textbf{Total Cost} = &(sum(tsFC) + oc_{ME\ 1} + oc_{ME\ 2} + oc_{DG}) \cdot \\ &\cdot (1 + Penalty\ 9 + Penalty\ 10 + Penalty\ 11) \quad (€) \end{aligned} \quad (6.81)$$

6.4.4 Hybrid Energy System Penalty Equations

If some constraints are not met, then a penalty, which is the multiplication of a large coefficient with the amount of violation, is imposed in order to lead to the optimizer in solutions which respect constraints. In the following equations a penalty factor of 100 is imposed.

The penalty for not covering electric load is:

$$Penalty\ 1(t) = |[Electric\ Load(t) - (P_{el\ ME\ 1}(t) + P_{el\ ME\ 2}(t) + P_{ST\ el}(t))] \cdot 100| \tag{6.82}$$

If the Power Plants' load factor is higher than the maximum permitted value, a penalty is imposed:

$$Penalty\ 2(t) = |(fl_{ME\ 1}(t) - 67) \cdot 100| \tag{6.83}$$

$$Penalty\ 3(t) = |(fl_{ME\ 2}(t) - 67) \cdot 100| \tag{6.84}$$

$$Penalty\ 4(t) = |(fl_{DG}(t) - 100) \cdot 100| \tag{6.85}$$

If the Power Plants' load factor is lower than the minimum permitted value, a penalty is imposed:

$$Penalty\ 5(t) = |(20 - fl_{ME\ 1}(t)) \cdot 100| \tag{6.86}$$

$$Penalty\ 6(t) = |(20 - fl_{ME\ 2}(t)) \cdot 100| \tag{6.87}$$

$$Penalty\ 7(t) = |(20 - fl_{DG}(t)) \cdot 100| \tag{6.88}$$

In order for the simplify the problem, the steam after expansion must be inside the saturation curve thus, its entropy must be lower than that of the saturated steam [8.1488 (kJ/(kg · K))]. If the entropy is higher than this value a penalty is imposed:

$$Penalty\ 8(t) = |(s_4(t) - 8.1488) \cdot 100| \tag{6.89}$$

The total Penalty is:

$$\begin{aligned} Total\ Penalty(t) = {} & Penalty\ 1(t) + Penalty\ 2(t) + Penalty\ 3(t) \\ & + Penalty\ 4(t) + Penalty\ 5(t) + Penalty\ 6(t) \\ & + Penalty\ 7(t) + Penalty\ 8(t) \end{aligned} \tag{6.90}$$

When all time slots are examined, **a second penalty function** checks if the travel distance is covered and the battery charge state upper and lower limits are respected.

If the distance is not covered a penalty is imposed

$$Penalty\ 9 = |(travel\ distance - sum(v) \cdot Dt) \cdot 100| \tag{6.91}$$

If the battery state of charge exceeds maximum charge then:

$$\begin{aligned}
&for\ t = 1 : end \\
&\quad if(E_0 + P_{bat}(1:t) \cdot Dt > E_{max}) \\
&\quad\quad Penalty\ 10 = |Penalty\ 10 + (E_0 + P_{bat}(1:t) \cdot Dt - E_{max}) \cdot 100| \\
&\quad end\ if \\
&end\ for
\end{aligned} \tag{6.92}$$

If the battery state of charge drops below minimum charge then:

$$\begin{aligned}
&for\ t = 1 : end \\
&\quad if(E_0 + P_{bat}(1:t) \cdot Dt < E_{min}) \\
&\quad\quad Penalty\ 11 = |Penalty\ 11 + [E_{min} - (E_0 + P_{bat}(1:t) \cdot Dt)] \cdot 100| \\
&\quad end\ if \\
&end\ for
\end{aligned} \tag{6.93}$$

Chapter 7

Scenarios and Results

Four scenarios are studied in total: High Speed travel for Conventional and Electric Propulsion and Slow Steaming travel for Conventional and Electric Propulsion.

In each scenario, a journey with a stopover is studied. The first leg of the journey is 92 nautical miles, while the second leg is 82 nautical miles. The fuel cost is assumed to be 0.8 €/kg or 800 €/ton.

7.1 High Speed

Each leg of the trip is covered in 4.5 hours or 9 half hours (optimized time). The 10^{th} half-hour is considered to be the arrival at the intermediate station.

7.1.1 Conventional

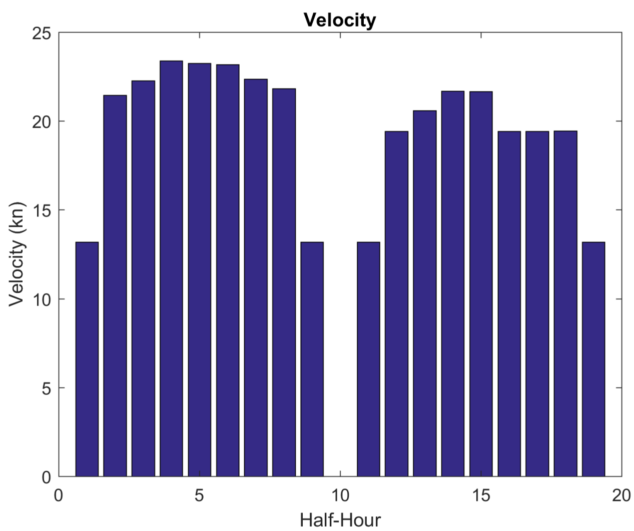


Figure 7.1: Velocity

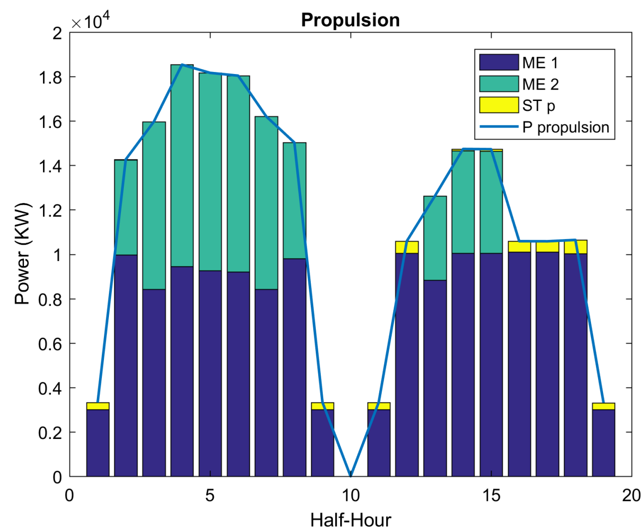
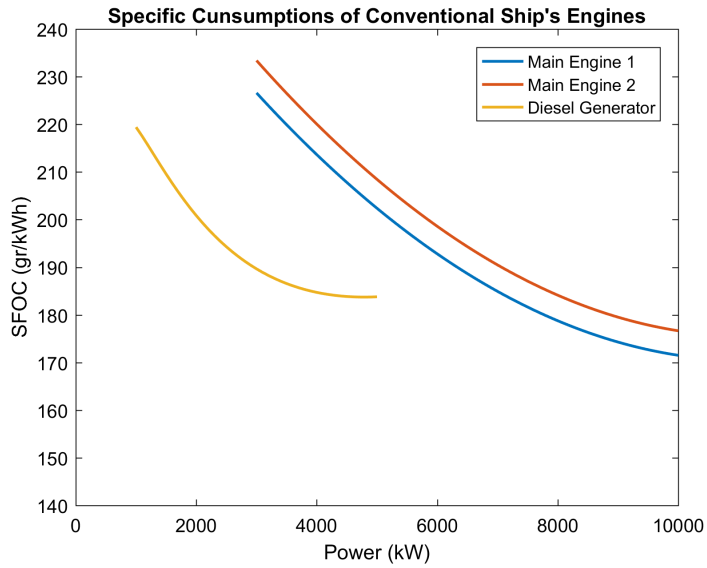


Figure 7.2: Propulsion Power

It is observed that the speed creates a smooth curve at high speeds in the open sea which also meets the real conditions of a ship's journey but also reduces the required power and the cost for propulsion as spikes are avoided which, as has been analyzed, increase the cost of operation.

In the first half an hour the engine works at low power due to operational limitations. Initially the optimizer drives it to the highest possible speed (13.2 knots/h) in order to "lighten" the load as much as possible from the next half hours when the speed is already high and each additional knot per hour costs more than when the engines are operating at low power. Since the 1st engine is cheaper, it is chosen to open it first. The required propulsion power is (3,330 kW) and since at low power the engine does not operate efficiently in terms of consumption, it is chosen to produce as little power as possible (3,000 kW = 20% load factor - constraint). The remaining 330 kW is covered by the mechanical power of the cogeneration system. After the required propulsion power is met from 1the engine and the cogeneration system, the surplus power helps meet electrical needs.



It is illustrated that in four time slices the power is maintained at the maximum (10 MW) that the first (and cheapest) engine can cover. If the specific consumption curve is studied, it is found that the optimum operating point is 10 MW. When the second (and more expensive) main engine is running, because its minimum operating power is 3 MW, the load will be shared between the two engines. So on the one hand the more expensive engine will work at low power where the specific consumption is very high and on the other hand since the first engine covers a lower load, the specific consumption is not optimal.

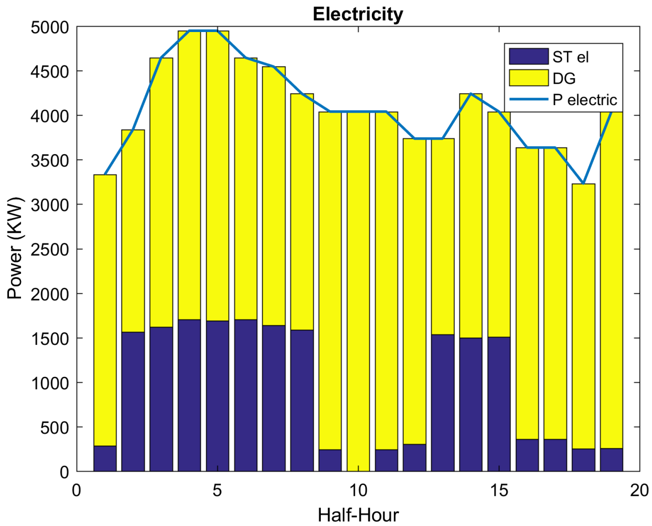


Figure 7.3: Electric Power Needs and Coverage

In the open sea, it is preferred by the optimizer that the cogeneration power covers electrical needs. This is justified by the fact that the diesel generator has a higher specific consumption than the combined consumption of the two main engines. So, since the diesel generator is less efficient, the power it produces is reduced as much as possible and the deficit is filled by the electric power of the cogeneration system.

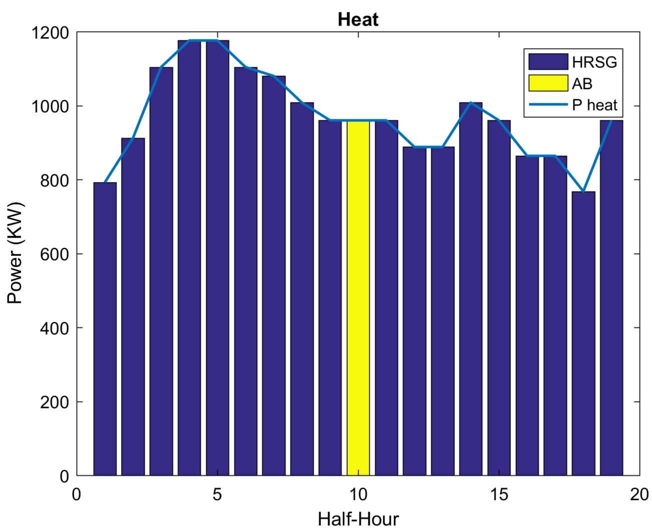


Figure 7.4: Heating Power Needs and Coverage

The optimizer firstly covers thermal needs with the cogeneration system power when the main engines are running (except for time-slot 10 where the ship stops). This is because the thermal power of the cogeneration is fully utilized by the heating system, unlike the turbine, which acquires energy equal to the difference in the enthalpy of the steam before and after expansion.

7.1.2 Electric Propulsion

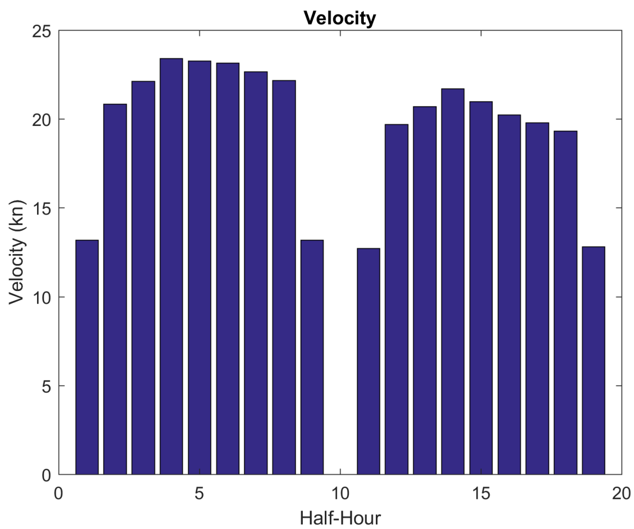


Figure 7.5: Velocity

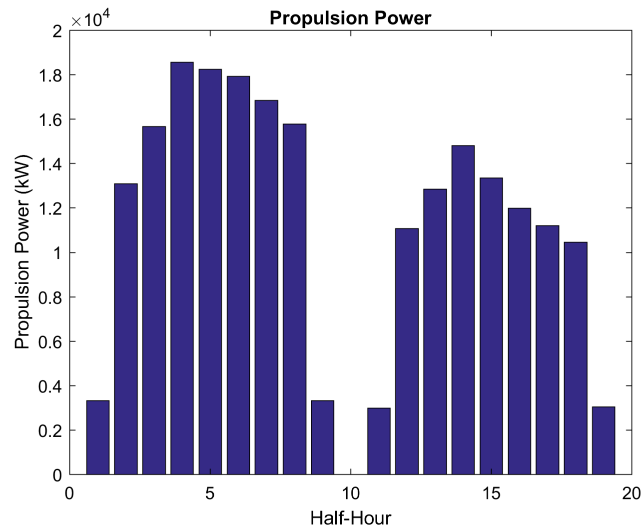


Figure 7.6: Propulsion Power

In the electrical power graph, the power used for the ship's operational needs and passenger comfort has been summed with the (electrical) power required for propulsion.

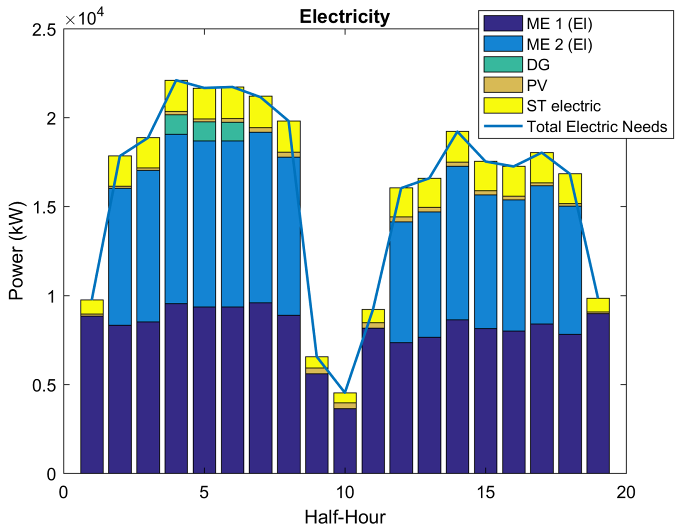


Figure 7.7: Electric Power Distribution

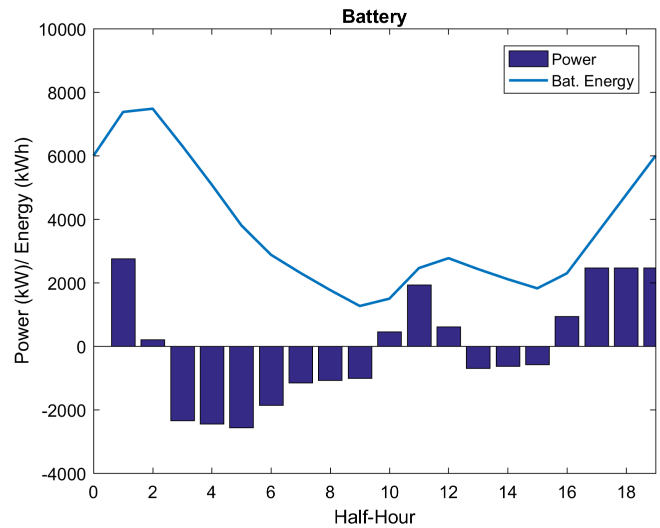


Figure 7.8: Battery Energy/Power

The first trip is longer as are the power requirements and the battery discharges so that less power needs to be covered by the diesel generator or it does not work at all because it is the least efficient. In the second leg of the journey the battery is charging and the power covered by the two main engines is kept below the power where the diesel generator opens, because on the one hand it is not efficient and on the other hand there are opening/closing costs.

The graph above is also affected by battery behavior. When it discharges, it "lightens" the load on the power generation systems, while when it charges, the they are "burdened" with the obligation to provide the power that will charge the battery.

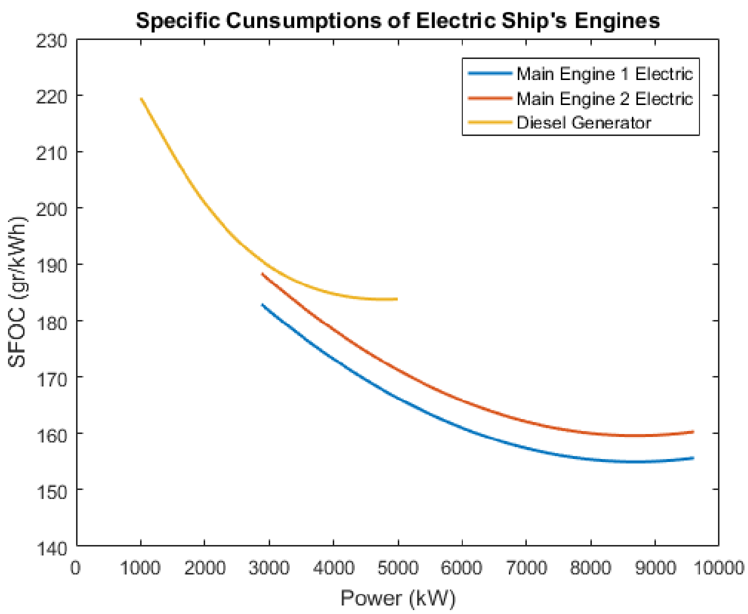


Figure 7.9: SFOC of Electric Ship's Power Generation Units

The order of engine operation preference is first main engine 1, then main engine 2 and lastly the diesel generator. The specific consumption graph 7.9 explains this behavior. It appears that the power plants do not have the same operating range as the rated power of the diesel generator is 5 MW while the main engines are 15 MW but they operate at 10 MW for the reasons previously discussed.

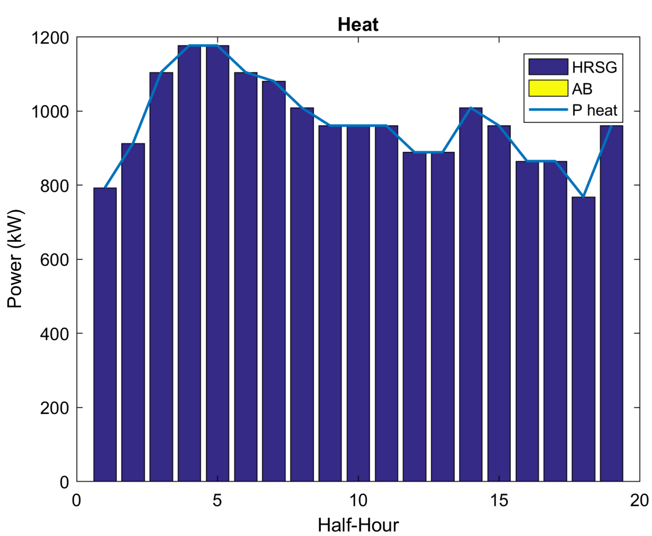


Figure 7.10: Electric Power Needs and Coverage

In the 10^{th} half an hour, where the ship is docked in port and the electrical power is spent on hotel services, the first engine operates, giving the system the capability of exploiting cogeneration to meet thermal and electrical needs even when the ship is not moving.

The boiler does not operate at all during the trip, because at all times at least one main engine is open and the thermal power of the exhaust gases is used to heat water through the cogeneration system.

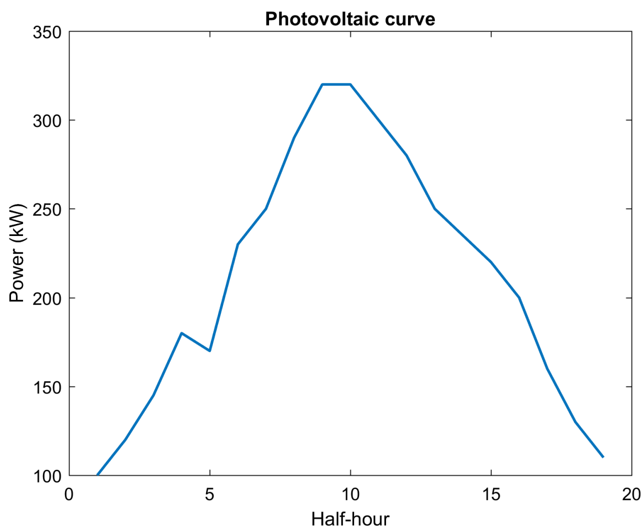


Figure 7.11: PV power production

The photovoltaic curve based on the sun radiation curve 5.6 is shown. It appears that the power generated by the photovoltaics is a very small part of the total power the ship needs to operate as shown in Fig. 7.7, and their usefulness lies more in charging the battery during all hours of sunshine regardless of whether the ship is travelling, than in contributing to meeting the needs during the trip.

7.1.3 Comparison of Energy Systems

	High Speed	
	Conventional	Hybrid
Propulsive energy (mech) (kWh)	106,993	107,269
electrical energy (hotel services) (kWh)	38,788	38,788
Sum (kWh)	145,781	146,047
Electric energy for propulsion (kWh)	-	111,739
Energy produced by power plants (kWh):		
ME 1	72,879	77,431
ME 2	32,320	57,653
DG	29,532	1,598
Sum	134,731	136,682
Energy produced by CCP (kWh)	11,048	13,689
Energy produced by photovoltaics (kWh)	-	2,005
Total Cost	21,210 €	19,130 €

The electric ship requires more energy due to the losses of the generators connected to the main engines and the electric motor connected to the propeller. Also, because more work is produced by the two main engines in the electric propulsion ship, the energy produced by the cogeneration system is greater.

The energy from photovoltaics is very small, covering 1.4% of the total energy.

Percentage cost difference between conventional and electric propulsion ships in the 1st scenario: 10.312%

7.2 Slow Steaming

For the 2nd scenario the route is the same, but more time is given to complete the journey. More specifically, everyone is given a margin of 5.5 hours on each leg of the route, while previously it was 4.5 hours. In the additional travel time the electrical and thermal needs take intermediate values to maintain the shape of the curves.

The time slices are now 23 = 11.5 hours, i.e. 11 hours of travel and a half hour layover (at 12th half an hour).

7.2.1 Conventional

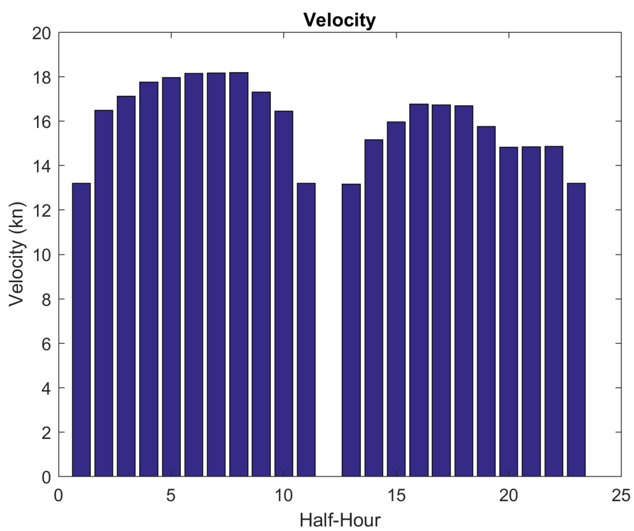


Figure 7.12: Velocity

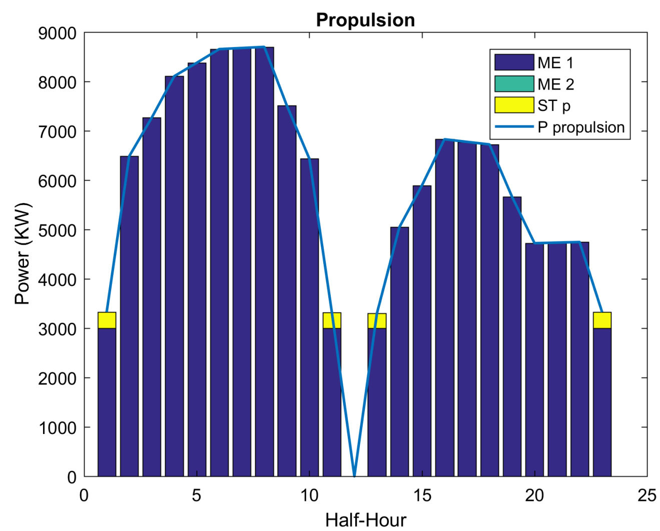


Figure 7.13: Propulsion Power

The extra time given allows the speed to be distributed so that it is not needed to operate the 2nd and more expensive main engine. During the periods when the ship is close to the port and the propulsion power must be low, which forces the main engine 1 to operate at a non-efficient point, the cogeneration power is used to cover propulsion needs, as the latter presents a higher specific consumption than the diesel generator.

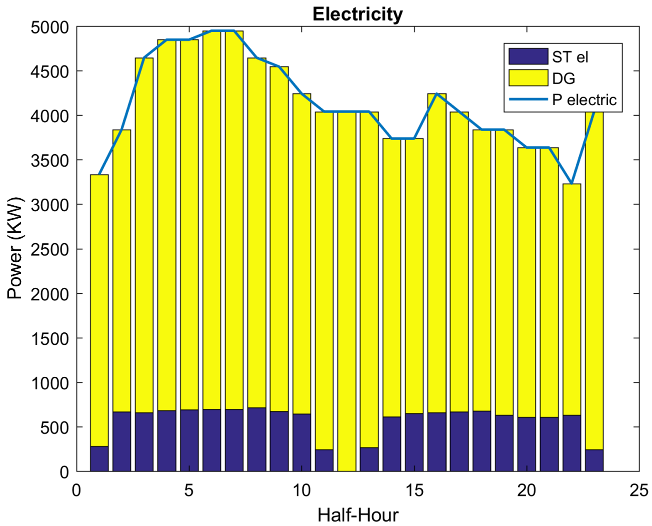


Figure 7.14: Electric Power Needs and Coverage

When offshore, the benefit in grams of fuel is greater when the turbine power is converted to electricity reducing the load that the diesel generator has to cover, so this practice is chosen by the optimizer.

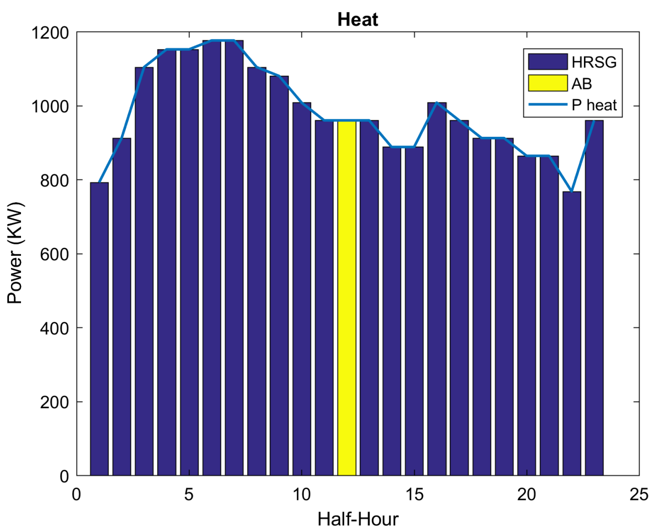


Figure 7.15: Heating Power Needs and Coverage

Again, when the ship is moving, the exhaust gasses thermal power is enough to cover heating needs. When the stepover occurs, the auxiliary boiler operates.

7.2.2 Electric Propulsion

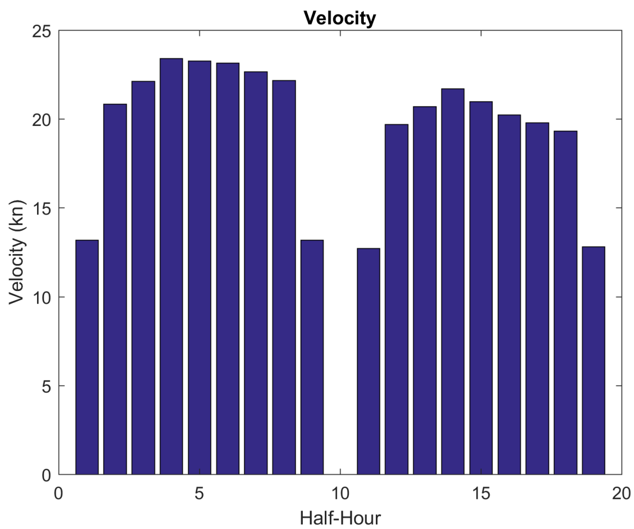


Figure 7.16: Velocity

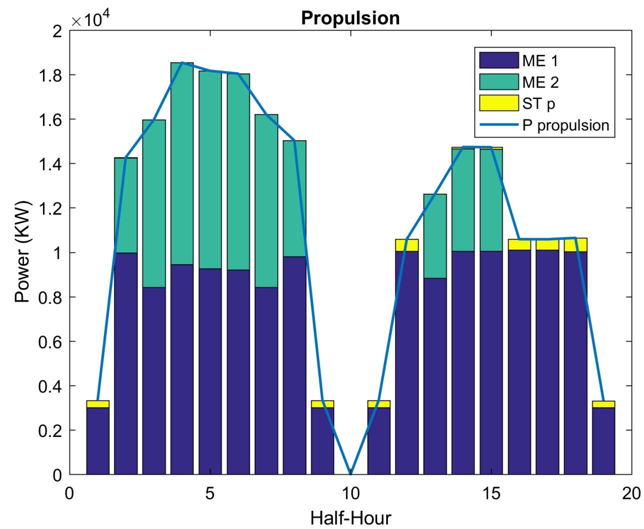


Figure 7.17: Propulsion Power

In the first leg the speed is gradually increased so that the propulsive power is low and allows the battery to charge to lighten the load of the engines when the speed will increase in the open sea. It is also observed that the speed is kept constant at the 2nd leg of the journey. This happens so that the sum of the electric propulsion power and the electrical needs is kept at such a level that, with the help of the battery, only the 1st main engine operates.

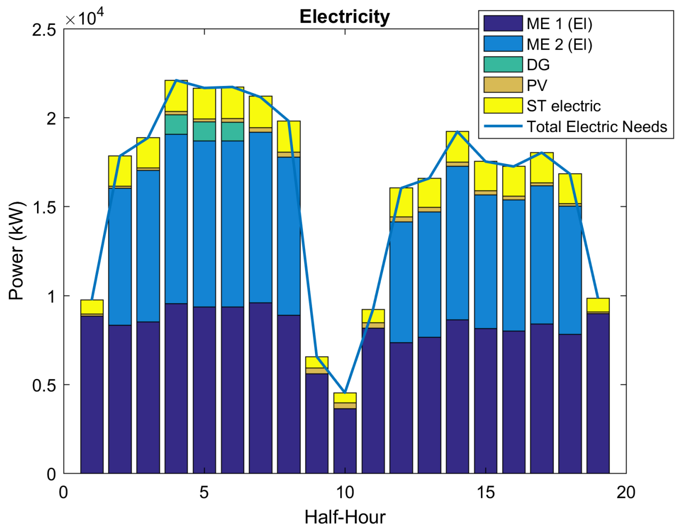


Figure 7.18: Electric Power Distribution

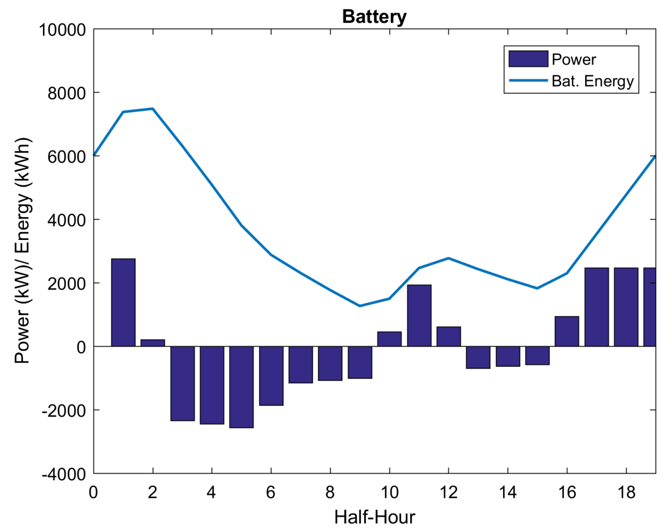
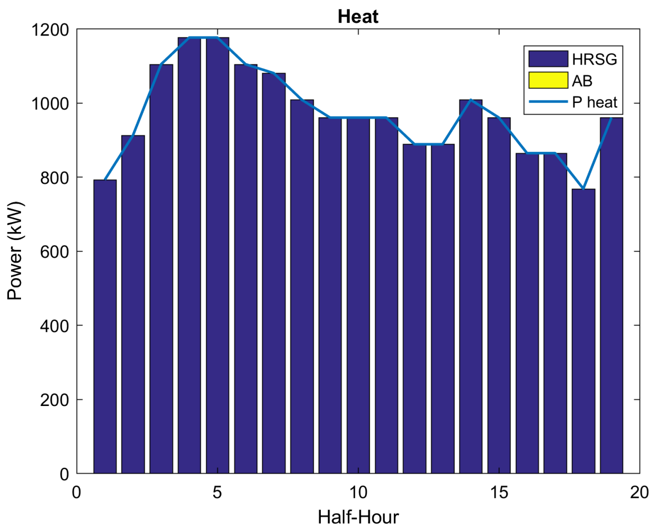


Figure 7.19: Battery Power / Energy

It is found that at points where the system does not require much power, such as when the ship is near a port, the battery charges to push the engine to operate at a point with lower specific consumption as in time slices 1, 11, 12, 13, 23 .In the points mentioned above the power stored has been produced in the most economical way possible (from the cheapest engine at its optimum operating point). So, when it discharges, it will cover power that would be produced in a non-optimal way, ultimately leading to an economic benefit for the system.



Again, because the 1st main engine is open during the entire trip and the thermal power of the cogeneration is sufficient to cover the needs, the boiler is not started.

7.2.3 Comparison of Energy Systems

	Slow Steaming	
	Conventional	Hybrid
Propulsive energy (mech) (kWh)	67,322	67,826
electrical energy (hotel services) (kWh)	47,474	47,474
Sum (kWh)	114,796	115,300
Electric energy for propulsion (kWh)	-	70,652
Energy produced by power plants (kWh):		
ME 1	66,683	91,306
ME 2	0	14,820
DG	40,948	0
Sum	107,631	106,126
Energy produced by CCP (kWh)	7,164	11,122
Energy produced by photovoltaics (kWh)	-	2,485
Total Cost	17,025 €	14,674 €

The conventional ship uses the diesel generator as the main means to cover the electrical needs, which however does not allow the exploitation of the exhaust gases produced with its operation. This is why while overall the engines produce almost similar amounts of energy, electric, which receives work only from the main engines, enjoys considerably more energy than cogeneration. Finally, the energy from photovoltaics covers 2% of the total electricity needs.

Percentage cost difference between conventional and electric in the 2nd scenario: 14.832 %

7.3 Comparison of Scenarios

7.3.1 Conventional

	Conventional	
	High Speed	Slow Steaming
Propulsive energy (mech) (kWh)	106,993	67,322
electrical energy (hotel services) (kWh)	38,788	47,474
Sum (kWh)	145,781	114,796
Energy produced by power plants (kWh):		
ME 1	72,879	66,683
ME 2	32,320	0
DG	29,532	40,948
Sum	134,731	107,631
Energy produced by CCP (kWh)	11,048	7,164
Total Cost	21,210 €	17,025 €

The slow steaming tactic brings significant economic benefits by drastically reducing the energy required to move the ship from 107,000 kWh to just over 67,000 kWh. Electricity needs for auxiliary functions and heat needs increase as the ship travels for longer time. In the second scenario, the second main engine is not used at all, which is more expensive, so the start/stop costs are also avoided.

The total reduction in energy needs for propulsion and electricity is 23.78%

The reduction in total travel cost is 21.89%

7.3.2 Electric Propulsion (Hybrid Energy System)

	Hybrid	
	High Speed	Slow Steaming
Propulsive energy (mech) (kWh)	107,269	67,826
electrical energy (hotel services) (kWh)	38,788	47,474
Sum (kWh)	146,047	115,300
Electric energy for propulsion (kWh)	111,739	70,652
Energy produced by power plants (kWh):		
ME 1	77,431	91,306
ME 2	57,653	14,820
DG	1,598	0
Sum	136,682	106,126
Energy produced by CCP (kWh)	13,689	11,122
Energy produced by photovoltaics (kWh)	2,005	2,485
Total Cost	19,130 €	14,674 €

Similarly to conventional, slow steaming reduces the propulsion energy from 107,000 kWh to just over 67,000 kWh. The less power required, the smaller the losses in electric motors and generators, since they are defined as a percentage of the power produced. Electricity needs for auxiliary functions and heat needs increase as the ship travels for a longer period of time (The duration of the trip is 11.5 hours compared to 9.5 in the first scenario).

The total reduction in energy needs for propulsion and electricity is 23.53%

The reduction in total travel cost is 26.36%

Chapter 8

Conclusions

According to the results of the scenarios studied, the electric propulsion ship requires more energy during the voyage due to the losses in the conversion of mechanical to electrical power in the generator and electrical to mechanical power in the electric motor. Thanks to the advancement of technology in electric engines,generators and power electronics the losses for converting and transforming energy are minimal.The main engines produce this energy with less fuel due to the variable operating speeds allowed by the decoupling from the propeller and due to the increased degrees of freedom offered to the system by the "fusion" of propulsion power with electric power and the possibility of energy storage. Apart from the economic benefits, electric propulsion ships are more maneuverable and the engines are less strained. Especially near ports where the propulsion power is low, the electric propulsion ship can cover all its needs (propulsion, electrical, thermal) with the operation of a single engine and the cogeneration system resulting in less exhaust gasses at a lower temperature and less noise nearby residential areas.

Slow steaming brings significant economic benefits by drastically reducing the energy required to move the ship, even though electricity needs for auxiliary functions and heat needs increase as the ship travels for longer. The slower the ship moves, i.e. the more strictly slow steaming is applied, the greater the benefit of the electric ship compared to conventional, because when the load factor is low the difference in specific consumption between constant and variable speed engines is maximized. So the electric propulsion ship's optimal operation point coincides with the slow steaming practice and its benefits.

The Cogeneration System utilizes main engines waste heat which otherwise would be lost, saving the system from operating at least one more power plant, the boiler, for covering thermal needs while also in most cases contributes to the electric and/or propulsion needs. Furthermore, the exhaust fumes exiting the ship have significantly less temperature worsening the climate of areas near the ports less.

The battery allows power plants to operate more optimally improving the fuel efficiency of the produced energy and therefore the overall cost. Additionally,it can discharge during short periods of high energy demand covering load that would otherwise be covered inefficiently while saving for those power plants' opening and closing costs.

The photovoltaics produce a vary small amount of energy compared to the total, due to limited space and varying orientation. Their contribution becomes more significant the more strictly slow steaming is applied because the energy demands are decreasing.

As long as all-electric energy systems are not economically and practically viable on large scale vessels, hybrid energy systems with electric propulsion will play an important role in achieving more economical sea travel by providing an improved alternative to conventional and showing the way to the future of shipping.

Bibliography

[1] M.A. Boles and D. Yunus A. Cengel. *Thermodynamics: An Engineering Approach*. McGraw-Hill Education, 2014.

[2] Mamadou Baïlo Camara and Brayima Dakyo. Coordinated control of the hybrid electric ship power-based batteries/supercapacitors/variable speed diesel generator. *Energies*, 16(18), 2023.

[3] Simone Castellan, Roberto Menis, Alberto Tessarolo, Fabio Luise, and Teresa Mazzuca. A review of power electronics equipment for all-electric ship mvdc power systems. *International Journal of Electrical Power & Energy Systems*, 96:306–323, 2018.

[4] Ahmed G. Elkafas, Mohamed M. Elgohary, and Akram E. Zeid. Numerical study on the hydrodynamic drag force of a container ship model. *Alexandria Engineering Journal*, 58(3):849–859, 2019.

[5] A.B. Gallo, J.R. Simões-Moreira, H.K.M. Costa, M.M. Santos, and E. Moutinho dos Santos. Energy storage in the energy transition context: A technology review. *Renewable and Sustainable Energy Reviews*, 65:800–822, 2016.

[6] R.D. Geertsma, R.R. Negenborn, K. Visser, and J.J. Hopman. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Applied Energy*, 194:30–54, 2017.

[7] Fotis D. Kanellos, Amjad Anvari-Moghaddam, and Josep M. Guerrero. A cost-effective and emission-aware power management system for ships with integrated full electric propulsion. *Electric Power Systems Research*, 150:63–75, 2017.

[8] Fotis D Kanellos, John M Prousalidis, and George J Tsekouras. Control system for fuel consumption minimization–gas emission limitation of full electric propulsion ship power systems. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 228(1):17–28, 2014.

[9] Fotis D. Kanellos, George J. Tsekouras, and John Prousalidis. Onboard dc grid employing smart grid technology: challenges, state of the art and future prospects. *IET Electrical Systems in Transportation*, 5(1):1–11, 2015.

[10] Hyun-Keun Ku, Chang-Hwan Park, and Jang-Mok Kim. Full simulation modeling of all-electric ship with medium voltage dc power system. *Energies*, 15(12), 2022.

[11] Hai Lan, Shuli Wen, Ying-Yi Hong, David C. Yu, and Lijun Zhang. Optimal sizing of hybrid pv/diesel/battery in ship power system. *Applied Energy*, 158:26–34, 2015.

[12] J. M. Prousalidis, G. J. Tsekouras, and F. Kanellos. New challenges emerged from the development of more efficient electric energy generation units. In *2011 IEEE Electric Ship Technologies Symposium*, pages 374–381, 2011.

[13] George N. Sakalis and Christos A. Frangopoulos. Intertemporal optimization of synthesis, design and operation of integrated energy systems of ships: General method and application on a system with diesel main engines. *Applied Energy*, 226:991–1008, 2018.

[14] G.J. Tsekouras and F.D. Kanellos. Optimal operation of ship electrical power system with energy storage system and photovoltaics: Analysis and application. *WSEAS Transactions on Power Systems*, 8(4):145 – 155, 2013.

[15] Andreas Wiesmann. Slow steaming– a viable long-term option?, 2010.

Bibliography

Image Bibliography

[1] (Fig. 2.3) Comparison of Electric (EV) and Fossil Fuel (Gasoline-Diesel) Vehicles in Terms of Torque and Power, ResearchGate https://www.researchgate.net/figure/Torque-Curves-of-Electric-Motor-and-Internal-Combustion-Engine-2-The-electric-motors-can_fig5_370553199

[2] (Fig. 3.1) Temperature Entropy (T-s) Diagram , https://www.engineersedge.com/thermodynamics/temp_enthalpy_th_diagram.htm

[3] (Fig. 3.2) Boles, M.A. and Yunus A. Cengel, D., Ideal Rankine Cycle, Engineering Thermodynamics

[4] (Fig. 3.3) Boles, M.A. and Yunus A. Cengel, D., Ideal and Actual Rankine Cycle, Engineering Thermodynamics

[5] (Fig. 3.4) Boles, M.A. and Yunus A. Cengel, D., Ideal Rankine Cycle, Engineering Thermodynamics

[6] (Fig. 3.6) Heat Recovery Steam Generator cross section, ChemicalEngineeringWorld https://chemicalengineeringworld.com/heat-recovery-steam-generator-hrsg/

[7] (Fig. 4.3) Specific fuel consumption graph for representative diesel generator versus engine speed and load, ResearchGate https://www.researchgate.net/figure/Specific-fuel-consumption-graph-for-representative-diesel-generator-versus-engine-speed_fig2_241091063

[8] (Fig. 4.4) Kanellos, Fotis D. and Tsekouras, George J. and Prousalidis, John, SFOC for fixed-speed and variable rpm, Onboard DC grid employing smart grid technology: challenges, state of the art and future prospects, SFOC curve for fixed and variable speed operation

[9] (Fig. 4.6) Boles, M.A. and Yunus A. Cengel, D., Ideal Rankine Cycle, Engineering Thermodynamics

[10] (Fig. 5.1) Bloomberg, Lithium Battery Prices Plunge, Statista https://www.statista.com/chart/23807/lithium-ion-battery-prices/ , Li-ion batteries price over time

[11] (Fig. 5.2) Energy.gov, Energy Density of Lithium-ion battery packs 2008-2020, https://www.energy.gov/eere/vehicles/articles/fotw-1234-april-18-2022-volumetric-energy-density-lithium-ion-batteries, Li-ion batteries energy density over time

[12] (Fig. 5.3) Semiconductor Technology, n Doping with phosphorus, https://www.halbleiter.org/en/fundamentals/doping/, n-junction chemical bonds

[13] (Fig. 5.4) Semiconductor Technology, p Doping with boron, https://www.halbleiter.org/en/fundamentals/doping/,n-junction chemical bonds

[14] (Fig. 5.5) Planete Energies, How Does a Photovoltaic Cell Work ?, https://www.planete-energies.com/en/media/article/how-does-photovoltaic-cell-work,Photovoltaic cell cross-section and operation

[15] (Fig. 5.6) Hai Lan and Shuli Wen and Ying-Yi Hong and David C. Yu and Lijun Zhang, Optimal sizing of hybrid PV/diesel/battery in ship power system , Solar Radiation during the day