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Methodology to Evaluate the Potential Reduction of CO_2 Emissons in Hybrid Powered Ships

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This work is dedicated to my family.

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"It is the supreme art of the teacher to awaken joy in creative expression and knowledge."

(Albert Einstein)

Resumo

Segundo o relatório Emission Database for Global Atmospheric Research (EDGAR) de 2021, as emissões dos navios já ocupam a oitava posição no ranking dos maiores emissores mundiais. Embora a Organização Marítima Internacional (IMO) tenha estabelecido em 2008, uma meta ambiciosa de reduzir em 40% as emissões de CO_2 até 2030, a falta de uma preocupação global com as emissões dos navios levou a um crescimento de 18% nas emissões de CO_2 entre 2008 e 2021. Isso mostra que há um longo caminho a ser percorrido na redução das emissões dos navios para que se atinja a meta do IMO.

Neste trabalho iremos analisar o sistema de potência de um navio, o navio analisado neste trabalho é um Platform Supply Vessel (PSV), que é um navio que suporta plataformas de óleo e gás. Normalmente, o sistema de potência desse navio é formado por quatro geradores divididos em dois ramos separados por um elo de barramento que em operações de posicionamento dinâmico é mantido aberto. É proposto neste trabalho o uso de baterias como reserva de energia para que a operação com o elo de barramento fechado possa ser realizada. As cargas do navio são as cargas de hotelaria, iluminação, cargas de posicionamento(gps e radares) e os propulsores. As soluções analisadas incluem geradores auxiliares, sets de gerador com tamanhos diferentes e baterias, além da redução de velocidade em trechos de viagem.

O principal objetivo deste trabalho é desenvolver uma metodologia para avaliar o potencial de redução de emissão de CO_2 que cada solução pode alcançar. Para desenvolver essa metodologia, são necessários dados de demanda, dados do navio, curvas de consumo dos geradores e dados da bateria. Através dos resultados obtidos com o uso dessa metodologia, nós conseguimos estimar o potencial de redução de emissões de CO2 e de consumo de diesel em navios novos e em navios existentes. Para realizar cada passo dessa metodologia é necessária uma otimização que considere os diferentes pontos de eficiência do gerador. A otimização usada nesse trabalho é através do software HOMER PRO. Como objetivos secundários, temos o desenvolvimento de modelos que estimem o combustível consumido, as emissões de CO_2, e a vida útil da bateria desconsiderando o envelhecimento.

Primeiramente, esta metodologia possibilitará a avaliação, de qual grupo gerador apresenta a maior redução de combustível em cada parte da missão, esta primeira análise irá considerar um despacho ótimo utilizando bateria apenas como reserva, para calcular o consumo em cada trecho da missão o software HOMER será usado. Além disso, a partir de uma análise estatística dos valores da demanda, é possível obter o melhor set de geradores que se encaixaria considerando os valores de demanda da curva da missão. Como resultado, obtemos o mesmo set de geradores tanto para a análise de consumo quanto para a análise estatística.

Como resultado dessa primeira fase, o uso de um set composto de geradores com diversos tamanhos, nomeado como CASE4, mostrou a maior redução de consumo em relação ao set de geradores composto de apenas um tamanho (1820kW). Além da redução em consumo, esse set também obteve ganhos em relação ao tempo em que os geradores operam abaixo de 50%. É mostrado que mesmo quando a operação de posicionamento dinâmico ocorre sem o despacho otimizado, o uso do CASE4 obteve reduções consideráveis em relação ao consumo.

Em seguida, o despacho da bateria será considerado, avaliando diferentes profundidades de descarga, eficiencias de carga e descarga e tamanhos de bateria. Esses despachos serão avaliados para cada set de geradores analisado no passo anterior.

O despacho de baterias não promove redução de consumo quando aplicada durante operações de viagem. Por outro lado durante operações de baixa carga, como carregamento no porto e espera, o uso de baterias pode promover uma redução de consumo maior do que a obtida apenas com o despacho ótimo para alguns dos casos analisados, o mesmo ocorre quando a bateria é despachada durante a operação de posicionamento dinâmico. Nessas duas primeiras partes da metodologia, a redução de consumo durante os trechos de viagem é percentualmente baixa, considerando que os trechos de viagem são os trechos de maior consumo, uma outra solução que possa promover reduções de consumo maiores deve ser analisada.

A solução proposta é a avaliação da redução da velocidade do navio. A velocidade do navio PSV é calculada usando os dados de projeto de um PSV real. A partir desses dados, uma curva relacionando potência e velocidade é gerada. Como não tínhamos uma curva real, apresentamos também uma análise para navios-tanque reais. A partir desta análise, avaliamos os resultados apresentados para a redução da velocidade de um navio PSV.

Uma redução relativamente pequena (5%) na velocidade trafegada promove diminuições consideráveis no consumo no caso de navios existentes (12.4% - 13.8%) e em navios novos (16.8% - 17.3%). Essas reduções podem ser ainda maiores se uma redução de velocidade de 10% for analisada, para navios existentes o consumo de diesel pode ser entre 24.1% e 25.2% menor do que o consumo quando o navio opera na velocidade base analisada. Para navios novos esses números são ainda maiores, chegando a valores entre 27.1% e

28.4% dependendo do tipo de viagem analisada. Por fim, as reduções de consumo obtidas quando a velocidade é reduzida em 15% também são mostradas.

Palavras-chave: Redução de emissões de CO_2 em navios, Navios de suporte a plataforma, baterias, redução da velocidade do navio.

Abstract

According to the 2021 Emission Database for Global Atmospheric Research (EDGAR) report, emissions from ships already occupy the eighth position in the ranking of the world's largest emitters. Although the International Maritime Organization (IMO) set in 2008 an ambitious goal of reducing emissions by 40 percent by CO_2 percent by 2030, the lack of global concern for emissions from ships has led to an 18 percent growth in emissions of CO_2 percent between 2008 and 2021. This shows a long way to go in reducing ship emissions to reach the IMO target.

In this work, we will analyze the power system of a ship. The ship analyzed in this work is a Platform Supply Vessel (PSV), which is a ship that supports oil and gas platforms. Typically, the power system of this ship consists of four generators divided into two branches separated by a bus tie breaker that, in dynamic positioning operations, is kept open. It is proposed in this work to use batteries as a power reserve so that the operation with the closed bus-tie breaker can be carried out. The ship's cargoes are the hotel loads, lighting, positioning loads (GPS and radars), and thrusters. The solutions analyzed in this work include auxiliary generators, generator sets with different sizes and batteries; the speed reduction in voyage operations is also evaluated.

The main objective of this work is to develop a methodology to evaluate the potential for emission reduction of CO_2 that each solution can achieve. Demand data, ship data, generator consumption curves, and battery data are required to develop this methodology. Through the results obtained with this methodology, we were able to estimate the potential for reducing CO2 emissions and diesel consumption in new and existing ships. To carry out each step of this methodology, an optimization that considers the different efficiency points of the generator is required. The optimization used in this work is through the HOMER PRO software. As secondary objectives, we have the development of models to estimate the fuel consumed, the CO_2 emissions, and the battery lifespan without aging.

Firstly, this methodology will enable the evaluation of which generator set presents the greatest fuel reduction in each part of the mission. This first analysis will consider an optimal dispatch using a battery only as a reserve. The HOMER software will be used to calculate the consumption in each part of the mission. In addition, from a statistical analysis of the demand values, it is possible to obtain the best set of generators that would fit, considering the demand values of the mission curve. As a result, we get the same set of generators for both consumption and statistical analysis.

As a result of this first phase, the use of a set composed of generators with various sizes, named CASE4, showed the greatest reduction in consumption to the set of generators comprising only one size (1820kW). In addition to the reduction in consumption, this set also obtained gains in relation to the time the generators operate below 50%. It is shown that even when the dynamic positioning operation occurs without the optimized dispatch, the use of CASE4 has achieved considerable reductions to consumption.

Next, the dispatch of the battery will be considered, evaluating different depths of discharge, round-trip efficiencies, and battery sizes. These dispatches will be evaluated for each set of generators analyzed in the previous step. The dispatch of batteries does not promote consumption reduction when applied during voyage operations. On the other hand, during low-load operations, such as loading in port and standby, batteries can promote a greater consumption reduction than obtained only with the optimal dispatch for some of the cases analyzed. The same occurs when the battery is dispatched during the dynamic positioning operation. In these first two parts of the methodology, the consumption reduction during the voyage operation has a lower percentage reduction. Considering that voyages are the parts of the mission with greater consumption, another solution that can promote greater consumption reductions should be analyzed.

The proposed solution is the evaluation of the reduction of the ship's speed. The PSV ship's speed is calculated using an actual PSV's design data. From this data, a curve relating power and speed is generated. Since we didn't have a real curve, we also presented an analysis for real tankers. From this analysis, we evaluate the results presented for reducing the speed of a PSV vessel.

A relatively small reduction (5%) in the speed traveled promotes considerable decreases in consumption in the case of existing ships (12.4% - 13.8%) and in new ships (16.8% - 17.3%). These reductions can be even greater if a speed reduction of 10% is analyzed; for existing ships, the diesel consumption can be between 24.1% and 25.2% lower than the consumption when the ship operates at the base speed analyzed. For new ships, these numbers are even higher, reaching values between 27.1% and 28.4%, depending on the type of voyage operation analyzed. Finally, the consumption reductions obtained when the speed is reduced by 15% are also shown.

Keywords: Ship CO_2 emissions, Platform Supply Vessel, Batteries, Ship speed reduction.

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AC Alternate Current

AES Advanced Storage System

AVR Automatic Voltage Regulator

AP Adjustable Pitch

CII Carbon Intensity Indicator

CO_2 Carbon Dioxide

CNG Carbon Neutral Growth

CPP Controllable Pitch Propeller

DC Direct Current

DoD Depth of Discharge

DP Dynamic Positioning

DMFC Direct Methanol Fuel Cell

ECAs Emission Control Areas

ESS Energy Storage System

EEA European Economic Area

EU European Union

ESRDC Electric Ship Research and Development Consortium

EEDI Energy Efficiency Design Index

EEXI Energy Efficiency Existing Ship Index

FPP Fixed Pitch Propeller

GHG Greenhouse Gases

GDP Gross Domestic Product

HFO Heavy Fuel Oil

HOMER Hybrid Optimization of Multiple Energy Resources

HFAC High Frequency Alternate Current

IEA International Energy Agency

IMO International Maritime Organization

IPCC International Panel on Climate Change

IPS Integrated Power Systems

INV Inverters

INTERANKO International Association of Independent Tanker Owners

LVDC Low Voltage Direct Current

LFP Lithium Iron Phosphate

LTO Lithium Titanate Oxide

LNMC Lithium Nickel Manganese Cobalt

LNG Liquified Natural Gas

LP Loading in Port

LV Laden Voyage

MARPOL International Convention for the Prevention of Pollution from Ships

MATLAB Matrix Laboratory

MCFC Molten Carbonate Fuel Cell

MEPC Marine Environment Protection Committee

MPP Maximum Power Point

MPPT Maximum Power Point Tracker

MVDC Medium Voltage Direct Current

MVAC Medium Voltage Alternate Current

NREL National Renewable Energy Laboratories

NO_x Nitrogen Oxide

NDCs Nationally Determined Contributions

OCIMF Oil Companies International Marine Forum

PLL Phase Loop Lock

PEMFC Proton-Exchange Membrane Fuel Cell

PMS Power Management System

PM Particulate Matter

PV Photovoltaic

PSV Platform Supply Vessel

PLV Partial Load Voyage

REC Rectification

RTE Round Trip Efficiency

STATCOM Static Var Compensator

SEEMP Ship Energy Efficiency Management Plan

SOFC Solid Oxide Fuel Cell

SOC State of Charge

SCR Selective Catalytic Reduction

SO_x Sulphur Oxide

SO_2 Sulphur Dioxide

SO_3 Sulphur Trioxide

ST Standby

THD Total Harmonic Distortion

UNFCCC United Nations Framework Convention on Climate Change

UPS Uninterruptable Power Supply

VSC Voltage Source Converter

VP Variable Pitch

VSRIP Vessel Speed Reduction Incentive Program

VA Virtual Arrival

VSDG Variable Speed Diesel Generators

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Chapter 1

Introduction

This work aims at developing a methodology to evaluate the impact that different approaches would have on the CO_2 emission. Firstly, this chapter will describe an overview of ship emissions, then it will describe the PSV characteristics, its mission profile, and standard power system. Moreover, this chapter will describe the HOMER software used in this work to obtain the optimal energy dispatch.

1.1 Overview of Ship Emissions

This section aims at presenting an overview of ship emissions, this overview will focus on the three main pollutants presenting the limits established by international organizations and the solutions available in the literature.

Fig. 1.1 shows a timeline of the actions taken to reduce GHG emissions in ships. As can be seen, the first COP of the UNFCCC discussed maritime transport emissions in 1995. Two years after this first mention, COP 3 allocated maritime transport emissions to the IMO, this COP happened in Kyoto and was famous for the adoption of the Kyoto Protocol. This protocol was the first to introduce emissions limits and an agenda to prevent further global warming (SPRINGER, 2003) but did not indicate limits to maritime emissions.

The Kyoto Protocol was adopted in 1997 at the Kyoto Conference. This protocol was the first to introduce emissions limits and an agenda to prevent further global warming (SPRINGER, 2003). Moreover, the Kyoto Protocol brought in some mechanisms such as the International Emission Trading (IET), the Joint Implementation, and the Clean Development Mechanism (CDM) (BÖHRINGER, 2003). IET allowed industrialized countries, included in Annex B of the protocol, to buy and sell their assigned emissions.

The joint implementation mechanism allowed governments to develop projects that reduced emissions in other countries to earn emission reduction units (ERUs). In addition, the Clean Development Mechanism focuses on the relations between countries of Annex B and developing countries. Thanks to this mechanism, developing countries could sell

Certified Emission Reduction (CER) units to an industrialized nation. Unfortunately, the final deal did not set an objective for emissions reduction in the international shipping sector.

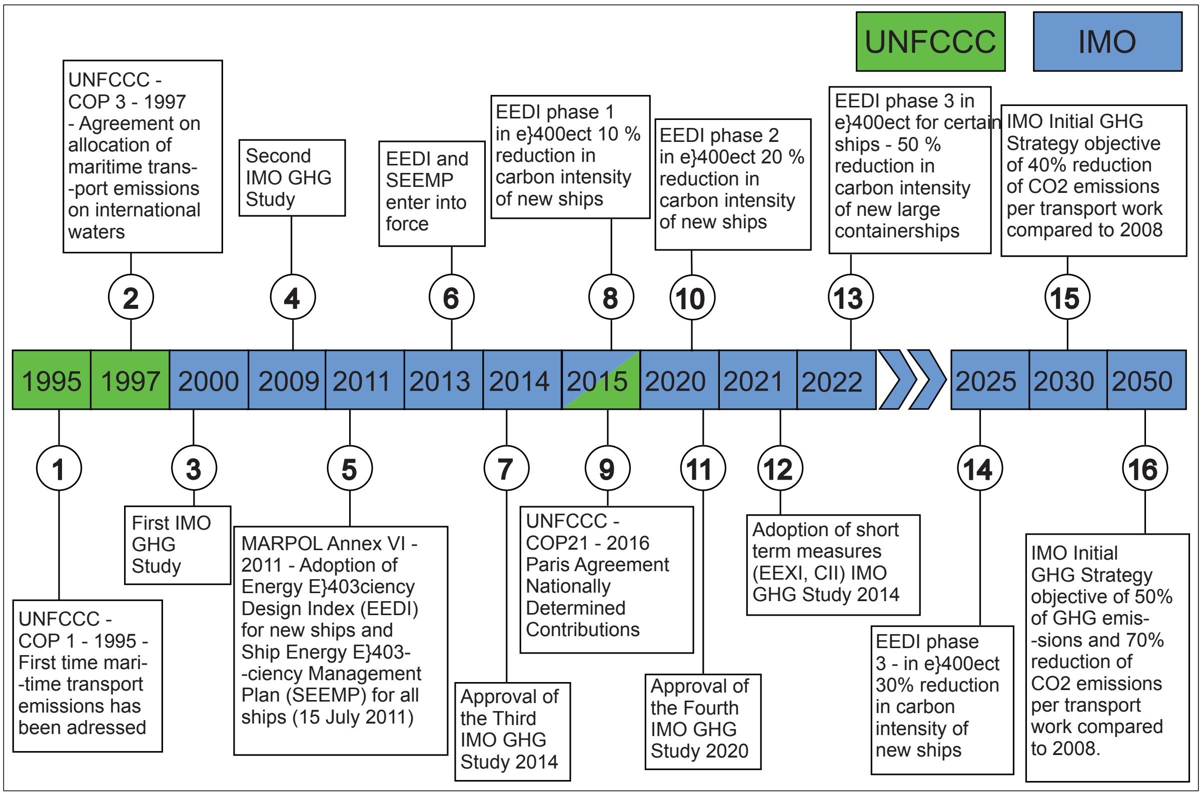


Figure 1.1 – Timeline of GHG emission reduction actions taken from IMO and UNFCCC (M. et al., 2022). Source: Author.

Three years after COP 3, the IMO presented their first study about GHG emissions. This study estimated that about 1.8% of the world's total CO_2 emission in 1996 was caused by ships engaged in international trade. According to (PSARAFTIS; KONTOVAS, 2020), this study evaluated two approaches, the first considered a fuel-consumption methodology, and the second used a statistical emission model. This first study was important to increase the research production about maritime GHG emissions (ENDRESEN et al., 2007; ENDRESEN et al., 2003; CORBETT; KOEHLER, 2003; EYRING et al., 2005; OBERTHÜR, 2003; EYRING et al., 2005).

IMO performed the second GHG study in 2009. In this study, around 2.7% of global CO_2 emission originated from international shipping according to data from 2008. In 2011, the International Convention for the Prevention of Pollution from Ships (MARPOL) adopted actions to evaluate other ships, creating a comparative group that would establish a minimum energy efficiency standard; this action was called Energy Efficiency Design Index (EEDI) and embedded around 85% of emissions from international shipping. New ships should present a reduced carbon intensity compared to these ships. This carbon intensity reduction would vary according to each phase of this project. Besides EEDI, IMO also adopted Ship Energy Efficiency Management Plan (SEEMP), whereas the first was developed only for new ships, the former included all ships. EEDI is the most important technical evaluation, promoting a comparison evaluating the energy efficiency level per capacity mile. On the other hand, SEEMP is an operational measure that cost-effectively analyzes ships. Even though these initiatives were adopted in 2011, they entered into force in 2013.

In 2014, the third study regarding CO_2 emissions from ships, in this investigation IMO found that around 2.2% of global emissions were emitted from international shipping. The next year had actions from the UNFCCC and the IMO. The UNFCCC presented at COP 21, the Paris Agreement. The signatory countries of the Paris Protocol agreed to keep the global average temperature increase limited at 2 °C above pre-industrial temperatures (Transport & Environment , 2016). As Kyoto Protocol, this agreement did not impose any limits to ship emissions (European Parliament, 2015). Even though the agreement does not specifically address shipping and aviation sectors, it is important to mention that, according to a recent legal evaluation of the agreement, their emissions would be controlled by each signatory country as a part of the Nationally Determined Contributions (NDCs) (DEHON, 2021). In this analysis, the IMO would not be responsible for the shipping sector's emissions but could voluntarily contribute to reducing them.

Still, in 2015, the first phase of the EEDI entered into force. From this phase, every new ship must emit 10% less carbon than a ship of the same class evaluated in 2013, when the EEDI was created. In 2020, phase two of the EEDI starts to be in effect. After this phase, new ships must emit 20% less carbon than ships evaluated in the EEDI. Still, in 2020, IMO produced its fourth GHG emission study. The highlights presented in this study are the 9.6% of GHG emissions increase from 2012 to 2018 and the increase of 9.3% of CO_2 emissions. Moreover, the survey presents that, in 2018, the emissions from ships represented around 2.9% of global anthropogenic CO_2 emissions.

In 2021, IMO adopted the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII); the first measure is applied to all vessels over 400Gt built before 1 January 2023. The EEXI is merely an EEDI for existing ships. It sets minimum requirements for technical efficiency and is based on three factors, the power of the main engine, the reference speed of the ship, and the fuel oil consumption from the test-bed. If the requirements are not met, the vessels can be detained in port, and a fine can be applied (KUBEL, 2021). The CII is applied to all ships of 5,000 gross tonnage and above. Ships of this size are already subject to the requirement for a data collection system for fuel oil consumption. Establishing the ship's operational carbon intensity reduction requires an annual reduction factor determined by the CII. This measure is a recent expansion of the SEEMP. These two measures have the same unit $\frac{CO_2}{DWT-nm}$ but cannot be compared to each other. CII is obtained from real operation whereas EEXI is accessed from a theoretical amount of fuel the ship power plant requires for propulsion.

From 2022, phase 3 of the EEDI applied to new large containerships requires a carbon reduction of 50% for these vessels. The other vessels subjected to EEDI will follow requirements for carbon intensity reduction of 30% after 2025.

IMO has set some ambitious objectives of reducing by at least 40% of CO_2 international shipping emissions by 2030, compared to the 2008 emission data. Furthermore, IMO considers that by 2050, 70% of 2008 CO_2 emissions should be reduced (IMO, 2018). Moreover, IMO aims at reducing 50% of GHG emissions by 2050.

Besides the actions taken from IMO and UNFCCC, some programs were developed without any connection to these actions. One of these programs is the Vessel Speed Reduction Incentive Program (VSRIP) that was adopted in some US ports; this project aims to reduce the ship speed in areas close to the port. Port of Los Angeles was the first to adopt this project in 2008; two regions were designed, 20 and 40 nautical miles from the port. The ships must keep their speeds lower than 12 knots in these regions. The program is based on reimbursement; in 2009, ships that accomplished reducing their speed for 40nm were eligible to receive a refund of 30% of their first day of dockage. For ships that reduced their speed only during 20nm, the refund was only 15%(Port of Los Angeles, 2008). Similar plans were adopted in other ports, such as New York, San Diego, Seattle, and South Korea(HAN; MA; MA, 2022).

Another program is the Virtual Arrival (VA), which was developed by two organizations, the Oil Companies International Marine Forum (OCIMF) and the International Association of Independent Tanker Owners (INTERANKO). This project aims at reducing the lack of space to receive ships in ports, to solve this problem, the port should send to the ship the expected amount of time that the ship would wait to be docked; with this information, the ship can reduce its speed, therefore reducing its consumption and emission(HAN; MA; MA, 2022).

Finally, the other plan implemented in recent years is the carbon tax program. Different prices per ton of CO_2 emitted are being assumed. Marshall and Solomon Islands adopted \$100 per ton since 2021. Japan plans to ask \$56 per ton after 2025. Japan's proposal aims at increasing the tax every five years. In 2030 the tax would reach \$135; in 2035, it would be \$324, and as high as \$637 per tonne by 2040 (Bloomberg Tax, 2022). In European Union (EU), shipping companies with vessels above 5,000 GT that use EU ports will be required to buy percentages of their verified emissions. 20% in 2023, 45% in 2024 and 70% in 2025, reaching 100% in 2026. These verified emissions will be calculated using 100% of the emissions from all voyages intra-EU and 50% of emissions from all voyages that start or end in an EU-port (Norton Rose Fulbright, 2021).

1.1.1 CO_2 emissions

If the regulations do not affect shipping emissions, these emissions can reach 17% of global CO_2 emissions in 2050 (Transport & Environment , 2016). It is possible to evaluate if the reduction objectives set by IMO are being followed. Every year, the European Commission releases a report comprising the previous year's emission data from most countries and the shipping and aviation sector. If we consider the 2020 report, released in 2021, and compare it to the data of 2008, which is the comparison point set by IMO. It is possible to calculate the variation in this period. For shipping emissions, there was a growth of 18.1% between these 12 years(CRIPPA et al., 2021; European Commission, 2018). Therefore, it shows that we must significantly reduce between 2020 and 2030 to accomplish the objectives set by IMO.

According to the latest report from the European Commission, the shipping sector is responsible for approximately 1.9% of global CO_2 emissions, placing this industry in the top ten ranking of CO_2 emitters, as presented in Fig 1.2 (M. et al., 2022). In Fig 1.2, a yellow bar presents the emissions for the European Union; if we considered only data of countries isolated, this data would be erased, and for that reason, it is highlighted in the graph. The black bars present data of isolated countries; their emission is presented on the vertical axis, and the respective percentage related to global emissions is displayed above the graphs. In blue, the emissions from ships are presented; if only the black bars were considered, it would be the seventh biggest CO_2 emitter.

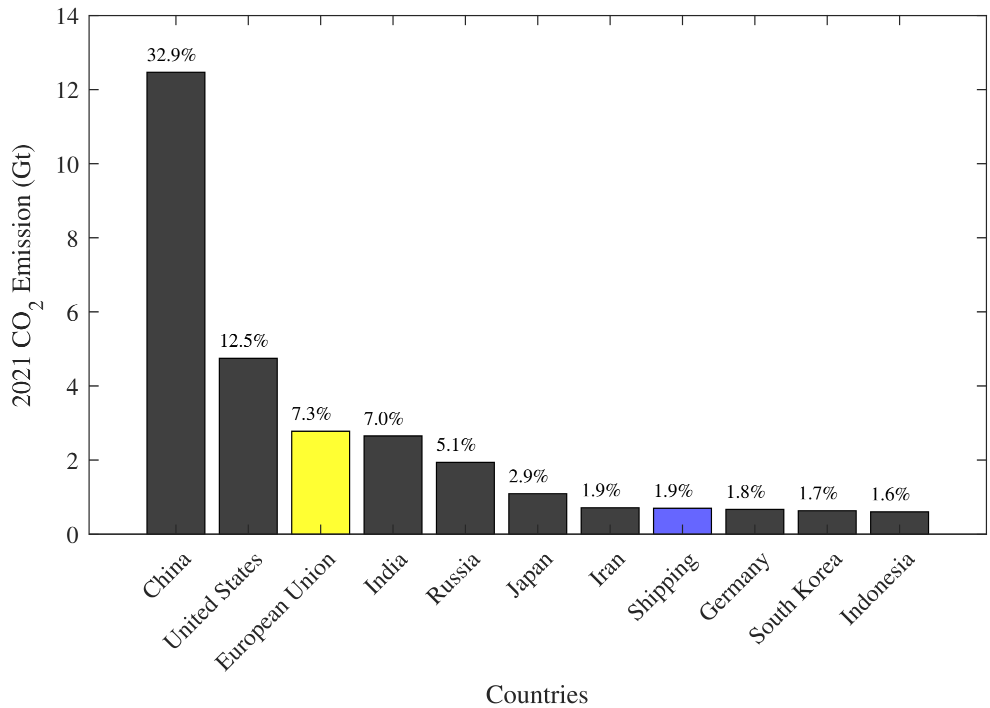


Figure 1.2 – CO_2 emissions ranking of 2021 (M. et al., 2022) .

Source: Author.

This lack of global concern on ship emission of international protocols has led some international organizations from the shipping sector, such as DNV-GL, Lloyds Register, IMO, and the United States Environmental Protection Agency, to pursue tremendous efforts on establishing limits of Nitrogen Oxide (NO_x) and Sulphur Oxide (SO_x) emissions

(WANKHEDE, 2021; ALLEN et al., 2019; United States Environmental Protection Agency, ; Diesel Net,, ; International Maritime Organization, 2009; European Commission, 2020). The regulations to reduce sulfur and nitrogen oxides emission are related to the fuel and the engine, respectively, CO_2 emissions will be controlled for monitoring ships that use European ports.

This section aims at clarifying the aspects of the recent regulations that were developed to establish limits on GHG emissions and the three main gases (CO_2, NO_x, SO_x) emitted are also discussed.

In (BEECKEN et al., 2014), a study is described in which many ships are evaluated, and the emission factors for Sulphur Dioxide (SO_2), NO_x and Particulate Material are presented. Moreover, a comparison of the emission factor among the method used to capture these emissions, and several other methods is also shown.

1.1.1.1 CO_2 emissions related to oil production and global economy

Looking at Fig. 1.3, it is possible to see that the worldwide production of oil barrels has increased in the last decades.

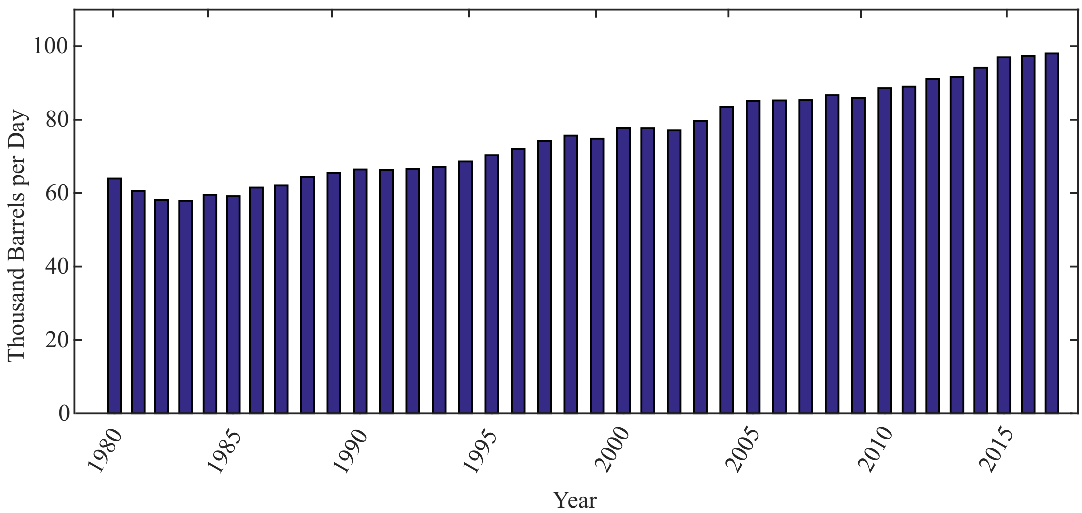


Figure 1.3 – Number of Oil barrels produced worldwide during the last 37 years. Data acquired from (U.S.Energy Information Administration, 2018)

Source: Author.

From 2007 to 2017, there was a growth of 14.93%, which can be understood as an increase in the efficiency of the platforms or as an increase in the number of platforms. This increase may signal that, in the near future, a higher number of ships will be needed to move these barrels around the world and support these platforms.

Considering the contrast between the CO_2 emissions from ships and for countries, we can analyze the perspective for the shipping sector in the next years. According to (United Nations Conference on Trade and Development (UNCTAD), 2018), it is predicted that the seaborne trade will have an annual growth of 3.2% from 2018 to 2022. This growth will force the shipping industry to increase the required new ships' efficiency to achieve the emission targets imposed by the International Maritime Organization (IMO). In (INDERPREET, 2019), a forecast was traced before the pandemic. This forecast expects a growth rate of 3.4% over the next five years. This growth is mainly driven by the expected growth between 2019-2024 on containerized and dry bulk, which is around 4.5% and 3.9%, respectively.

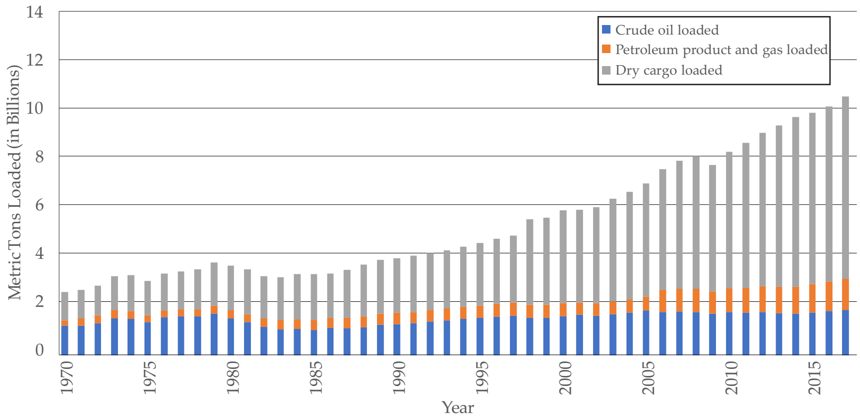


Figure 1.4 – Annual world seaborne trade from 1970 to 2017 according to the United Nations Conference on Trade and Development (United Nations Conference on Trade and Development, 2018).

Source: Author.

Figure 1.4 shows the rise of the world seaborne trade. We observe that the crude oil-loaded trade has remained stable during the 37 years analyzed and that the trade involving petroleum products and gas has slightly increased. We also observe that the dry cargo ship-loaded trade has increased very significantly.

The fact that ships are responsible for 90 % of the global trade (GREEN,) combined with the rapid growth in maritime trade (Figure 1.4) highlights the urgency of lowering CO_2 emissions from this sector.

In (KANELLOS, 2014), Kanellos presented an algorithm to optimize the energy dispatch in an all-electric ship considering constraints such as power balance, generator loading, GHG emissions, and ramp rates. The article included a cost to start the generators, which is not considered in our article. On the other hand, (KANELLOS, 2014) neither studied the potential of hybrid power systems nor investigated the influence of the minimum load level of generators.

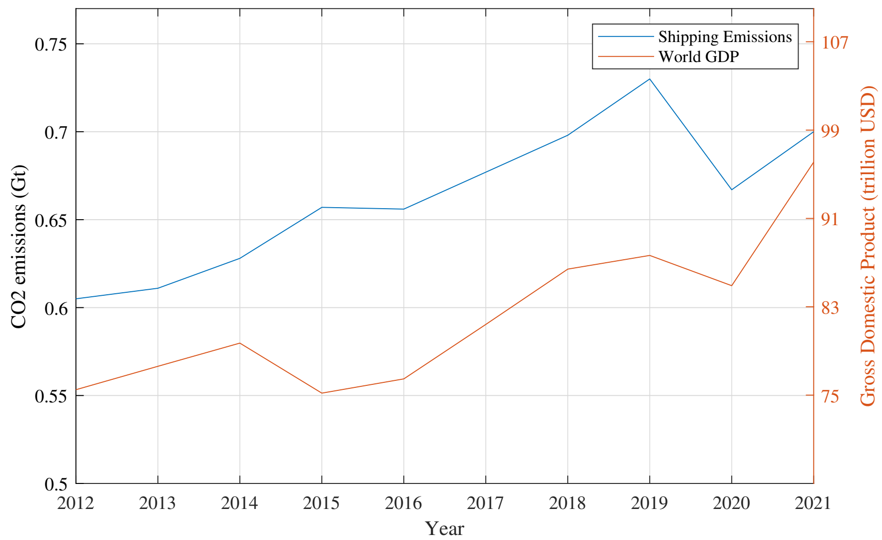


Figure 1.5 – Shipping emissions and world Gross Domestic Product between 2012 and 2021 (Data Commons, 2022; M. et al., 2022) .

Source: Author.

From 2012 to 2021, whereas the global emissions growth was around 6.6%, the growth in shipping emissions was around 13.55%. Shipping had the fourth biggest increment during this period among the ten biggest emitters. Only India, China, and Iran had a more extensive emissions expansion. Fig.1.5 presents the emission curve of the previous decade. As can be seen, there is a similar trend in the growth of shipping emissions and world GDP.

A connection between economic expansion and a trade increase between countries is explained by using ships to exchange most of these products. Fig.1.5 contrasts the shipping emissions to the world Gross Domestic Product (GDP) from 2012 to 2021. As can be seen, the trend of GDP for most of the period also reflects the same direction for shipping emissions. Only the period between 2014 and 2016 did not show the same tendency. Furthermore, the coupling tendency of this figure highlights the importance of innovative solutions to develop greener ship power systems since most ship power systems use diesel engines to supply the demand. It leads to high emission levels of CO_2 , NO_x, SO_x, and Particulate Matter (PM).

1.1.2 Other Pollutants

Evaluate NO_x, SO_x, and PM emissions is essential. Even though the emissions of NO_x and SO_x for European Union countries are reducing, the shipping emissions are increasing (KAMIL; MUSLIM; SAAT, 2020). To reduce these emissions, several international organizations developed policies applied to marine air pollution to diminish the emission of multiple pollutants (GÖSSLING; MEYER-HABIGHORST; HUMPE, 2021). Nevertheless, these emissions are believed to triplicate between 2020 and 2050. In (DENG et al., 2021), the authors review the technologies applied to reduce NO_x and SO_x emissions.

1.1.2.1 Sulfur Oxides (SO_x)

According to (WANKHEDE, 2021), sulfur oxides or (SO_x) are formed in the engine during the combustion process due to sulfur in the marine fuel. SO_x are present in the smoke emitted by the combustion of marine fuel, and the sulfuric acid is formed by the oxidization of the smoke in the presence of NO_2, which works as a catalyst.

Sulfuric acid is one of the major causes of acid rain. Nowadays, according to the MARPOL Annex VI, the global limit for sulfur content in marine fuels is 3.50% m/m (mass by mass), and it will be reduced to 0.50% m/m, effective from January 1, 2020 (International Maritime Organization(IMO), 2020; BAZARI, 2020). This limit does not change the limits of SO_x and particulate matter imposed on Emission Control Areas (ECAs) that is 0.1% m/m and has been in force since January 2015. There are four existing ECAs: the North Sea, the US Caribbean ECA, the Baltic Sea, and the Emission Control Area that includes most of the US and Canadian coast, called as North American ECA. The mainly methods to reduce the emission of (SO_x) are (CHOPRA, 2019; Transport & Environment, 2018):

1. Use of fuels with low sulfur;

2. Apply a scrubbing liquid to the exhaust gas reducing the SO_x to 95% ;

3. Finally, a good quality cylinder lubrication also achieves a SO_x emission reduction.

The European regulation has been more restrictive in recent years, with GHG and CO_2 emissions on Emission Control Areas from large ships navigating into EU ports. According to (WANKHEDE, 2021), the current global limit for sulfur content on fuel oil used in ships is 3.5% m/m (mass by mass), and the new global limit is 0.5% m/m, and it will be applied from January 1, 2020. This limit does not change the limit imposed on Emission Control Areas (ECAs), which is 0.1% m/m, and it has been in force since January 2015. Fig.1.7 shows the NO_x limits for each Tier according to the Rated Engine Speed. Tier I standards entered into force in 2000, Tier II in 2011, and Tier III in 2016. According to (Diesel Net,,), Tier I and II limits are global, whereas NO_x Emission Control Areas are covered by Tier III standards.

During the combustion process, the sulfur in the marine fuel is burnt, and sulfur oxides(SO_x) are formed in the engine and emitted to the environment (WANKHEDE, 2021). Figure 1.6 shows the SO_x limits for Global and ECAs areas.

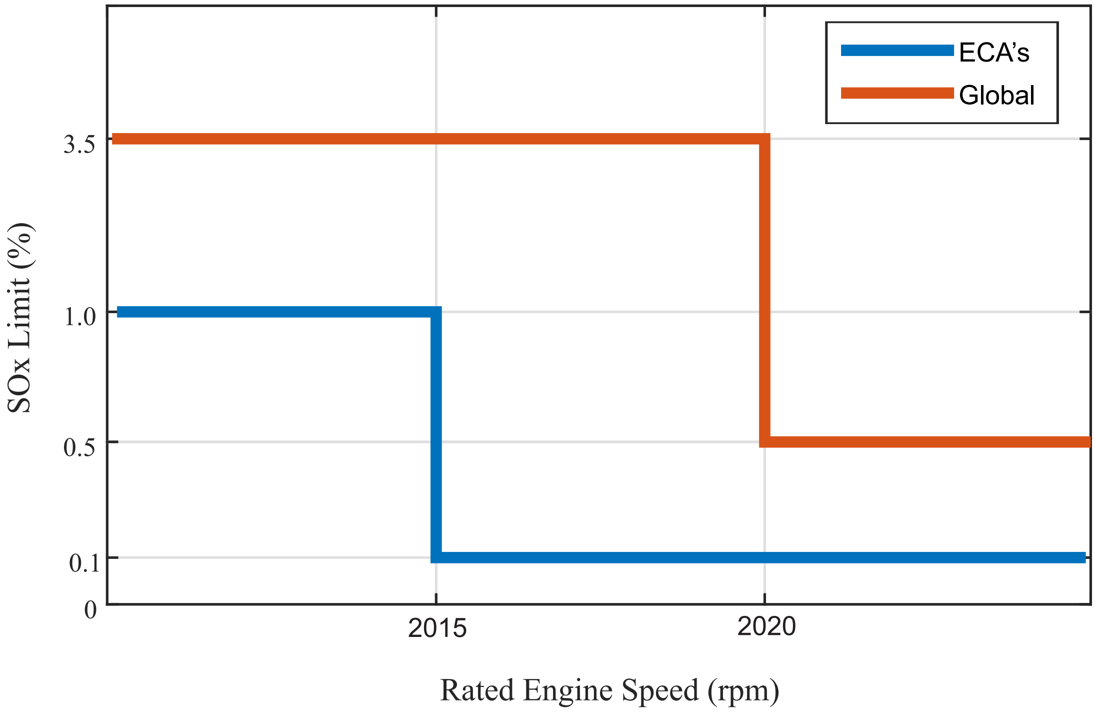


Figure 1.6 – SOx limits according to Marpol Annex VI. Global and ECAs standards entered in force in different moments and have different limits.

Source: Author.

According to (International Maritime Organization, ; **??**), the current global limit for sulfur content on fuel oil used in ships is 0.5 % m/m (mass by mass); this limit has been applied since January 1st, 2020, after a reduction from the limit of 3.5 % m/m that was applied before. This reduction did not change the limit imposed on Emission Control Areas (ECAs), which is 0.1 % m/m and has been in force since January 2015. There are four existing ECAs: the North Sea, the US Caribbean ECA, the Baltic Sea, and the Emission Control Area that includes most of the US and Canadian coast, called as North American ECA.

Among the formed sulfur oxides(SO_x), the main component is the SO_2, around 80% of the SO_x are SO_2 (ZHOU et al., 2019). SO_2 emissions are dangerous to human health and to the environment, contributing to acidification which causes severe damage to sensitive ecosystems. Another SO_x is the Sulphur Trioxide (SO_3) that reacts with rain water and produces sulfuric acid. Nitrogen Dioxide acts as a catalyst to convert SO_2 in SO_3(CLARK, 2013).

1.1.2.2 Nitrogen Oxides (NO_x)

According to (WANKHEDE, 2019), Nitrogen represents 78% of the air mixture, whereas oxygen represents 21%. At certain operation conditions, inside a marine engine, this air mixture can form Nitrogen Oxides(NO_x) that are produced by the reaction between the nitrogen and the oxygen; because of the operating conditions, it is said that this reaction is dependent on peak temperatures and high pressure in the engine cylinders - above 1200°C the formation is significant and above 1500°C it becomes rapid. However, in (LATARCHE, 2019), the main causes to form NO_x in Marine Engines are shown.

Some methods to reduce the emission of NO_x are (CHOPRA, 2019):

1. Mixing humid air to the combustion air before it goes to the cylinder it can achieve a reduction of 70-80% of NO_x;

2. Mixes the combustion air with the gases exhausted by the engine reducing the amount of oxygen present in the combustion chamber;

3. Use of water to reduce the combustion temperature. Combustion happening at high temperatures increases the formation of NO_x.

In Table 1.1 is shown the Tier division established in the MARPOL Annex VI. As can be seen in Figure 1.7, which represents Table 1.1 graphically, Tier III is the most stringent because it refers to the newest ships built since 2016. The NO_x limits varies according to the engine rotational speed.

Table 1.1 – MARPOL Annex VI NOx emission limits.

Tier	Date	NOx Limit (g/kWh)		
		n<130	130≤ n<2000	n≥2000
Tier I	2000	17	$45 * n^{-0.2}$	50
Tier II	2011	14.4	$44 * n^{-0.23}$	7.7
Tier III	2016	3.4	$9 * n^{-0.2}$	50

Adapted from (LATARCHE, 2019).

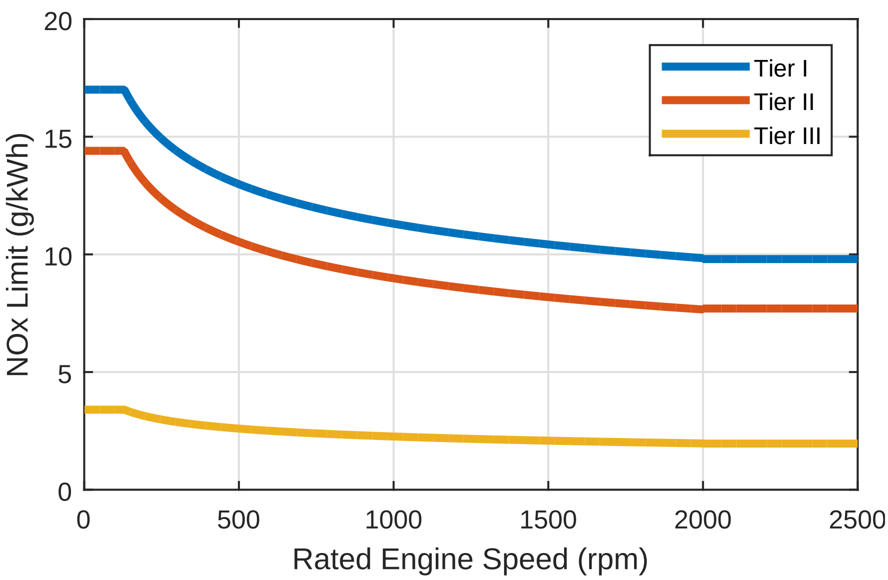


Figure 1.7 – NO_x limits according to Marpol Annex VI.

Source: Author.

As described above, there are different limits for NO_x, SO_x, furthermore the presence of these gases in fuels varies, for example, Liquified Natural Gas (LNG) does not contain SO_x in its composition. The next section adds more motivations for this project.

1.2 Motivation

The recent regulation created by the European parliament (European Commission, 2020), the growth forecast on ship emissions by 2050 (Transport & Environment , 2016), the increasing media coverage on the topic (VIDAL, 2016; GARCIA, 2015; HARVEY, 2016; KINTHAERT, 2017) are the main motivations to study ways to solve the challenge of ship emissions growth. The power density increase in lithium-ion batteries opened markets in which the batteries can operate at much higher power(BLOMGREN, 2017; AGOSTINI et al., 2017). Although the power density has increased, the prices of lithium-ion batteries have fallen in recent years (ROMM, 2017). Moreover, the possibility of implementing a CO_2 tax for the shipping sector and the international media coverage on the ship emissions are factors that would push the shipbuilders towards more efficient and less emitters vessels (A; S; C, 2019; PARRY et al., 2018; GARCIA, 2015; KINTHAERT, 2017) are the main motivations to study ways to solve the challenge of ship emissions growth. Although the power density has increased, the prices of lithium-ion batteries have fallen in recent years (ROMM, 2017). Moreover, the increase of power density in lithium-ion batteries opened markets in which the batteries can operate at much higher power(BLOMGREN, 2017; AGOSTINI et al., 2017).

1.3 Objective

The main objective of this research is to develop a methodology to evaluate the impact of solutions highlighted from IMO on reducing emissions of the maritime sector. The secondary objectives are developing models from which the fuel consumed, the amount of CO_2 emitted, and battery lifespan can be estimated. The ship analyzed in this work will be the PSV, which has a considerable load variability. Some parts of the PSV mission are comparable to parts of the mission of other ships. The solutions investigated in this work will be auxiliary engines, sets of generators with different sizes, and batteries. Moreover, this work will evaluate the ship speed reduction.

1.4 Materials and methods

To pursue the analysis of each part of the methodology implemented in this work, an optimization that considers the different efficiency points is required; coding this optimization in Python could be a solution; in this analysis, the software Hybrid Optimization of

Multiple Energy Resources (HOMER) was chosen due to the small computational effort that the optimization used in this software needs.

The product used to perform the simulations is HOMER PRO. Data from datasheets will be used to model the diesel generators analyzed in this work. Moreover, sensitivity analysis will be performed varying some electrical parameters such as round-trip efficiency, batteries, and diesel generator size, minimum load to turn on the generators, demand variation during a voyage through speed variation, and various levels of Depth of Discharge (DoD).

The methodology used in this work comprises three phases. In the first phase, the investigation considers various diesel generator sizes using the battery only as a reserve. These generators are again analyzed in the second phase, but the battery is dispatched in this phase. Finally, the third phase comprises the evaluation of the ship speed variation.

To pursue this methodology, it is necessary to have various diesel generator datasheets comprising the fuel consumed per percentage of rated power. Moreover, ship structural data and various equations need to be used to estimate the relation between power and speed.

The following chapters will discuss more details of the technologies analyzed and their impact on emissions.

1.5 Publications

The published works during the Doctorate period are summarized below.

Publications in Journals:

1. VIEIRA, G. T. T., PEREIRA, D. F., TAHERI, S. I., KHAN, K. S., SALLES, M. B. C., GUERRERO, J. M., & CARMO, B. S., "Optimized Configuration of Diesel Engine-Fuel Cell-Battery Hybrid Power Systems in a Platform Supply Vessel to Reduce CO2 Emissions". Energies, v. 15, no. 6 2022.

2. TAHERI, S. I., VIEIRA, G. T. T., SALLES, M. B. C., AVILA, S. L., "A trip-ahead strategy for optimal energy dispatch in ship power systems". Electric Power Systems Research, 2020.

3. PERALTA P., C. O., VIEIRA, G. T. T., MEUNIER, S., VALE, R. J., SALLES, M. B. C., CARMO, B. S., "Evaluation of the CO2 Emissions Reduction Potential of Li-ion Batteries in Ship Power Systems". Energies, v. 12, 2019.

Publications in international conferences:

1. VIEIRA, G. T. T., SALLES, M. B. C., MONARO, R. M., CARMO, B. S, "CO2 Emission and Fuel Consumption Evaluation for Variable-Speed Diesel Generators

and DC grids for Ship Power Systems". In: 7th International Conference on CLEAN ELECTRICAL POWER Renewable Energy Resources Impact, Otranto, 2019.

1.6 Thesis Structure

The next chapters of this doctorate thesis are structured as follows:

- Chapter 2 displays the solutions evaluated from IMO to reduce emissions in the maritime sector and states the solutions analyzed in this work;
- Chapter 4 shows an evaluation of different generator sizes regarding ship CO_2 emissions, fuel consumption, and generator operation point.
- Chapter 5 presents an evaluation of batteries in these different generator sets.
- Chapter 6 presents the relation between ship speed and the power required from the PSV power system; from this relation, an analysis of the ship speed reduction is displayed.
- Chapter 7 provides the conclusions obtained from the results of this work.

Chapter 2

State-of-the-art of emission reduction solutions

As presented in the last chapter, maritime emissions should be addressed more dedicatedly. The approaches taken so far did not present considerable results. To accomplish the IMO's objectives for 2030, many ships will need to retrofit, whereas the new ships will need to follow a much more efficient design.

This chapter aims to provide an overview of energy solutions offered by the IMO to reduce emissions by ships. It will include an evaluation of different sizes in generator sets and batteries. Additionally, this work will discuss the ship speed reduction.

2.1 Energy Efficiency in ships

In (JIMENEZ; KIM; MUNIM, 2022), the authors present a review of ship energy efficiency. The review covered 336 studies that were filtered with VOSViewer; this filter revealed 119 coupled studies. Among these 119 studies, the 40 most relevant articles were selected. Afterward, these 40 studies were divided in five clusters that illustrated the five most studied areas regarding energy efficiency in ships. The areas are decarbonization and emission reduction measures, speed management, policy and regulations, economic and organizational factors and alternative fuels. The authors also suggest areas for future studies highlighting the lack of research on using big data analytics to reduce GHG emissions by ships.

An overview regarding EEDI is provided in (POLAKIS; ZACHARIADIS; KAT, 2019). The authors highlight the changes to existing regulations, as well as describe each parameter used in the EEDI's formula is described. In (ATTAH; BUCKNALL, 2015), the authors provide an estimation of EEDI for different LNG ships powering options. These options include steam turbine propulsion (STPS), dual fuel diesel electric (DFDE), and slow-speed two-stroke diesel engine with re-liquefaction plants (SSDR). Gas injection engines have a 30% lower EEDI than diesel-electric drives. An evaluation of EEDI in bulk carriers is written in (ANČIĆ; ŠESTAN, 2015). The authors observed a reduction of CO_2 emissions obtained by technical measures, such as EEDI and operational measures. The CO_2 emission reduction by technical measures in a period from 2020 and 2040 is around 1420 million tons. Moreover, the reduction using operational measures per year would be around 168 million tons. Considering both measures, the CO_2 emission in 2040 would be around 246 million tons.

2.2 Emissions reduction in specific ships

The authors investigate emissions in specific ships in (AMMAR; SEDDIEK, 2017; KARATUĞ; DURMUŞOĞLU, 2020; LETAFAT et al., 2020; AMMAR; SEDDIEK, 2021; İNAL; DENIZ, 2021). The proposed solutions and the ships analyzed are in Table 2.1.

Ro-ro ships are evaluated in (AMMAR; SEDDIEK, 2017; KARATUĞ; DURMUŞOĞLU, 2020). In (AMMAR; SEDDIEK, 2017), the authors investigate a ro-ro ship operating in the red sea; they evaluate two methods. The Selective Catalytic Reduction (SCR) was able to reduce 90% of NO_x and 98% of SO_x emissions. The emission reduction of these pollutants had a cost-effectiveness of 873.5 \$/ton for NO_x and 3115 \$/ton for SO_x emissions when using seawater scrubbing. On the other hand, using LNG would reduce around 77.6%, 92.5% and 14.5% of NO_x, SO_x and CO_2 emissions. In (KARATUĞ; DURMUŞOĞLU, 2020), the paper investigates the potential emission reduction that can be obtained using a PV power system in a ro-ro ship navigating between Pendik/Turkey and Trieste/Italy. The results show that the PV solar system with 426.8kW of peak power provides 334,063 kWh per year. This system provides a reduction of 0.312 tons of SO_x, 3.942 tons of NO_x, 232.393 tons of CO_2, and 0.114 tons of PM.

In (LETAFAT et al., 2020), the authors evaluate ferry ships running an optimal component sizing for the battery and the fuel cell to achieve a zero-emission ferry. The battery and fuel cell sizes are 296.809 kWh and 418.95 kW, respectively. It used around 300kg of hydrogen, and investment costs for battery and fuel cells are shown.

A passenger vessel is assessed in (AMMAR; SEDDIEK, 2021). In this research, the authors compare a diesel-electric (DE) system to a combined gas turbine electric and steam (COGES). The COGES system is more energy efficient in design and operation by 9.3% and 27.55%, respectively. Life-cycle costs for the COGES systems are higher, around 6,042 \$/kW, against 5,013\$/kW for DE systems. It is shown that the COGES system achieved lower CO_2, SO_x and NO_x emissions. In (İNAL; DENIZ, 2021), the use of Molten Carbonate Fuel Cell (MCFC) in a chemical tanker ship is investigated. The MCFC evaluated has 2.8MW, the average LNG consumption is around 615.12 m^3/h. The use of such a solution managed to reduce more than 99% of NO_x, SO_x and PM, as well as achieved a reduction of 33% in CO_2 emission reductions. Total emission reductions by only one ship in 27 voyages in the Mediterranean Sea have the following numbers, 53668 kg NO_x, 11402 kg of SO_x, 9506 kg of PM, and 1223 tons of CO_2 emissions.

Vessel	Solution	Reference
Ro-Ro Ships	SCR LNG	(AMMAR; SEDDIEK, 2017)
Ro-Ro Ships	PV Solar Panel Peak Power: 426.8kW 334,063kWh per year	(KARATUĞ; DURMUŞOĞLU, 2020)
Ferry Ships	Battery: 296.809kWh Fuel Cell: 418.95kW	(LETAFAT et al., 2020)
Passenger Vessel	Combined Gas Turbine Electric and Steam	(AMMAR; SEDDIEK, 2021)
Chemical Tanker Ship	Molten Carbonate Fuel Cell : 2.8MW	(İNAL; DENIZ, 2021)

Table 2.1 – Vessels and Solutions proposed to reduce GHG emissions

2.3 Solutions to mitigate the problem and their negative points

In (GÖSSLING; MEYER-HABIGHORST; HUMPE, 2021), a set of solutions proposed by IMO is presented. Table 2.2 gathers part of these solutions in groups that demand reduction, the use of greener sources such as renewable energy and alternative fuels, and reduction of speed can help to reduce ship emissions. Even though using batteries as a reserve to allow the optimal dispatch is not portrayed in Table 2.2, this work will show that it can provide fuel and CO_2 emission reductions.

Some review papers present a discussion about these solutions proposed by IMO (YUAN et al., 2020; INAL; CHARPENTIER; DENIZ, 2022; SANTOS; SILVA; SERRANO, 2022; PAN et al., 2021; MIYAZAKI; SøRENSEN; VARTDAL, 2016; MIYAZAKI et al., 2016; VIEIRA et al., 2017; P et al., 2019; TAHERI et al., 2021; VIEIRA et al., 2022; DANIEL; TROVÃO; WILLIAMS, 2021; HSIEH; FELBY, 2017; RAFIEI; BOUDJADAR; KHOOBAN, 2020; D'AGOSTINO et al., 2019; ALZAHRANI et al., 2021).

In (YUAN et al., 2020), the authors analyze articles discussing hybrid energy systems, specifically the types of power transmission structure. Moreover, the review highlights the importance of optimizing the dispatch of the power sources involved in a multi-energy power system to improve its performance.

In (INAL; CHARPENTIER; DENIZ, 2022), the authors discuss hybrid ships and highlight some batteries' power density numbers, cycles, and cost per kWh. Additionally, a table discusses the availability of energy storage systems, power generation systems, and propulsion architecture for some ship types.

In (SANTOS; SILVA; SERRANO, 2022), the authors compile papers about renewable energy, biofuels, low-carbon fuels, hydrogen, and other topics. After this compilation,

Group	Solution
Use of renewable energy	
Reduction of auxiliary power demand	Reduce energy lightning and others
Wind Power	Towing kite
	Wind Power (fixed sails or wings)
	Wind Engine (Flettner rotor)
Solar Energy	Solar Panels
Alternative Fuels with carbon	Use of LNG in Internal Combustion Engine or Fuel Cells
Use of alternative fuels	
Alternative fuels without carbons	Hydrogen in Internal Combustion Engine or Fuel Cells
	Ammonia in Internal Combustion Engine or Fuel Cells
	Synthetic methane in Internal Combustion Engine or Fuel Cells
	Biomass methane in Internal Combustion Engine or Fuel Cells
	Synthetic methanol in Internal Combustion Engine
	Biomass methanol in Internal Combustion Engine
	Synthetic ethanol in Internal Combustion Engine
	Biomass ethanol in Internal Combustion Engine
Speed reduction	
Speed Reduction	Reduce speed by 10%

Table 2.2 – Solutions proposed by IMO to reduce emissions (GÖSSLING; MEYER-HABIGHORST; HUMPE, 2021)

the authors excluded articles unrelated to maritime transportation and decarbonization. Then, they provided a graph showing the number of publications per year that presents an increase in the number of publications in recent years.

In (PAN et al., 2021), the authors examine using fuel cells, wind energy, and solar energy in conventional ships. They provide block diagrams of solar and wind power connected to the grid and examples of vessels using such solutions.

In (MIYAZAKI; SøRENSEN; VARTDAL, 2016), a model to calculate fuel savings and the emissions reduction potential that can be obtained by an energy storage device considering various constraints and different battery dispatches is proposed. Moreover, in (MIYAZAKI et al., 2016), a model of a hybrid power system is presented, and it is validated experimentally. The authors evaluated the effect of the battery efficiency, considering a variation of the efficiency from 80 % to 100 %. Other variables were evaluated in this work, such as the storage capacity and the genset angular speed.

An evaluation of the battery potential to reduce CO_2 emissions is pursued in (VIEIRA et al., 2017). A curve comparing the CO_2 emission reduction to the increase of battery size and a curve comparing the participation in energy generation of each diesel generator with the increase of battery size are presented. The percentage of time connected of each diesel generator for scenarios with and without battery was also analyzed.

In (P et al., 2019), the authors evaluate batteries and auxiliary generators connected to a conventional PSV power system. As a result, the authors show the impact of the battery round trip efficiency on CO_2 emission reduction and on the total energy generated by the system analyzed. The authors also evaluate the impact that the C-rate and time of discharge variation would have on CO_2 emission reduction.

In (TAHERI et al., 2021) designs an optimal dispatch of the generators using a trip-ahead strategy. This dispatch is then compared to Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm, and HOMER software. Considering calculation velocity, the proposed algorithm was faster than the other two compared algorithms. Compared to HOMER PRO, the results and the computational time are similar.

An evaluation of auxiliary diesel engines, batteries, and fuel cells with three levels of hydrogen is performed in (VIEIRA et al., 2022). The authors evaluate the emission reduction impact that each component would have when connected to the conventional PSV power system composed of four 1.8MW diesel generators. All evaluations were done for three levels of demand. Two sizes of three battery chemistries leading to six batteries were considered, and the best reduction achieved a reduction of 10.69%.

Fuel cells applied in a ferry boat are evaluated in (RAFIEI; BOUDJADAR; KHOOBAN, 2020). The authors evaluate fuel cells, batteries, and cold ironing to achieve zero emission, although the costs for the proposed power system are higher than the cost for the power system composed only of diesel generators or by diesel generators and batteries. The gain of reaching zero emission can surplus the higher costs. International Energy Agency (IEA) issued a report evaluating biofuels for the marine shipping sector(HSIEH; FELBY, 2017). The authors analyze the infrastructure sector, fuel technologies, and regulations. Information regarding ship bunkering is given; large ships can take 9-12 hours to be refueled, typically 10 hours at a rate of 500-700 tons per hour.

In (DANIEL; TROVÃO; WILLIAMS, 2021), the authors assess the potential of shore power to modify EEDI in dry bulk carriers. Firstly, the authors pursue a SWOT analysis appraising Strenghts, Weaknesses, Opportunities, and Threats. As a result, the authors show that CII index is improved in 7.8%, EEDI and EEXI indexes present a reduction in their scores from 1.2% to 10%.

A discussion about the decarbonization of seaports is provided in (ALZAHRANI et al., 2021). This review paper searched for a set of keywords in different databases; then, the authors measured the growth of the research papers that studied the decarbonization of seaports. Besides showing the evolution of the numbers, (ALZAHRANI et al., 2021) also presents the articles related to each keyword analyzed. Seaports can have an important role in ship emission reduction since 70% of this pollution occurs near coastal areas (<400km)(CORBETT et al., 2007).

Ship emission estimation methods are described in (SIMONSEN; GÖSSLING; WALNUM, 2019; HUANG et al., 2020; CHEN et al., 2016; DRAGOVIĆ et al., 2018; NUNES et al., 2017). These methods may have drawbacks based on how the emissions are measured.

In (CHEN et al., 2016), it is mentioned that the more realistic approach would be to estimate emissions based on a ship's actual speed. For ships with only main engines, the relationship between ship speed and power output of the generators can be calculated by the cubic law(GOLDSWORTHY; GOLDSWORTHY, 2015). A discussion regarding the cubic law will be further presented. This relationship is much more complex when auxiliary generators, fuel cells, and batteries are considered. It is necessary to use detailed models, tools, and studies to more accurately measure the effects that ship power systems' hybridization will have on GHG emission levels.

2.3.1 Main and auxiliary Diesel engines

The use of auxiliary engines can be helpful in ships that deal with a huge power variation. Considering that at low loads, the use of the main engine would force these engines to operate up to 40% of the rated capacity. In (TUFTE, 2014), the authors show that an increase in the maintenance periodicity, reduction of efficiency, lower cylinder pressure, and lower temperature are the main problems caused by low load operation. Using batteries as reserve allows using a combination of gensets with different sizes. In this situation, the small generators would operate during low load and, during parts of the mission with bigger demands, generators would be turned on to meet the demand. Additionally, dispatching batteries could help in two moments; first, batteries are used to meet the demand turning off the diesel generators that would be used; second, batteries are charged, increasing the demand, therefore increasing the operation point of the generators.

2.3.2 Batteries

The battery connection to conventional ship systems, making it hybrid, can help the diesel generators operate closer to their optimal points, saving diesel and reducing the CO_2 emission. As mentioned before, considering the same demand, the variation of the operation point in a hybrid system is possible because the battery can work as a load when there is a power surplus and as a power source when there is a lack of generation or when the generators would be forced to operate at low load. This subsection presents an overview of the batteries currently in the market.

According to (CROMPTON, 2000), batteries can be divided in primary (non-rechargeable) and secondary (rechargeable). Recently, the battery industries have endured tremendous growth. Besides that, there was an increase in energy density and a decrease in battery cost.

The reduction in battery cost is the result of the popularization of batteries. Batteries have become popular in diesel-electric systems because they can absorb the power peaks and valleys better than diesel generators, which can be oversized, leading to an operation out of their optimal point. Besides covering peaks and valleys on some power systems, batteries can help operate diesel generators at their optimal point, consuming less diesel and emitting less CO_2.

In power systems composed of batteries and diesel generators, batteries can improve system reliability since they have a faster response than diesel generators. Also, this system reliability improvement will not pose an environmental concern since an alternative way to improve reliability would be to have two or more generators running the system. This would move the operation point of the generators to the worst point of operation.

Figure 2.1 shows a comparative analysis between discharge time at rated power and system power ratings of different battery technologies and their basic characteristics (LABORATORIES, 2013). The comparisons therein are very general and try to show the reality of 2013. Duration and power ranges are possibly broader because of the advance of the technologies. A few candidates might fit ships' needs with special attention to the green area. The most common batteries are lead-acid and lithium-ion (or Li-Ion). However, flow and NaS (sodium–sulfur) batteries could be interesting options for systems requiring high power ratings and high periods of discharge(ASSOCIATION, 2015).

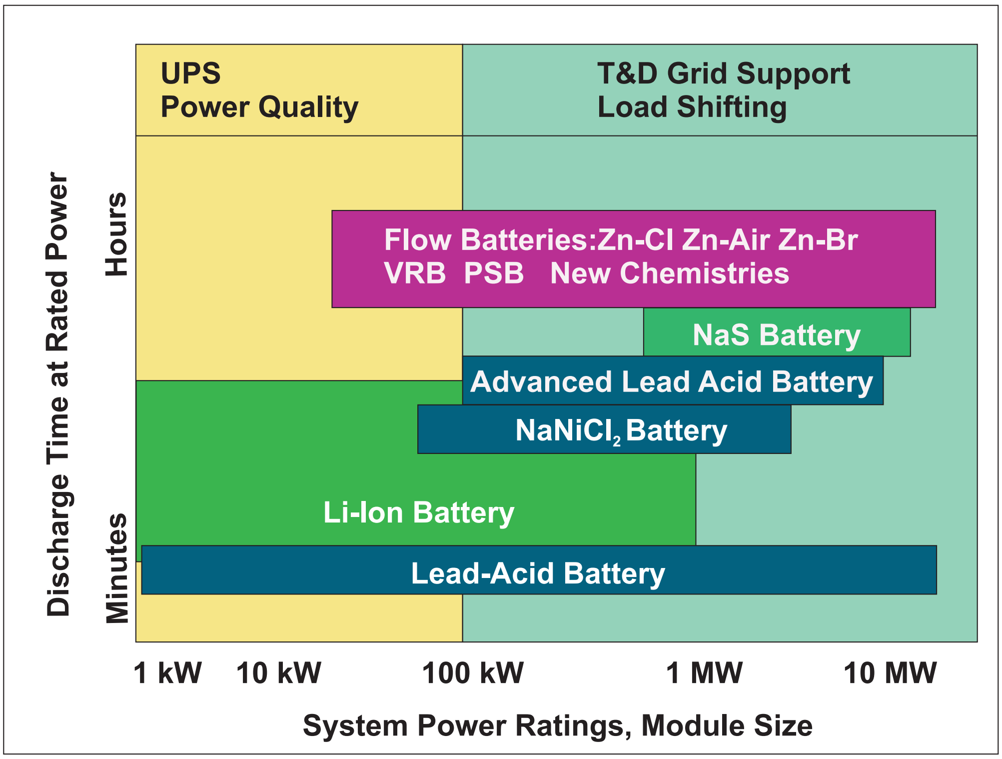


Figure 2.1 – Power and discharging time characteristic of electrical energy storage technologies.

Source:Adapted from (LABORATORIES, 2013).

The requirements for ship applications are similar to microgrids or isolated power systems (MCCOY, 2015). In (CROMPTON, 2000), a list of minimum requirements is shown to achieve a better battery selection. The next subsection shows different methods to calculate the size and cost of batteries.

2.3.2.1 Battery Sizing and Cost

In (PAWEL, 2014), it is shown how to calculate the levelized cost of the stored energy (LCOE), which is a relation between the total installed cost for the total lifetime of the project and the energy injected by the battery. This work presents a calculation of the LCOE for three battery technologies, a Lithium-ion, a Redox-Flow, and a Lead-Acid. The conclusion is that if we consider that the installed storage power, the number of cycles, and the utilization of the storage capacity are the same for the three batteries and also consider the specific parameters that are applied to each battery, we have that the redox-flow battery presents a lower LCOE of storage of 0.338€/kWh, whereas LCOE for lithium-ion was calculated as 1.678€/kWh and LCOE for lead-acid was calculated as 3.072€/kWh.

In (SARKER et al., 2017) the objective was to find an optimal operation considering the cycle-life degradation and testing two mechanisms, variable C-Rate, and variable efficiencies. This work shows that the more you operate at a high C-rate, the largest will be the decrease in the battery's State of Health(SoH) when the battery is operating at room temperature. The work also shows that the increase in the C-rates gives rise to a quadratic growth of the charging/discharging power losses.

In (PALIZBAN; KAUHANIEMI, 2016) it is presented a matrix showing which technology is more suitable for each application. Moreover, this paper shows that energy storage systems can have four main applications: Bulk Energy applications (energy arbitrage and peak shaving), Ancillary Service Applications (voltage support, frequency regulation, spinning reserve, black start and load following), Customer Energy Management Applications (power quality and power reliability) and Renewable Energy Applications. It is also shown in (PALIZBAN; KAUHANIEMI, 2016) that the location of the storage system is highly relevant because its function derives therefrom. Although this work says that electrochemical batteries are not suitable for energy arbitrage, there are some works that have studied this application (BRIVIO; MANDELLI; MERLO, 2016; TELARETTI; IPPOLITO; DUSONCHET, 2015; PETERSON; APT; WHITACRE, 2010; PELZER; CIECHANOWICZ; KNOLL, 2016).

2.3.2.2 Li-ion Batteries

In (SABIHUDDIN; KIPRAKIS; MUELLER, 2014) is presented a table containing several data from various battery technologies, including lithium-ion batteries. Compared to the other types of batteries presented in (SABIHUDDIN; KIPRAKIS; MUELLER, 2014), lithium-ion presents very good results when energy and power density are highlighted.

Normally, battery installations in ships are sold in containers. The container should be big enough to store the batteries, the refrigeration equipment, and the control systems and have enough space for maintenance. In a 20ft container, if we separate 60% of the space for the batteries, we would have around 19.82 m^3 available to install the battery system.

Lithium-ion batteries are the most mature battery for power systems applications. In Australia a project which is under construction and is expected to be ready by August 2019 aims to install 20 MW/34 MWh lithium-ion battery; alongside the batteries will be installed 56 wind turbines adding up 194 MW of generation capacity (COLTHORPE, 2018). In California, more precisely in Orange County, a 35 MW/140MWh lithium-ion battery is going to be installed by 2020: the objective of this installation is to give electrical capability and extra grid balance to that area (Convergent Energy + Power, 2016).

In (IEA, 2022), it is mentioned that, at the end of 2021, the total installed grid-scale battery storage capacity reached around 16GW, this number was 60% or 6GW higher than the numbers of 2020. United States, China, and Europe lead the annual grid-scale battery storage additions in 2021 with 2.9GW, 1.9GW and 1GW, respectively. Nonetheless, to achieve a net zero scenario by 2030, the battery storage capacity needs to grow significantly to reach 680GW by 2030. Considering that it is expected to around 140GW of battery is installed in 2030 alone, the annual additions must increase from the 2021's 6GW to over 80GW(IEA, 2022).

This scale-up on battery installation will need to deal with the uncertainty about lithium reserves and resources. According to (VARGAS, 2018), resources refers to the total amount of material, including undiscovered and non-economically recovered materials. On the other hand, the word reserve refers to existent materials with a high level of certainty and are economically recoverable with current technologies. In terms of reserves, the latest report of the U.S Geological Survey (JASKULA, 2022), describes that Chile has the highest levels of reserves, followed by Australia and Argentina.

On the other hand, Bolivia led the ranking of lithium resources, and Argentina and Chile followed. The total reserves around the world are around 22 million tons, whereas the resources are about 89 million tons. Even though the unit for reserves and resources is given in million tons, when we look at the mine production, this number falls deeply. The world's production is around 100 thousand tons. The highest producer is Australia which produces 55% of all, in second comes Chile with around 26% and then China with 14%.

In (VARGAS, 2018), the authors present a calculation to evaluate the number of batteries that could be produced with the current worldwide lithium resources. This calculation resulted in 2,1 billion cars. The authors have considered that an 85kWh NCA battery from Tesla would require 6.29kg of lithium. Moreover, data from 2017, presented by the authors, showed that 46% of the lithium extracted was destined for batteries. Since the numbers grew from the years before, the authors updated this number to 50%. Finally, the author has considered that only 50% was economically recoverable. If, instead of considering the number of resources, the authors evaluated the number of lithium produced, in 2021, in mines worldwide, the result would present the number of batteries that can be made in a year.

The multiplication of the number of electrical vehicles sold in 2021, presented in (HONGYANG; HALL, 2022), to this number of 6.29kg of lithium per battery, results in the quantity of lithium required in 2021 to produce all these electric vehicles. Furthermore, contrasting this number to the amount of lithium extracted in mines in 2021 resulted in 43% of the mine production destined to produce the batteries of these 6.8 million light-duty electrical vehicles sold in 2021. The problem is that, from 2020 to 2021, the mine production increased by 21.2%, whereas the number of EV cars sold raised around 107%.

Some manufacturers have set some ambitious targets by 2030. Volkswagen and Ford expect around 50% of their sales to be electric by 2030, whereas Toyota aims at achieving 3.5 million sales a year by 2030 (PAOLI; GüL, 2022). Tesla aims at selling 20 million EVs a year by 2030 (NEDELEA, 2022). Besides bunkering these targets of light-duty vehicles, batteries will also need to supply heavy-duty vehicles, such as buses and trucks, maritime applications, stand-alone systems such as houses and wind and solar farms, and all-electric aircraft. So, one can say that the production of batteries for all these appliances will require a massive increase in mine production since

Even if it is not going to prevent shortness in lithium, using LFP batteries may help reduce the amount of lithium used in each battery. But, on the other hand, this battery's efficiency and lower energy density may be a bottleneck for its growth depending on what the user will request from a car(KORUS, 2022).

To conclude this discussion about the lack of lithium production, many people are out of the EV market and will enter. According to (PAOLI; GüL, 2022), huge markets such as Brazil, Indonesia, and India have only 1% of their overall sales being EV sales. This possible bottleneck in lithium production highlights the need for other solutions.

2.3.3 Reduction of ship speed

Table 2.2 shows that IMO suggests a reduction of 10% on ship speed as a solution to reduce ship emissions. The ship speed reduction is investigated in many papers (LACK; CORBETT, 2012; PSARAFTIS; KONTOVAS, 2014; PSARAFTIS; AMBOY; PSARAFTIS, 2019; ADLAND; CARIOU; WOLFF, 2020; YANG et al., 2020; TASKAR; ANDERSEN, 2020; LI et al., 2020; MOREIRA; VETTOR; SOARES, 2021; GE; BEULLENS; HUDSON, 2021; MA et al., 2021; KARAGIANNIDIS; THEMELIS, 2021; FAN et al., 2021; TRAN; LAM, 2022; HAN; MA; MA, 2022).

In (LACK; CORBETT, 2012), the authors investigate black carbon emissions. According to (COMER, 2019), ships emit black carbon when the engines are fed with fossil fuels such as Heavy Fuel Oil (HFO). Considering the emission of carbon dioxide for a ship operating for 20 years, black carbon represents around 20% of these emissions. To reduce these emissions, it is important to use greener fuels such as LNG, methanol, biodiesel, and distillate fuels. IMO intends to begin banning enforcement of HFO as a fuel for ships in the Arctic in 2023. This ban is crucial because ships operating in the Arctic have a high load variation, 25-100% of the engine's rated power, depending on the ice conditions. The emission factor of black carbon increases considerably (up to 6.5 times) when engines are operated at very low loads (<25%). Therefore, optimizing the ship speed to avoid engine operation at these points is necessary to reduce black carbon emissions (LACK; CORBETT, 2012).

In (PSARAFTIS; KONTOVAS, 2014) the authors investigate the optimal speed for different routes considering different payloads and different prices for the cargo. For the scenario considering the payloads without a price for the cargo, payloads, and speed are inversely related, the highest optimal speed, around 13.5 knots is found in the scenario without load. Moreover, the authors evaluate a scenario considering a fixed optimal speed for the same trajectory. The total costs are higher in relation to a scenario with optimal speeds depending on the payload. The trip time presents a slight variation, the fixed speed scenario presents a longer journey, 5.35 vs 5.3. Finally, it is presented that more valuable loads sail faster, it produces higher costs and a higher CO_2 emission. Although it is not evaluated by the authors, the taxation of CO_2 emission would probably present a saturation on speed increase in order to reduce the costs.

Chapter 10 of (PSARAFTIS; AMBOY; PSARAFTIS, 2019) presents that the optimal speed is higher while the price of the HFO is lower. Moreover, this chapter presents that worldscale 60 has a more abrupt variation of speed for the same variation of HFO prices than worldscale 120. According to (STOPFORD, 2008), Worldscale 100 is the cost of having a standard vessel transporting a ton of cargo on a round voyage. This standard vessel is updated from time to time. The use of worldscale is given in (STOPFORD, 2008), if a tanker accepts a rate of worldscale 50 to transport a load from Jubail to Rotterdam, in order to calculate his earnings, he needs to first consider the rate for WS100 for the same route. Considering a rate of $17.30 for the WS 100, the rate for WS 50 would be half of that, $8.65. For transportation of 250,000 tonnes, the income from this transportation would be $2,162,500. A voyage to another destination would follow the same approach. Another evaluation shown in (PSARAFTIS; AMBOY; PSARAFTIS, 2019) addresses the reduction of CO_2 emissions with the increase of HFO costs. Besides that, the authors debate over the speed limit discussion. South American countries such as Chile and Bolivia don't agree to adopt speed reduction since it would create a limitation on their exports to Asia.

In (ADLAND; CARIOU; WOLFF, 2020), the authors discuss the development of a fuel consumption curve formula estimated from real data obtained from a tanker company. One of the variables considered in this formula is the speed elasticity (β), which is usually set as three.

$$Power = Speed^{\beta} \tag{1}$$

According to (ADLAND; CARIOU; WOLFF, 2020), setting β as three does not represent reality when data from real operations is analyzed. The authors conclude that for lower speeds β is much lower than three. Moreover, they present a literature review regarding β for different ships. The real data presented refers to tankers ships, 10 Aframax and 6 Suezmax. Aframax is named after the Average Freight Rate Assessment (AFRA) system, whereas Suezmax is the biggest ship that navigates the Suez Canal. According to the evaluation of the real data, β for Aframax is around 1.9 and for Suezmax around 2. Moreover, it is stated that β does not have a significant variation for the laden voyage and ballast voyage, which considers a voyage with the ship fully loaded and partially loaded, respectively.

A fuel-saving investigation due to speed reduction is presented in (TASKAR; ANDERSEN, 2020). The paper evaluates the speed reduction for bulk carriers, container ships, and a tanker in different weather conditions. As presented in (ADLAND; CARIOU; WOLFF, 2020), the cubic relation between power and speed also presents significant errors from real values as also evaluated in (TASKAR; ANDERSEN, 2020). The evaluation of real data shows that a speed reduction of 5% presents a fuel consumption reduction per mile from 12 to 18% depending on the type of ship. Moreover, a speed reduction of 10% can decrease fuel consumption from 22% to 32%.

In (LI et al., 2020), the authors provide a discussion regarding speed optimization applied in a container ship taking into account the voluntary speed loss. Neural networks, trained with real data, showed very good accuracy in predicting ship speed and fuel consumption in (MOREIRA; VETTOR; SOARES, 2021). The use of neural networks trained with real data to predict ship fuel consumption is also described in (KARAGIANNIDIS; THEMELIS, 2021). A speed optimization algorithm is presented in (GE; BEULLENS; HUDSON, 2021).

Algorithms evaluating the chain effect of speed optimization and the relation between speed and future profit potential are developed. A multi-objective algorithm is proposed in (MA et al., 2021). The algorithm used is an NSGA-II that evaluates the optimized speed for a route around the US coast considering the different prices in Emission Control Areas (ECAs). In (FAN et al., 2021) the authors evaluate speed optimization using dynamic programming considering real data of a Yangtze River ship. The authors pursue a regression analysis to estimate the relation between the ship speed and fuel consumption to the main engine speed.

The effects of optimizing the ship speed would have on CO_2 emissions, cargo lead time, and supply chain costs for a container ship are presented in (TRAN; LAM, 2022). The authors highlight the importance of goods inventory on ship speed optimization and estimate that ship speed affects only 25% of the supply costs, around 50% of the lead time, and around 70% of the emissions. Finally, in (HAN; MA; MA, 2022), the authors develop an improved quantum genetic algorithm to optimize the ship speed. This algorithm considers different emission reduction regulations such as ECAs, VSRIP, carbon tax policy, and VA. The model developed used a route on the US West Coast. The three main findings are the use of one single policy may present better results than more policies applied coordinately. The algorithm resulted in a reduction of the total costs considering these policies. VA is the strategy that can represent more benefits in comparison to the other policies.

2.4 Evaluation of these solutions in vessels

As mentioned at the beginning of this chapter, the problem regarding emission reduction should have solutions that can be applied to existing ships and solutions that will be feasible only if implemented in new ships.

For new ships, batteries can play a different role, being used only as a reserve to allow an optimal dispatch of the generators. Considering the battery as a reserve, the diesel generator sets can comprise different generators to feed the demand more optimally. This evaluation is performed in chapter 4.

Among the solutions mentioned so far, batteries have been evaluated in the literature as the most promising solution for ship retrofit. Containerized solutions comprising the battery monitoring system, HVAC, firefighting and fire detection system, and battery modules are the most suitable solutions for existing ships. This analysis is illustrated in chapter 5.

Finally, ships that have part of their mission operating on voyages can have their emissions reduced by reducing the ship's speed. It can be applied for both new and existing ships, the level of reduction will be further discussed in chapter 6.

Chapter 3

Modeling and Methodology

This chapter presents the modeling of the components of ship power system and the modeling of the demand curve. Moreover, it will present the methodology developed in this work and the analysis pursued in each step of this methodology.

3.1 Modeling

In this section the components of the ship power system will be modeled. Moreover the demand analyzed will be portrayed. To amplify the number of ships that this methodology can be applied, the evaluation herein will be carried out in relation to each part of the mission.

3.1.1 Demand Curve Evaluated

The demand curve evaluated in this work comprises five parts: LP, LV, DP, PLV, and Standby (ST). In each of these parts, the PSV pursues a different operation. In LP, we try to portray the moment in which the ship is at the port being loaded. Here, the ship is steady, so the generators are used to feed base and hotel loads. ST operation is a moment that can happen at any time of the operation, it can occur during DP operation due to bad weather or operational restrictions. It can also happen due to port restrictions. The amount of time during this operation should be as minimal as possible since during this operation the ship is operating at a very low load considering the engines that are installed.

DP is the most dangerous operation pursued by the PSV. In this operation the ship is close to the platform, and the PSV's thrusters are used to compensate for all forces that are trying to move the ship. This operation has different classes such as DP1, DP2, and DP3. DP1 is the most basic system, in ships with this system, the DP system can keep the position in automatic mode. DP2 is more reliable than DP1 since this system has the ability to cover a failure of an active component using a redundant system that automatically substitutes the DP system with a failure and leads the ship to a safe place, in which the operation can be stopped. Finally, DP3 also covers a failure on a static component, besides the active component of DP2. Another difference is that in DP3 class the systems of redundancy must be physically separated from the other systems.

Both voyages are related to the trip that the ship does toward the platform or to the port. For LV, the ship is fully loaded whereas PLV illustrates a voyage with the ship partially loaded. In the next chapter, the amount of power required during these two voyages will be changed from curves that will correlate power and ship speed.

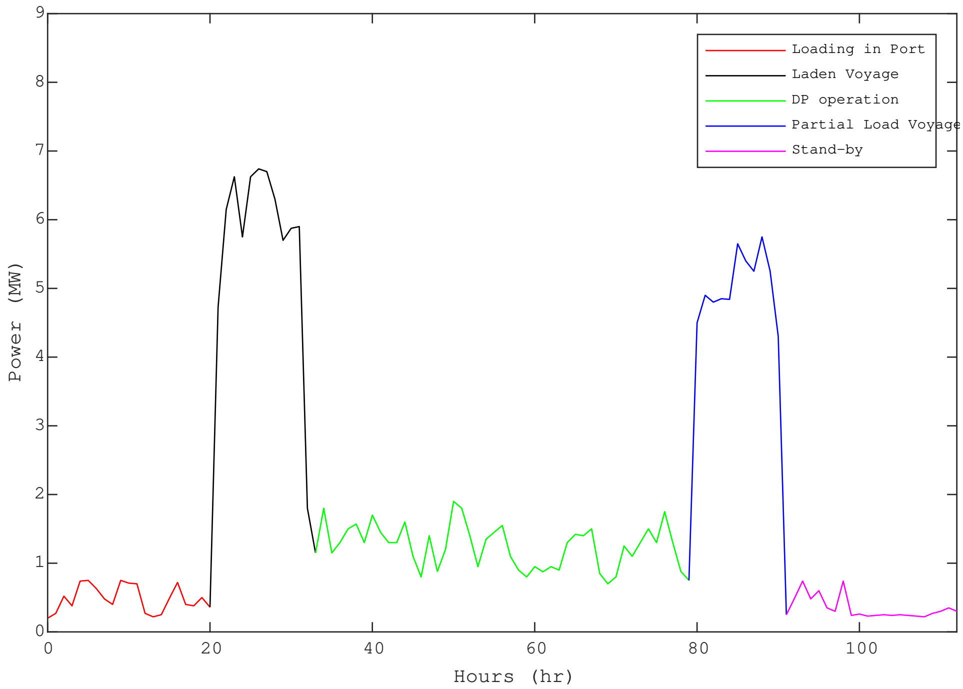


Figure 3.1 – PSV power demand during a standard mission.

Source: Author.

Fig.3.1 shows the demand curve considering the five parts of the mission mentioned before. This complete mission lasts for 115 hours. The mean of this curve is 1752.8kW and the standard deviation is around 1956kW. The mean calculated among the values located between the second and the third quartiles shows a value of 1004.4kW. An analysis comprising these values will be presented on the next chapter, contrasting the best generators chosen from the demand to the generators evaluated in each case.

3.1.2 Diesel Generators Evaluated

In this section, the diesel generators evaluated are shown. Firstly, Fig. 3.2a presents the fuel consumed in liters per hour by the main generators manufactured by the caterpillar. A linear pattern could be traced interconnecting the dots that represent the value of fuel consumed for 50%, 75% and 100% of the rated power of these diesel generators. The data was taken from different sources; 1100kW from (Caterpillar, 2020), 1360kW from (Caterpillar, 2021), 1550kW from (Caterpillar, 2014), 1820kW from (Caterpillar, 2010), 2200kW from (Caterpillar, 2015a), 2420kW from (Caterpillar, 2015b) and 2600kW from (Caterpillar, 2013).

In Fig. 3.2b the values for fuel consumed per liter are divided by the respective power level, then the calculated values are related to 1kWh, it leads to a curve that corresponds to a curve y-axis constant, it shows reinforces the idea of a pattern among the diesel generators.

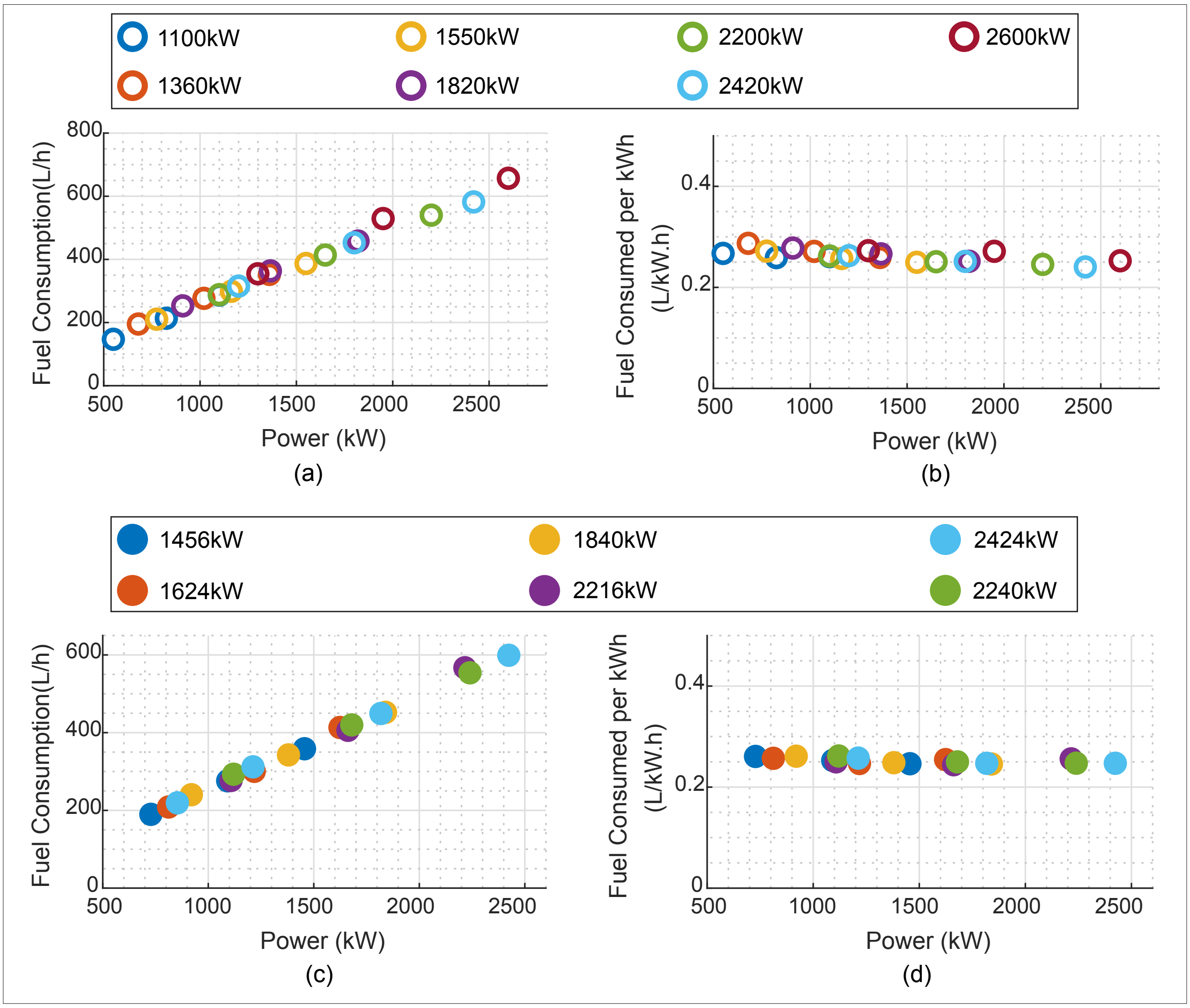


Figure 3.2 – Fuel Consumed in Liter per hour and in Liter per kilowatt hour for 50%, 75% and 100% of the rated power of MTU and CAT diesel generators.

Source: Author.

Figs 3.2a and 3.2b provide the same analysis than Figs 3.2c and 3.2d. However, Figs 3.2c and 3.2d are applied to MTU generators. The data for MTU generators was taken from different sources: 1456kW from (MTU, 2019a), 1624kW from (MTU, 2019b), 1840kW from (MTU, 2019c), 2240kW from (MTU, 2019d) and 2424kW from (MTU, 2019e).

The analysis of the generators evaluated in this work will also comprise the analysis of the maximum and minimum percentage of the rated power. The maximum values consist of 60%, 70%, 80%, 90% and 100%. Even though it is possible to operate at 100%, in a real operation the maximum operation is around 80% or 90%. That is the reason for evaluating different scenarios of maximum percentage. The change on the minimum percentage is done to avoid operation at low loads, last chapter described the reasons for not operating at this zone.

The variables analyzed in this work are:

- Generator Size, brand and fuel consumption curve: These variables are discussed in Fig 3.2. HOMER will choose in each part of the mission which generator will feed the demand;

- Maximum percentage of rated power: This variable limits the maximum rated power that the generator may dispatch. Limiting the maximum power may force the use of another generator which may increase the amount of fuel consumed. Real operation usually sets this value between 80% and 90%;

- Minimum percentage of rated power: This variable only allows a generator to operate if the demand remaining to be fed represent a value above the minimal value set. In other words, the generator operates in a range from the minimum and maximum percentages of rated power;

- Battery round-trip efficiency (RTE): It refers to the amount of electricity put into the battery that is later recovered, this efficiency is given in percentage and the higher it is, the less energy is lost in the storage process. The round-trip efficiencies investigated in this work varies from 92% to 98%. The test that determines the battery's RTE is known as "Stored Energy Test Routine" and is presented in (ROSEWATER; SCHOENWALD, 2021; CONOVER et al., 2014);

- Converter size and efficiency: To connect the batteries to the AC ship power system evaluated in this work AC-DC and DC-DC converters should be used. The converter's size is set to 3MW and the full efficiency of both converters combined is equal to 95%.

3.2 Methodology

This work aims at developing a methodology to evaluate the potential of different solutions to reduce CO_2 emissions of PSV. In Fig. 3.3 the flowchart of the methodology is portrayed. Phase A shows the first step, in this phase different generator sets will be evaluated, in this step we selected a number of generators and created sets of generators that had a similar sum of total power. These generators comprises two brands of diesel engines, Caterpillar and MTU. An analysis of the demand curve shows how the optimal generator set could be selected based on the mission that the ship usually pursue. In this first step, the optimal dispatch will use the battery as reserve. Considering the cost of changing the generator set, this analysis is more applied for new ships than retrofit.

The second step evaluated the impact that batteries would have in the analyzed cases if they were dispatched instead of only being used as reserve. This analysis can be applied for new ships and retrofit. This analysis is illustrated in Fig. 3.3 as phase B.

Furthermore, the methodology will adress the speed reduction on voyage missions, showing that reducing speeds leads to a reduction on power demand. This speed reduction will vary from 5% to 15% and will evaluate all the cases presented in the first step. Reducing the speed can be applied to the existing and to new ships, then the amount of fuel reduced differs from each generator set analyzed.

The investigation pursued in these steps use HOMER PRO to evaluate the optimal dispatch and Matlab to read the files exported from HOMER and calculate some variables, such as fuel consumed and reduction, percentage of time that the generators are used in each operation zone, battery cycles and CO_2 emissions.

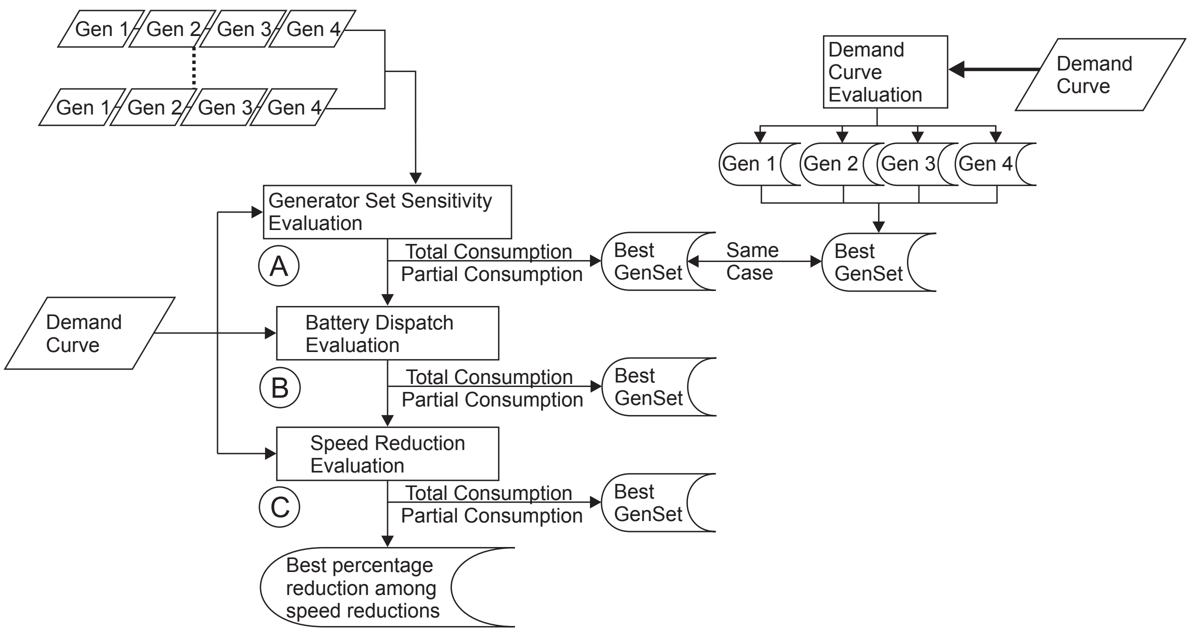


Figure 3.3 – Flowchart of the methodology. Phase A is more indicated to be applied in new ships. Phase B and C can be applied in new ships and for retrofits.

Source: Author.

Finally, besides the characteristics of the diesel generators analyzed, this methodology will evaluate some parameters of batteries, such as four different minimum state of charge (30%, 50%, 70%, 90%), and seven round-trip efficiencies, from 92% to 98%.

3.3 HOMER PRO

HOMER is a commercial software developed by HOMER Energy. HOMER software have more than 250,000 users in 193 countries. It is a established global leader for design optimization and feasibility. Since 2019, it is owned by UL, a global safety science leader. HOMER Pro is a generic energy dispatch optimization software for isolated systems.

There are some restrictions regarding the use of HOMER to model ship power systems. Changing the objective function is one of them. HOMER considers the objective function as cost. To evaluate the potential of batteries and fuel cells that are more expensive than diesel generators their cost was set to minimal. Therefore, HOMER would consider dispatching it the most, providing the highest fuel/CO_2 emissions reduction.

This work modeled diesel generators and batteries on HOMER using data from the literature and from datasheets of the manufacturers. HOMER also requires data from the demand. The simulations performed by HOMER can consider different time-steps. To determine the net present cost HOMER extends the time window of the demand analyzed for the whole life time of the project. HOMER does not perform dynamic simulations, only energetic evaluations.

Currently, there are very few simulation and design optimization tools available for hybrid power systems in the shipping sector (JAUROLA et al., 2018). General applications frequently use HOMER software for the optimal design of hybrid power grids (RAZMJOO et al., 2020; MORIA et al., 2020; GOSPODINOVA; DINEFF; MILANOV, 2020; BATISTA et al., 2020), but HOMER can also be used for maritime applications (P et al., 2019; ZAHBOUNE et al., 2016; TAHERI et al., 2021; VIEIRA et al., 2019; DIAB; LAN; ALI, 2016; DAWOUD, 2021).

In previous works (P et al., 2019; VIEIRA et al., 2019), HOMER can be used to estimate the CO_2 emissions of ships. Moreover, the main and auxiliary engines' load factors will be set according to the software's optimal energy-dispatch algorithm.

3.4 Application of the modeling and methodology on a real case

During the period of this PhD, some real data of a PSV was considered. From this data, it was possible to evaluate the difference on fuel consumption that HOMER has in comparison to the real consumption. To pursue this evaluation, firstly data was acquired, with a time-step of 5 minutes, from the PSV, such as fuel consumption and emission of the generators. The vessel operating profile with the power demands was also provided. Afterwards, we built a model using HOMER, for an operation of around 740 hours, HOMER simulations presented an error around 1.35% in fuel consumption when compared to field measurements. Fig. 3.4 portrays this comparison. The paper regarding this study is not yet finished.

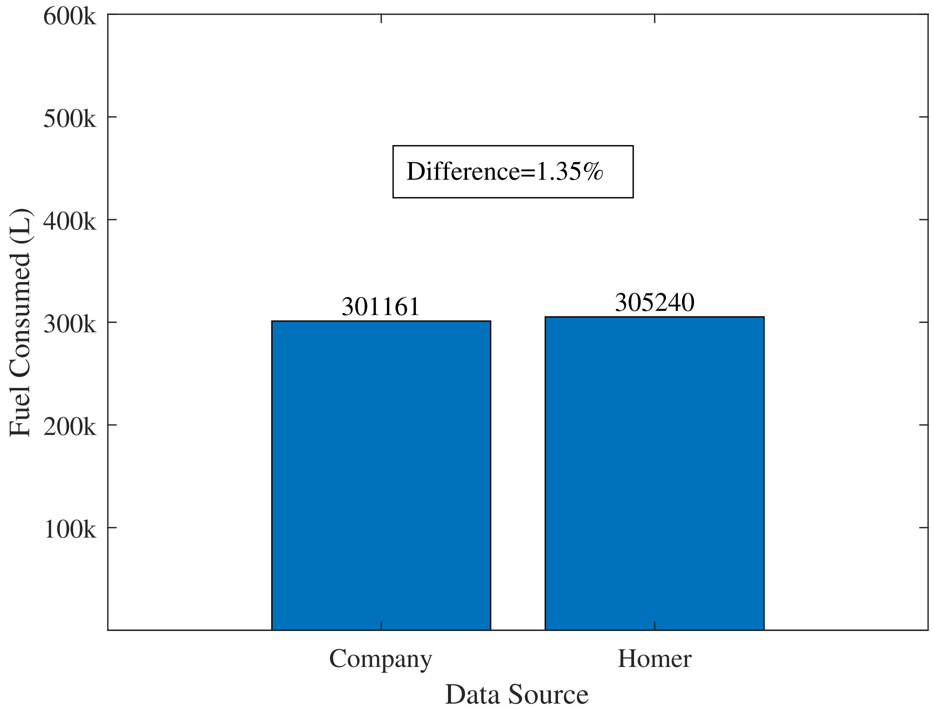


Figure 3.4 – Comparison between the real fuel consumption given by the company and the fuel consumption estimated by HOMER.

Source: Author.

The mainly results from this work are related to how the optimized dispatch can reduce the amount of fuel consumed. The average fuel reduction among the five months analyzed was 13.53% keeping the bus-tie opened and around 20.6% when the bus-tie was closed, both results considering a maximum percentage of rated power equals to 80%.

In this work we received the operational emission curve of the engines for CO_2, NO_x and PM, then we could calculate the CO_2 emission reduction obtained for a maximum percentage equals to 80% during DP operation with bus-tie opened and closed, this numbers were 10.64% and 20.14%, respectively.

Chapter 4

Impact of generator size change on emissions

Restrictions imposed by DP operations have limited the use of different generators, which could improve the operation of the system. The recent growth in batteries and their operation as a reserve can allow a ship power system with multiple sizes of gensets.

Even though this work discusses CO_2 emissions, the reader will see that the percentage reduction will be based on fuel. The percentages for fuel are the same for CO_2 emissions. HOMER considers a linear relation of 2.633 kg of CO_2 per liter of diesel. At the end of the chapter, a discussion regarding the amount of emissions that can be saved will be provided.

As mentioned before, the first step of this methodology is the evaluation of different generator sets to see which set provides the best results considering, reduction of fuel, generator participation and a lower percentage of operation on lower loads.

Table 4.1 – Cases including Caterpillar generators.

Cases	Sum of Power	Side A			Side B			Sum of Power (kW)	
	Sum Side A(kW)	**Aux Gen A (kW)**	**Main Gen A (kW)**	**Main Gen B (kW)**	**Main Gen C (kW)**	**Main Gen D (kW)**	**Aux Gen B (kW)**	Sum Side B (kW)	Total Sum (kW)
Case 1	3640		**1820**	**1820**	**1820**	**1820**		3640	7280
Case 2	3700		**2600**	**1100**	**1100**	**2600**		3700	7400
Case 3	3750		**2200**	**1550**	**1360**	**2420**		3780	7530
Case 4	3700		**2600**	**1100**	**1550**	**2200**		3750	7450
Case 5	3700		**2600**	**1100**	**1360**	**2420**		3780	7480
Case 6	4095	**455**	**1820**	**1820**	**1820**	**1820**	**455**	4095	8190

This analysis will consider two generator sets manufacturers to avoid conclusions based on data from only one company. The analyzes will be done considering only generators from the same corporation. The cases mentioned in Table 4.1 refer to Caterpilar gensets, whereas the cases illustrated in Table 4.2 are related to MTU gensets. In this chapter we will focus on the results for CAT generators considering the full mission and each part of the mission, it will also provides the results for MTU generators considering the full mission. The results for each part of the mission when MTU generators are used are available in Annex A.

As can be seen, eight caterpillar generators were chosen. The generator's power is highlighted in bold. These generators were divided into six cases, the first two differ in the use of auxiliary generators, which are much smaller than the main generators. For the other cases, generators with different sizes are selected. The base case includes four 1820 kW generators, the fuel consumption and emissions from this case will be used to determine the percentage reduction or increase obtained from the other cases.

For the analysis on MTU generators, five engines were chosen to form five cases, in this analysis auxiliary generators were not used. The base case, that will be used as a comparison is Case 1. Different from the Caterpillar base case, here the generator size is 1840kW.

Table 4.2 – Cases including MTU generators.

Cases	Sum of Power	Side A		Side B		Sum of Power	
	Sum Side A(kW)	**Main Gen A(kW)**	**Main Gen B(kW)**	**Main Gen C(kW)**	**Main Gen D(kW)**	Sum Side B(kW)	Total Sum(kW)
Case 1	3680	**1840**	**1840**	**1840**	**1840**	3680	7360
Case 2	3880	**2424**	**1456**	**1456**	**2424**	3880	7760
Case 3	3864	**2240**	**1624**	**1624**	**2240**	3864	7728
Case 4	3696	**2240**	**1456**	**1624**	**2240**	3864	7560
Case 5	3880	**2424**	**1456**	**1624**	**2240**	3864	7744

One important point is shown in the columns named as "Sum of Power" in both tables. Failures can bring one side of the power system down, so the amount of power on each side must be close, if possible equal, so DP2 requirements can be met. All cases evaluated present a higher number in this criteria than both base cases. For CASE1, all generators have the same amount of power and a failure of one would cause a maximum loss of 25%. It does not occur on the other cases that have different sizes for the main generators. In these cases a failure could reach higher values, reaching 35% in case 2 of caterpillar engines, which is the worst number in terms of failure. Using a battery as a reserve can surplus the power required for a given amount of time, which would allow the ship to finish the DP operation.

In this chapter the figure results portraying the percentage of fuel consumption reduction have three colors, red represents the configurations that have an increase of fuel consumption in comparison to the base case. Moreover, yellow represents the reductions smaller than 2%, this number was selected due to the reduction of 1.35% achieved in comparison to real numbers as presented in the last chapter. So, for this yellow region, the real reductions may be close to zero. Then, green represent the reductions that are above this level of uncertainty set to 2%. In this region, the probability of having real reductions in the real world are higher than the yellow region.

4.1 CAT results

The first results evaluated are regarding the fuel consumption of diesel generators. For these results, batteries do not dispatch, they are used only as a reserve, allowing the generators to operate without restriction during DP. In Fig. 4.1, the numbers regarding the percentual reduction of fuel consumption for the complete mission are presented. Horizontal axis presents the two minimal power evaluated, 10% and 50%. It means that the generator will feed the load only if the generators are above this minimal percentage of its rated power. This minimal percentage is applied only for LV, DP, and PLV. In LP and ST, the generators must operate under 50% to attend to the load. The horizontal axis also presents a variation of the maximum rated power allowed. This maximum rated power is applied for LP, DP, and ST operation. For LV and PLV the maximum rated power is fixed at 100%. So, for example, the last column represents that the generators will operate in a range that goes from 50% to 60%, whereas in the first column the generators operate on a scale from 10% to 100%.

As can be seen, CASE1 which comprises all generators of the same size, four 1.85MW generators, has the worst results for an allowed maximum operation of 100% rated power. When we reduce the maximum power allowed, we can see an increase in fuel consumption, reaching an increase of almost 3% when the maximum is set at 60% of the rated power. CASE6 is similar to the cases that were evaluated in other papers (P et al., 2019; VIEIRA et al., 2022), it comprises four 1.85MW generators with two 450kW auxiliary generators. As can be seen, the use of auxiliary generators shows a reduction that varies from around 1.1% to 2.5% for a variation from 60% to 100% of maximum rated power. The elevation of the minimal power from 10 to 50 is not applied to the auxiliary generators. As can be seen, CASE1 only can feed the loads, without a power generation surplus with a minimal power of 50%, if the generator's maximum rated power is equal to 100%. For all other levels of maximum rated power, the operation is not possible.

For a minimum of 10% of the rated power, CASE2, operating with a maximum rated power of 60%, achieves a similar reduction to CASE6 operating with a maximum rated power of 100% (2.49% vs 2.53%). It can be considered an advantage since this amount of power from 60% to 100% can be used as a reserve. For a maximum rated power of 100%, the reduction obtained with CASE2 reached around 3.36%. For this level of maximum rated power, CASE2 obtains the fourth-highest fuel reduction. CASE2 with a minimum power of 50% only operates with a maximum of 100%, the reduction is a bit smaller than the reduction obtained for a minimum of 10% of its rated power.

CASE3 operating with a maximum rated power of 60% provides a higher fuel consumption reduction than CASE2 operating with 100%. As mentioned for CASE2 in comparison to CASE6, CASE3 also has this advantage in comparison to CASE2, the amount of power from 60% to 100% can be used as a reserve. Operating with the generator set presented on CASE3 with a maximum rated power of 100% achieves a reduction of 4.79%. Changing the minimal power from 10% to 50% on CASE3 provides similar results, but at this minimum percentage, the generators cannot operate with a maximum percentage under 80%. Finally, we can move the discussion to CASES 4 and 5, which are the cases with the highest fuel consumption results.

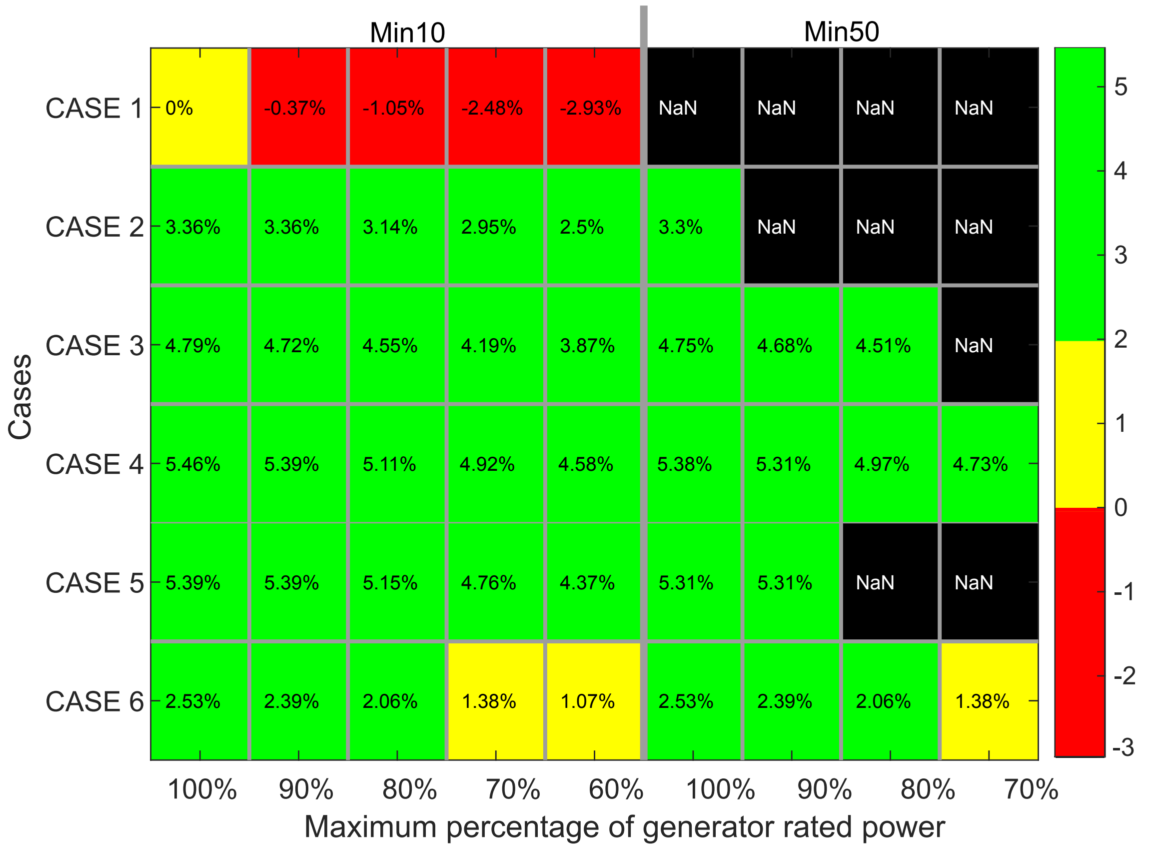


Figure 4.1 – Percentual reduction of all cases evaluated with CAT engines related to Case 1/Min10/Max100.

Source: Author.

Even though CASE5 did not reach the highest fuel consumption reduction among all cases, this case has the advantage of achieving the highest fuel consumption reduction with two maximum percentages of rated power. They are equal to 90% and 100%. Moreover, as can be seen, for 90% and 80%, this reduction is the highest among all cases. Moreover, it can be seen that for a maximum percentage of 70%, the reduction obtained is higher than the reduction obtained for the other cases for a maximum percentage of 100%.

Finally, we can discuss CASE4, which is the case that achieved the highest fuel consumption reduction. We can see that CASES 4 and 5 reached similar numbers for reduction when a maximum power of 90% is analyzed. For a maximum power of 100%, CASE4 provided the highest fuel consumption results, these numbers were slightly higher than those obtained with CASE5. Another difference we can see between CASE4 and CASE5 is that for a minimum percentage of 50%, CASE4 can operate for all levels of maximum percentage varying from 70% to 100%, whereas CASE5 has a varying range of operation from 80% to 100%. One interesting point by comparing CASE4 and CASE5 is that at 80%, CASE5 achieves a higher reduction than CASE4.

4.1.1 Evaluation of the demand curve

Considering the values for Interquartile Mean and Mean calculated for the demand provided in Table 4.3, we can see that considering these values as a value for the most efficient point of the generators, which is around 85% (LINDSTAD; ESKELAND; RIALLAND, 2017; HANSEN et al.,), we would have an optimal generator of 2062.15kW for the mean data and an optimal generator of 1181kW for the interquartile mean.

Table 4.3 – Demand curve statistics.

Cases	Mean	Standard Deviation	Quartiles 1st	Quartiles 2nd	Quartiles 3rd	Quartiles 4th	Interquartil Mean between the values of the 1st and 3rd quartiles
Demand	1752.83	1956.4	400	950	1570	6740	1004.455

Table 4.4 – Total Power Sum of the CAT generators highlighted in black. In red, CAT generators that fit better the numbers of interquartile mean and total mean of the demand are presented in Table 4.3.

	Gen Aux 1	Main Gen 1	Main Gen 2	Main Gen 3	Main Gen 4	Gen Aux 2	Sum without Aux	Sum with Aux
Case 1		1820	1820	1820	1820		3640	
Case 2		2600	2600	1100	1100		3700	
Case 3		2200	1550	1360	2420		3970	
Case 4		2600	1100	1550	2200		4150	
Case 5		2600	1100	1360	2420		3960	
Case 6	455	1820	1820	1820	1820	455	3640	4550

When we use these numbers to analyze the generators presented in Table 4.1 we can see that only cases 2,4 and 5 had the 1100kW generator which was the closest to the value obtained for the interquartile mean. On the other hand, the closest generator power to 2062.15kW is 2200kW. Contrasting the data of the mean value to this generator, it implies in an operation at 79.7%, which is close to the most efficient operation point. This generator is presented in cases 3 and 4.

Considering the mean data of 1752.8kW, around 77.9% of the demand data is under this level of demand. This analysis may present a reason for CASE4 to present the best results since it contains the two generators that best fit the demand curve. Considering that two generators were used to operate at the interquartile mean and the total mean, the other generators would be used to feed the loads during these variations. A final investigation regarding the amount of power that these other generators can supply, is depicted in Table 4.4. As can be seen, CASE4 is the one that also provides the highest amount of power, without considering the other two generators, it covers more than the sum of the total mean and the standard deviation.

4.1.2 Loading in Port(LP)

Fig 4.2 displays the amount of fuel consumed by each diesel generator during LP. It is highly important to have in mind that the diesel generator differs in each case. As mentioned in Table 4.4, for CASE1, generators from 1 to 4 are 1820kW. For CASE2, generators 1 and 2 are 2600kW, whereas generators 3 and 4 are 1100kW. CASE3 generator 1 is the 2200kW, whereas 2,3 and 4 are respectively 1550kW, 1360kW and 2420kW.

CASE4 and CASE5 have as generators 1 and 2 the 2600kW and the 1100kW diesel generators, respectively. Generator 3 of CASE4 is the 1550kW and generator 4 is the 2200kW diesel generator. Generator 3 of CASE5 is the 1360kW and generator 4 is the 2420kW diesel generator. Finally, generators 1,2,3 and 4 of CASE6 are the 1820kW diesel generators as CASE1, for CASE6 there are also two auxiliary generators. Besides that, the level of demand during LP forbids the use of generators operating at a minimal level of 50%. Therefore, in this operation, only the minimal level of 10% was analyzed.

As can be seen in Fig 4.2, during LP, which is an operation that requires a lower amount of power, each case has, most of the time, only one generator operating. As CASE1 has four identical generators, the operation for this case is run by generator 1. For CASE2, the operation is run almost entirely by one 1100kW generator, named as Generator 3 in Fig 4.2. When the maximum percentage of the rated power is decreased to 60%, the operation requires generator 4, which is also one 1100kW generator.

The comparison between CASE1 and CASE2 in Fig 4.2 portrays that for a maximum percentage varying from 70% to 100% the fuel consumption reduction during LP is around 19.1%, it is obtained by the simple change of the diesel generator from 1820kW to 1100kW. For the maximum percentage of 60%, this reduction slightly reduces to 18%.

For CASE3, the optimized dispatch from HOMER chooses generator 2, which is the 1550kW diesel generator, for all levels of maximum percentage analyzed. Considering the fuel reduction obtained compared to CASE1, the reduction is around 9.43%. If we compare CASE3 to CASE2, CASE2 consumes around 11.9% less than CASE3.

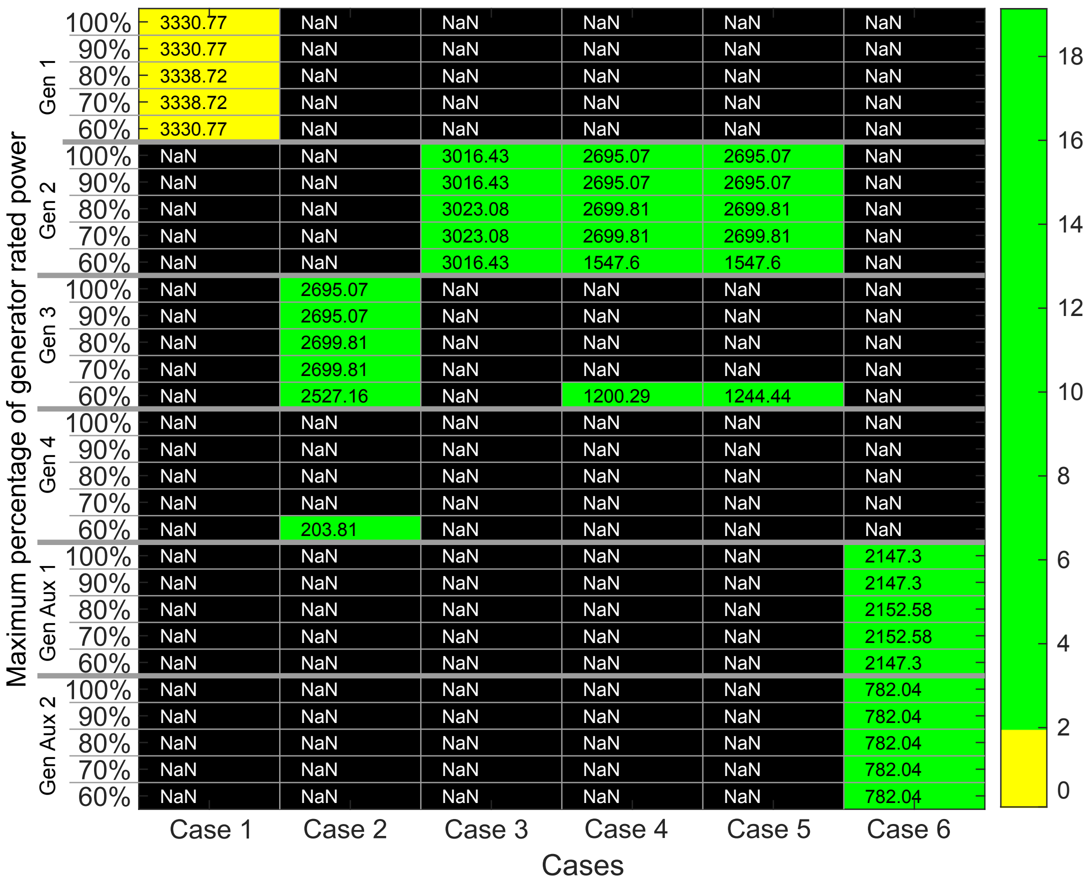


Figure 4.2 – Fuel Consumed during LP operation in liters per generator in each case for the different maximum percentage of generator rated power. The minimum load of generators was set to 10% for LP operation.

Source: Author.

The analysis of the fuel consumption of CASE4 and CASE5, the generator mostly used is generator 2 for both operations, for these cases, generator 2 is the 1100kW. As can be seen, the numbers are the same presented for the CASE2 operation. As occurred in other cases, the maximum percentage of 60% of the rated power requires a second generator, which is generator 3 for both cases. For CASE4, generator 3 is the 1550kW diesel generator, whereas for CASE5, generator 3 is the 1360kW. Here, as happened in CASE3, the 1550kW diesel generator provides a lower consumption than the 1360kW diesel generator for the same operation. It results from the fuel curves get from the datasheets. For a maximum percentage of 60%, the fuel consumed during this operation is marginally higher than the fuel consumption of CASE2. CASE2 generators consumed 2,730.97 liters, whereas CASE4 and CASE5 consumption was around 2747.89 and 2,792.04 liters, respectively.

Finally, a discussion about the use of auxiliary engines can be performed by analyzing CASE6 fuel consumption. As presented before, both auxiliary generators are 455kW and are used only in CASE6. During LP, auxiliary generator 1 consumes 2,147.3 liters, whereas auxiliary generator 2 consumes 782.04 liters. The total consumption for all levels of the maximum percentage of the rated power is 2929.34 liters which is lower than CASE1 and

CASE3. As discussed in other papers, for demands with considerable variations, the use of auxiliary generators presents a benefit, in terms of fuel consumption, when installed in a set with four generators of the same size. In a comparison between CASE2 and CASE6, CASE2 had a fuel consumption of around 7.2% lower than the fuel consumption of CASE6.

To summarize the analysis of Fig 4.2, the cases that had the 1100kW diesel generator obtained the lowest fuel consumption. For a maximum percentage of rated power equal to 60%, CASE2, which has two 1100kW diesel generators, obtained the lowest fuel consumption. Moreover, it is interesting to note that, in terms of fuel consumption, investing in auxiliary generators is worst than using 1100kW diesel generators.

4.1.3 Voyages - Laden and Partial Load Voyage

Moving the analysis to Fig 4.3 that portrays the results of fuel consumption for LV and PLV, we can see at least two main differences. First, differently from the results portrayed in Fig 4.2, the results displayed for the voyages show the numbers for the two minimal percentages of rated power analyzed, 10% and 50%. Secondly, most of the time, these two voyage operations use all generators allowed, it occurs due to the level of power demand.

The results are shown in two blocks, the upper block highlights the results for LV, whereas the lower block illustrates the results for PLV. For laden voyage, cases from 1 to 5 all four diesel generators are used. CASE6 uses all six generators. On the other hand, for the CASE6 set of generators, partial load voyage uses only five generators.

When we consider the results for the rated power's minimum percentage to turn on the generator equal to 10%, we can see that CASE1 mainly uses three diesel generators, around 98.5% of the total fuel consumed during partial load voyage is consumed by the diesel generators 1,2 and 3. For laden voyage, this number reduces to about 86.9%, as generator 4 increases its participation. The total fuel consumed during PLV was around 14,180.36 liters, whereas this number during LV was about 17,196.19 liters.

For laden voyage, the generators of CASE2 consume 17134.29 liters for a minimum percentage of 10%, and 17235.38 liters for a minimum of 50%. For partial load voyage the fuel consumption reached 14,175.05 liters for a minimum of 10% and 14,203.89 liters for a minimum of 50%. As can be seen, these numbers are close to those presented by the generators of CASE1. Considering the concentration of the fuel consumed by the two generators with the highest consumption. CASE2 has the highest concentration of fuel consumed, in only two generators, during laden voyage, 81% of the fuel consumed during HOMER dispatch was used by generators 1 and 2. When we consider generators 1,2 and 3 we see that 96.2% of the fuel consumption was consumed by these generators. For partial load voyage, this concentration increases to around 90.9% for a minimum percentage of

10%, whereas for a minimum percentage of 50%, this number reached 88.53%. Using three generators this concentration reached 97.5% for both minimum percentages.

In terms of fuel reduction, the comparison between CASE1 and CASE2 portrays almost no reduction for partial load voyage, around 0.04%. For laden voyage this number is also minimal, about 0.36%. The amount of fuel saved is 61.9 liters for partial load voyage and 5.31 liters for laden voyage.

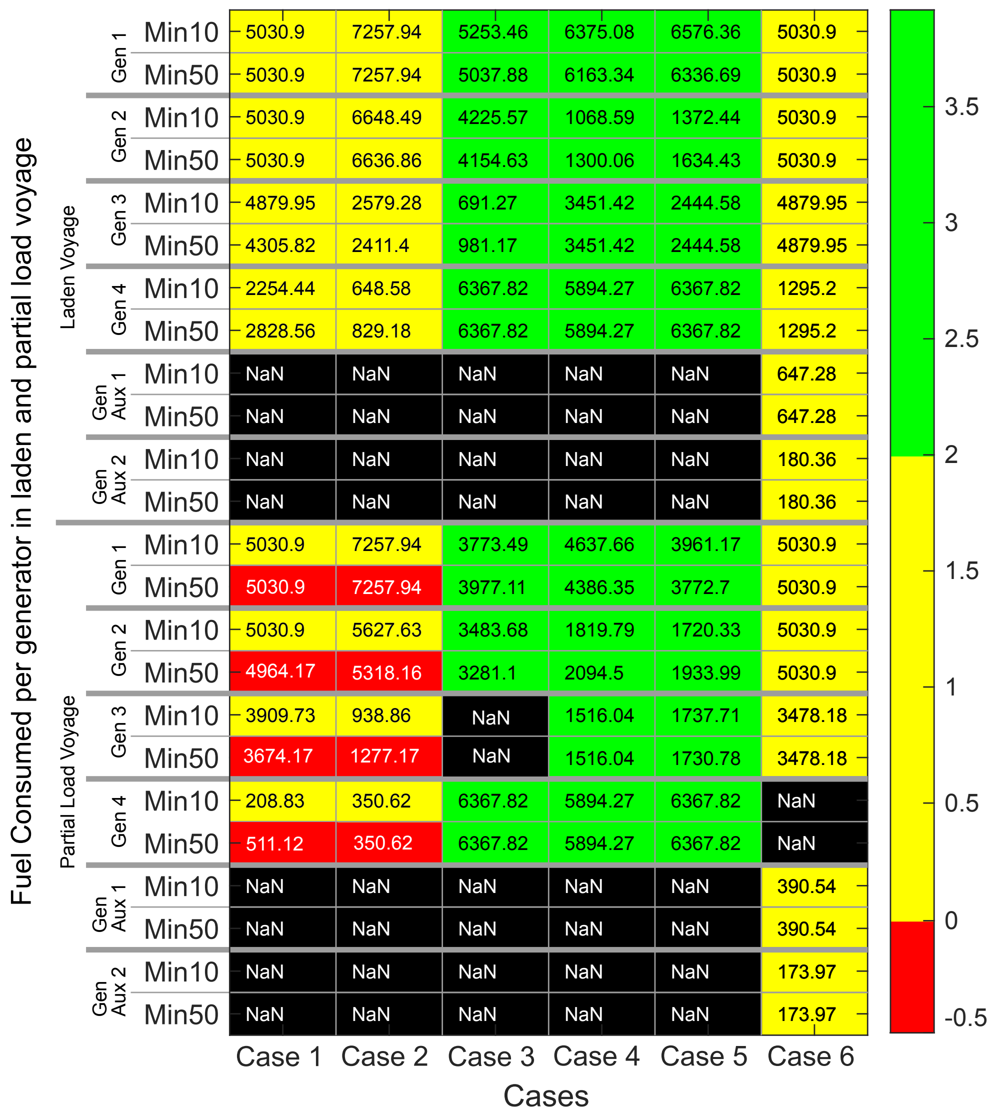


Figure 4.3 – Fuel Consumed during LV and PLV operation in liters for each generator in each case for a maximum percentage of generator rated power equal to 100%. The minimum load of generators was set to 10% and 50% for LV and PLV operation.

Source: Author.

The lowest consumption for these voyages is reached by CASE3. Comparing this consumption to the consumption obtained with CASE1, we have for laden voyage a reduction around 3.83% for both minimum percentages, whereas for partial load voyage the reduction is around 3.91%. Another advantage of CASE3 is the distribution of the fuel consumed by the generators. Considering the two generators that consumed more fuel, generators 1 and 4, their consumption equals 70.3% for laden voyage and 74.4% for partial load voyage. Considering that, the year has 8640 hours and that the full mission has 115 hours, this PSV would pursue this full mission about 75 times. So, without considering the amount of time without operation or the amount of time in maintenance, the number of liters saved would be around 41,652.75 liters, it is equivalent to 2.4 and 2.9 times the amount of fuel consumed using CASE1 during laden voyage and partial load voyage, respectively.

For a minimum percentage of 10% during laden voyage, the cases that had the highest overall reductions, CASE4 and CASE5 presented reductions around 2.37% and 2.53%, respectively. For a minimum percentage of 50%, these reductions are slightly lower, 2.25% and 2.4%. For partial load voyage, the numbers, when the minimum percentage of 10% is analyzed, are around 2.2% and 2.8%, whereas the reductions for the minimum percentage of 50% are 2.04% and 2.64%. When the concentration of fuel consumed is discussed, the numbers comprising two generators, for both cases gen 1 and gen 4, are 73.08% and 77.23% for CASE4 and CASE5, when laden voyage is considered. For partial load voyage, these numbers are about 75.9% and 74.9% for CASE4 and CASE5, respectively. In terms of concentration, these numbers are higher than those presented for CASE3 but lower than those displayed for CASE2. Concentration is important to evaluate the maintenance that will be required, lower numbers are better.

Finally, CASE6 has a reduction of around 0.8% for laden voyage and circa 0.5% for partial load voyage. Considering the calculation pursued for CASE3, we can say that in one year the total fuel reduction would be 5,690.25 liters for partial load voyage and 9,870 liters for laden voyage. Summing both reductions we have 15,560.25 liters, which is smaller than the amount of fuel consumed during laden voyage but higher than the fuel consumed during partial load voyage. Since in loading in port, auxiliary engines also presented higher numbers than using a set comprising different generators, it can be said that from the consumption point of view, using these generators does not present any advantage. A study on the generator operation point should be done to evaluate the auxiliary generator's role in reducing the percentage of time that the generators are operating at low load.

4.1.4 Dynamic Positioning (DP)

Considering the usual dispatch of a DP operation, we would have the fuel consumption presented in Table 4.5. For this operation, we have considered that the CASE6 operation would rely only on the main generators, so the fuel consumption would be the same as CASE1's consumption. It is also presented that, without considering any optimization, all other cases provided a fuel reduction. Here, we must discuss about reliability. In CASE1 and CASE6, if one generator fails, the substitution will consider a generator of the same size. The same does not occur with the other cases, this reliability can be increased with the battery.

So, without any optimization and using battery as a reserve to increase reliability, the case that achieved the lowest reduction is CASE5, this reduction was around 6.2%. CASE3 achieved a reduction of 7.8%. The amount of fuel reduced using CASE2 is equal to 8.4% and CASE4 reduced by 10% the fuel consumed.

Table 4.5 – Fuel consumed during DP operation with the four generators sharing the demand equally.

	CASE1	CASE2	CASE3	CASE4	CASE5	CASE6
Total Consumption (l)	22,184	20,318	20,461	19,960	20,819	22,184
Fuel Reduction (%)		8.4%	7.8%	10.0%	6.2%	0.0%

Now, moving to the discussion regarding the optimized dispatch of HOMER, we should analyze Fig 4.4. As mentioned before DP operation is the most dangerous operation, in a standard ship, without any energy reserve, all engines would share the loads equally, so in case of a failure in one of the generators, the load would be quickly distributed among the others. It leads to generators being used at bad points of operation which leads to a shorter time between maintenance and unnecessary use of diesel generators. The results portrayed in Fig 4.4 show the fuel consumption of all cases during DP. In these results, despite not using the battery on the dispatch, it provides energy reserve allowing diesel generators to operate at their optimal point.

Analyzing all the cases considering a minimum percentage of 10%, we can see that two generators are required for CASE1 and CASE2 when the maximum percentage evaluated is 90% or 100%. Three generators are required for CASE3, CASE4 and CASE2 with maximum percentages under 80%. Finally, CASE6 requires one main generator and two auxiliary generators. When we analyze the data considering the minimum as 50%, we can see that the operation is not possible for some maximum percentages. CASE4 operates with all percentages, CASE3 only above 80%, CASE5 above 90% and CASE2 above 100%. Here we can see the benefit of using auxiliary generators, their use expands the use of the generators used in CASE1 to all levels of restrictions evaluated.

When CASE1 is considered, with a maximum percentage of 100%, this set of diesel generators provided a total fuel consumption of 15,256.75 liters. Reducing the maximum percentage to 90% and 80%, the increase in fuel consumed during the operation is around 1.3% and 3.5%, respectively. Reducing the maximum percentage allowed to 70% and 60% would provide a considerable increment of fuel consumed, it would be around 8.5% and 10.2%, respectively.

When these numbers are compared to those provided in Table 4.5 for CASE1, we can say that the amount of diesel consumed during operation with CASE1 with a maximum percentage of 60% is deeply lower than the amount of fuel normally consumed during a

DP operation. The difference is around 24.2%. For the maximum percentage allowed this reduction increases to 31.2%. This 24.2% of reduction, in terms of liters, is equivalent to 5372.93 for one mission. For one year it is close to a reduction of 402,969.8 liters, which is huge considering that one full mission consumes around 53,229 liters. So, by using battery as a reserve and dispatching optimally the same generators that compose CASE1 with a restriction on the maximum percentage of rated power set to 60%, we can achieve a reduction that is equivalent to 7.5 times the amount of fuel consumed in one full mission. If we do not consider this restriction, this reduction can be equivalent to around 9.7 times.

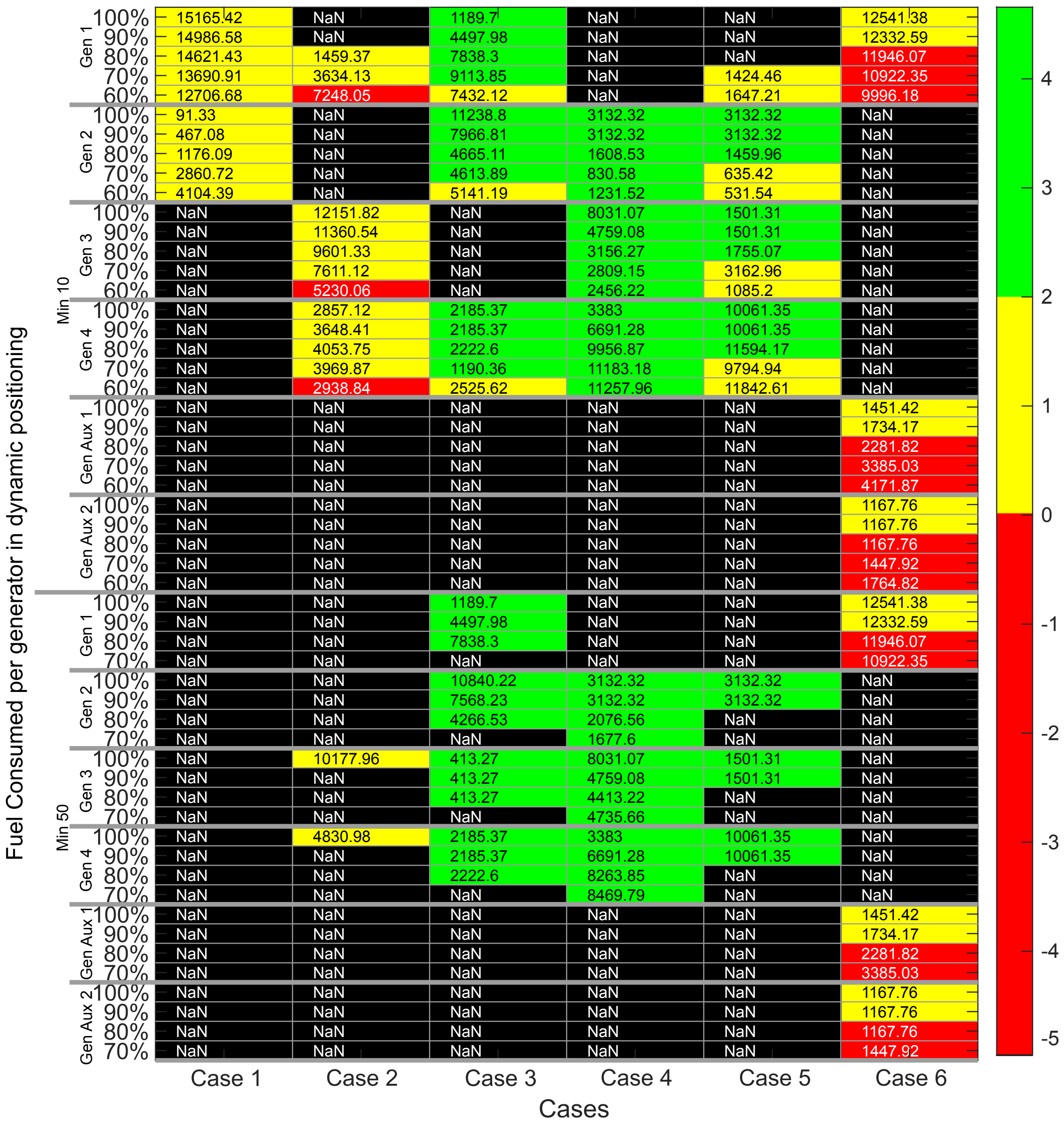


Figure 4.4 – Fuel Consumed during DP operation in liters for each generator in each case for different maximum percentage of generator rated power. The Minimum load of generators was set to 10% and 50% for DP operation.

Source: Author.

As mentioned, in CASE1, the decrease in the maximum percentage allowed, led to a considerable increase in the fuel consumed. The same does not occur in the other cases analyzed, the maximum increase comparing the fuel consumed without restriction and with a maximum percentage of 60% is around 5.1% for CASE6 and 3.3% for CASE3. Considering that, the battery would provide the reliability required from DP rules, the other cases analyzed would have the advantage of having a small fuel change as the maximum percentage increases. In terms of liters, CASE3 has the greatest difference between 100% and 60%, around 3.3%. It would consume 485.06 liters more per mission, in one year it would be equivalent to 36,379 liters. CASE4 has the smallest difference, about 2.7%. For their operation 399.31 liters more would be required in each mission, and 29,948.25 liters more in one year.

Comparing the numbers of CASE2 and CASE1 for an optimized dispatch of the generators during DP operation, we can see, for both cases with a maximum percentage of 100%, a reduction of fuel consumption of around 1.6%. When the maximum percentage is reduced to 90% for both cases, this reduction increases to 2.9%. The numbers of reduction when both cases have a maximum percentage of 80%, 70% and 60% are 4.3%, 8.1% and 8.3%, respectively. The amount of fuel consumed when CASE2 is used is only smaller than CASE6 and obviously CASE1, which has the worst fuel consumption. Moving to an internal analysis of CASE2, we can see that a reduction from 100% to 90% results in no increase of fuel consumption. It is a good advantage of CASE2 over CASE1, this set of generators can operate at 90% using the remaining 10% as a reserve without compromising the fuel consumption and still operating with only two generators. Moving forward the reduction from 100% to 80%, 70% and 60% provides an increase in the amount of fuel consumed by around 0.44%, 1.11% and 2.7%, respectively.

Moving the analysis to CASE3, we mentioned that this generator set requires the use of three diesel generators, even when these generators are not allowed to operate at their rated power. The total fuel consumption with the generators without any restriction to operate was 14613.87 liters, it is 4.21% lower than the total fuel consumption obtained with CASE1. Comparing both cases with a maximum percentage of 90%, 80%, 70% and 60% shows that CASE3 has lower numbers of fuel consumed, the reductions are 5.2%, 6.8%, 9.9% and 10.2%, respectively. So, considering the maximum percentage of 100%, the amount of fuel not consumed by the change from CASE1 to CASE3 is about 642.88 liters. This change would lead to a fuel saving of about 48,216 liters in one year. Besides this considerable fuel reduction, another advantage of CASE3 is that the reduction of the maximum percentage present much lower variations in the amount of fuel consumed when compared to CASE1. Reducing from 100% to 90%, 80%, 70% and 60% have the following increases of fuel consumption, 0.2%, 0.8%, 2.1% and 3.3%.

CASE4 achieved the highest fuel consumption reduction for all levels of maximum percentage. For 100%, 90%, 80%, 70% and 60% the reductions, in comparison to CASE

1, are 4.7%, 5.6%, 6.8%, 10.4% and 11.1%, respectively. Considering the number of liters saved, this case reaches a higher number than CASE3. Per mission, the reduction reaches 710.4 liters only considering this reduction in DP. Considering an annual mission, the change from CASE1 to CASE4, reaches a reduction of about 53,277.0 liters. We can measure this annual reduction in terms of operations.Considering the fuel consumed using CASE1, which is the worst case, the amount of fuel reduced is equivalent to almost 3.5 times the fuel consumed during DP, which is around 15,256.8 liters. Moreover, this annual reduction is about 3.1 times the fuel consumed in LV operation, which is around 17,196.19 liters and more than 3.7 times the fuel consumed during the operation of PLV, in this part of the mission the fuel consumed was around 14,180.36 liters. Considering an internal comparison of CASE4, by reducing the maximum percentage from 100% to 90%, we can see an increase in fuel consumption of 0.2%.This reduction to 80%, 70% and 60% causes an increase in fuel consumption of around 1.2%, 1.9% and 2.7%, respectively.

CASE5 presents the second-highest fuel consumption reduction. From the comparison with CASE1, the reductions when both cases operate with a maximum percentage of 100%, 90%, 80%, 70% and 60% are around 3.7%, 4.9%, 6.3%, 9.3% and 10.1%, respectively. A reduction from 100% to 90%, presents no increase in fuel consumption. This advantage was only obtained using CASE2 and CASE5. When the maximum percentage is reduced to 80% the increase is around 0.8%. For a reduction from 100% to 70% and 60%, the increase is about 2.2% and 2.8%.

Finally, moving the discussion to CASE6, we can see that in comparison to CASE1, CASE6 provides the smallest reduction. For a maximum percentage of 100%, 90%, 80%, 70% and 60%, this comparison shows that the fuel consumed using the generator set of CASE6 is 0.6%, 1.4%, 2.5%, 4.8% and 5.2% smaller than CASE1, respectively.

Comprising all numbers of fuel consumption, we can see that CASE4 operating with a maximum percentage of 90%, provides a lower consumption than CASE3 operating with a maximum percentage of 100%. When cases 3 and 4 operate with a maximum of 70%, the numbers of consumption are lower than the consumption achieved for CASE2 operating without restriction of maximum percentage. Moreover, when CASE2 operates with the restriction set to 70% and cases 3,4 and 5 with a restriction set to 60%, these cases have a lower fuel consumption than CASE1 operating without restrictions.

4.1.5 Standby(ST)

Moving the analysis to Fig. 4.5, we can see that for this final part of the demand curve, cases 2, 4 and 5 presented the lowest fuel consumption regarding a maximum percentage of rated power that varies from 100% to 70%. These cases reached a reduction of about 27.5% in comparison to CASE1. When we analyze the results for a maximum percentage of 60%, we can see that there is a difference between these three cases. CASE2 has the lowest fuel consumption for this level of percentage, this reduction was around 27.1%.

CASE4 and CASE5 obtain, for the same percentage, a reduction of around 26.9% and 26.5%, respectively.

These highest reductions of 27.5%, are equivalent to the amount of 828.54 liters, leading to an annual reduction of about 62,140.5 liters. This number is equivalent to four times the DP or the PLV operation, it is also similar to three times the fuel consumption during LV operation.

Compared to CASE1, the case that considers the use of auxiliary generators provides a reduction around 21.1% for all levels of maximum percentage. To be clear, the maximum percentage here does not influence due to the exclusive use of the auxiliary generators. As mentioned before, the auxiliary generators operate from 50% to 100% of their rated power. When we compare CASE3 to CASE1, we can find numbers around 12.2%, which are the lowest reductions.

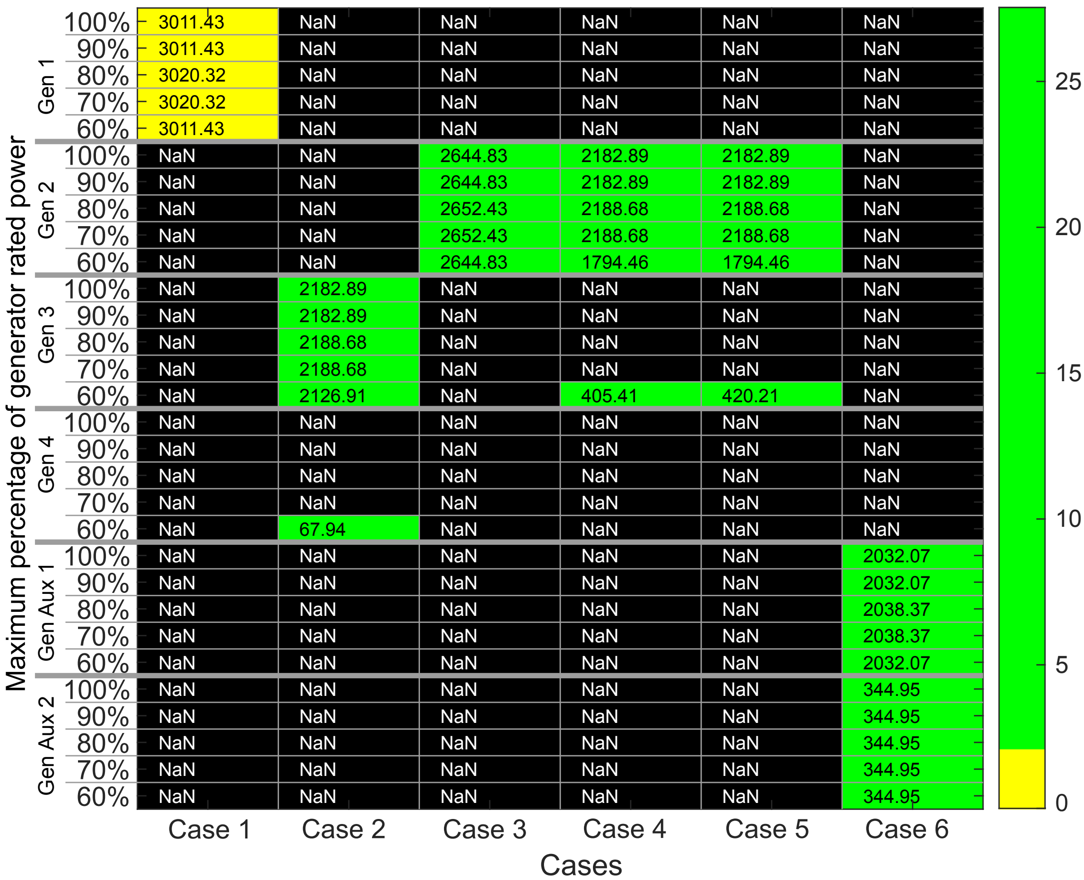


Figure 4.5 – Fuel Consumed during ST operation in liters per generator in each case for the different maximum percentages of generator rated power. The minimum load of generators was set to 10% for ST operation.

Source: Author.

4.1.6 Percentage of time in each operation zone

A final analysis of the CAT engines comprising the percentage of time in each zone of operation that the generators are is provided in Figs.4.6 and 4.7.

Figs.4.6 and 4.7 also have three colors as the previous ones. For these figures, red represents the avoidable region that goes from 0% to 25%, the ideal number portrayed in this region should be zero. Then, we have the yellow region that goes from 25% to 50%, the ideal number for this region should also be zero but it is not as bad as the red region. Finally, the green region, above 50% represent the zone in which the diesel generators should operate.

As can be seen, in CASE1, when the operation is LP or ST, the 1820kW diesel generator operates most of the time under 50%, in some operations the generators chosen by HOMER operate around 79.2% of the time under 25% of its rated power. When the operation is DP, we can see that whereas one of the generators operates for more than 75.2% of the time under 25% of its rated power, the other generator operates around 24% of the time between 25% and 50% of its rated power. Finally, when we analyze the voyages, we can see that for laden, two generators are operating close to their rated power, a third generator is operating above 50% the whole time, a fourth generator is used 60% of the time under 50% and 40% between 50% and 75%.

When we analyze the numbers for CASE2, we can see that as presented in the fuel consumption figures for LP and ST, When the maximum percentage is set to 60%, there are two generators operating. When we increase the maximum percentage to 70% we see that the percentage of time that the generators are under 50% reduce considerably, from 100% to 66.7% during LP and from 100% to 87.5% during ST. Moving the analysis to the DP operation and analyzing the numbers for the maximum percentage equal to 60%, we can see that CASE1 uses one generator 24% of the time under 50%, and the other the whole time under 50%. For CASE2 it changes completely, one generator is 19.8% of the time under 50%, whereas the other is only 67.9%. In other words, the two generators that are in operation reduce their operation under 50%. As we increase the maximum percentage the amount of time under 50% increases for the second generator but reaches zero for the first one. The percentage of time under 50% reaches 84.6% for a maximum percentage of 100%, the first 1100kW generator is equal to zero. For CASE1, these numbers were equal to 24% for the first gen and to 100% for the second generator, this percentage for the second refers to an operation under 25%.

Analyzing the numbers for LV and PLV for CASE2 we can see that the two 2600kW operate the whole time above 75%. One 1100kW generator operates 18.3% and the other 81.4% in a range from 25% to 50%. For PLV, one 1100kW generator operates 14.5% from 25% to 50%. In comparison to CASE1, we can see a reduction in the amount of time under 50% for PLV, from 17.6% to 14.5%. For laden voyage, CASE2 presents worst numbers than CASE1, concerning the amount of time under 50% but better numbers in relation to the amount of time under 25%. CASE1 had one generator operating 40% of the time under 25%, and CASE2 had 0% of the time under 25%. On the other hand, CASE1 had one generator operating 20% of the time from 25% to 50% whereas CASE2 had one generator operating 18.3% of the time from 25% to 50% and another operating 81.4% of the time from 25% to 50%.

CASE3 results for ST show numbers similar to CASE1, 79.1% of the time the 1550kW generator operates under 25% of its rated power. For LP, the numbers are slightly better in comparison to CASE1, with 37.8% under 25% against 47.4% under 25% for CASE1. In comparison to CASE2, CASE3 presents worst results for LP and ST.

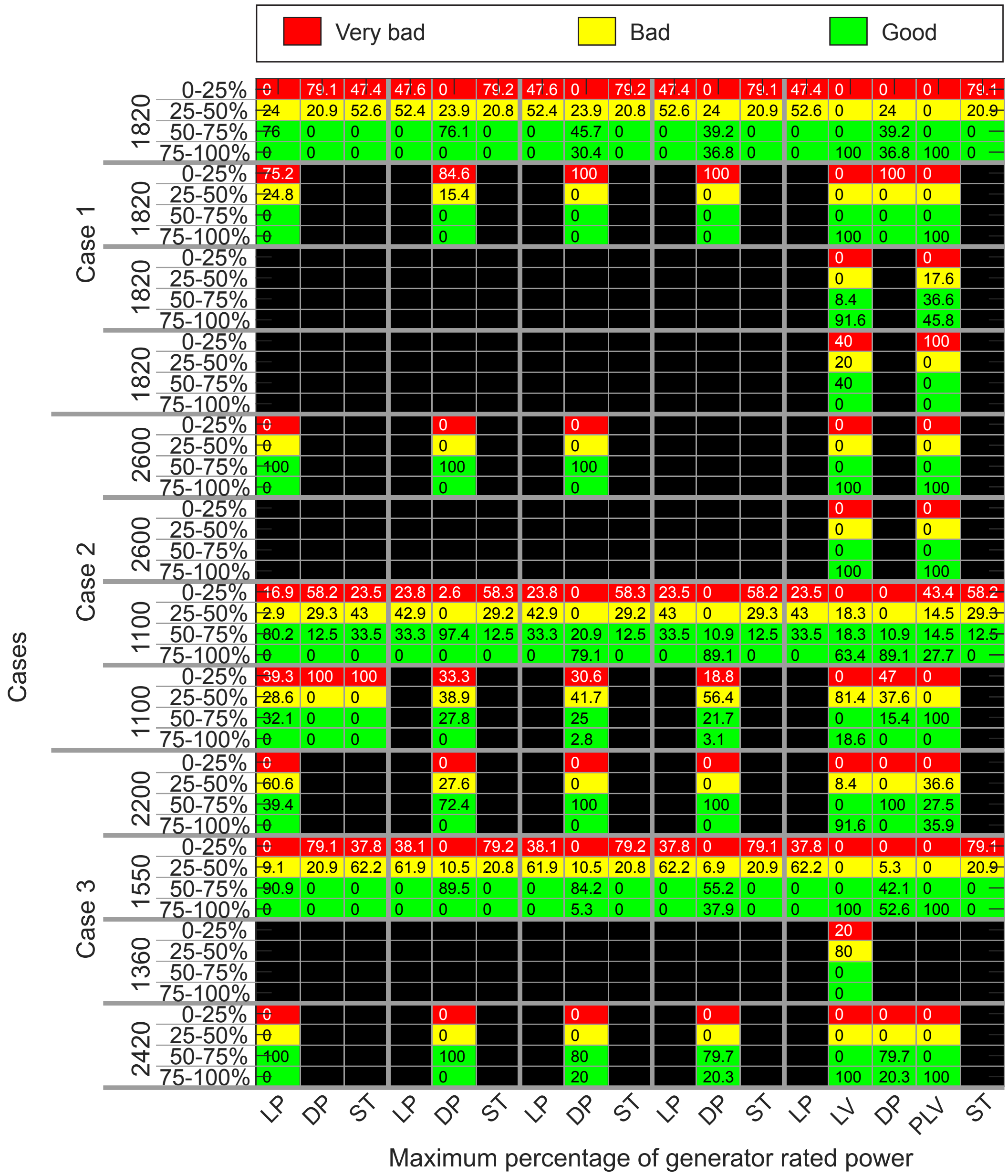


Figure 4.6 – Percentage of time that each generator is operating in each zone of operation.

Source: Author.

For DP, we have a considerable difference, as can be seen, for all levels of maximum percentage, three generators are used, this number is higher than the required for CASE2 and CASE1. On the other hand, CASE3 presents a lower percentage of time under 25% for a maximum percentage of 60%. For CASE3, the 2200kW, the 1550kW and the 2420kW diesel generators do not operate under 25%. Moreover, the 2200kW operates 60.6% of its operation between 25% and 50% of its rated power, besides that the percentage of time that the 1550kW generator operates in the same zone of operation is about 9.1%. When we consider a maximum percentage of 100%, we can see that only the 1550kW generator operates, around 5.3% on this operation zone between 25% and 50%. It is much lower than the numbers presented for CASE2 and CASE1.

Moving the analysis to the data of laden and partial load voyage when CASE3 is operating, we can see that for partial load voyage only three generators are used, neither of the three generators operate under 25%, the 2200kW generator operate around 36.6% of the time in an operation zone between 25% and 50%. This number is better than CASE2 and CASE1.

For laden voyage we can see that the 1360kW generator operates around 20% under 25% of its rated power.This number is the smaller in comparison to CASE1 but higher than CASE2. Moreover, the 2200kW generator operates 8.4% of its operation time in an operation zone that goes from 25% to 50%, and the amount of time that the 1360kW dispatches in the same operation zone is around 80%. These numbers are better than those presented in CASE2 and CASE1.

Moving the analysis to Fig 4.7, we can see that the numbers for CASE4 and CASE5 when LP is analyzed are better than those presented for CASE3 and CASE1, 63.5% vs 79.1% but they are worst than those portrayed for CASE2, 63.5% vs 58.2%. The same occurs for ST, CASE4, and CASE5, which have a lower percentage of the time, about 33% in an operation zone under 25%. This number is lower than the 37.8% of CASE3 and the 47.4% of CASE1 but higher than the 23.5% of CASE2.

When we analyze the numbers for DP, we can see that cases 4 and 5 have different results. CASE4 uses three generators, only the 1100kW generator was dispatched under 25% of its rated power. It occurred in 67% of the 1100kW generator's operation. This is better than the results presented for CASE1, 67% vs 75.2%, but worst than the results presented for CASE2 and CASE3.

CASE5 achieved better results than CASE1. It can also be said that the results for CASE5 are better than those obtained for CASE2 since CASE2 has two generators operating under 25%, the 1100kW operates 16.9% and the other 1100kW generator operates 39.3% and CASE5 has only one operating 43.4% of the time. On the other hand, CASE3 also provides better results than CASE5 for DP. Considering the operation zone from 0% to 50%, CASE4 has two generator operating in this zone, the 1100kW operates 94.4% of the time whereas the 1550kW only operates 18.2% in this zone.

Moreover, we can see, for CASE2, that one 1100kW generator operates about 9.8%, whereas the other last 67.9% of the time in this operation zone. CASE3 has the 2200kW generator operating under 50% for 60.6% of the time. For CASE1 the operation under 50% occurs 100% of the time for one 1820kW generator and 24% for another 1820kW generator.

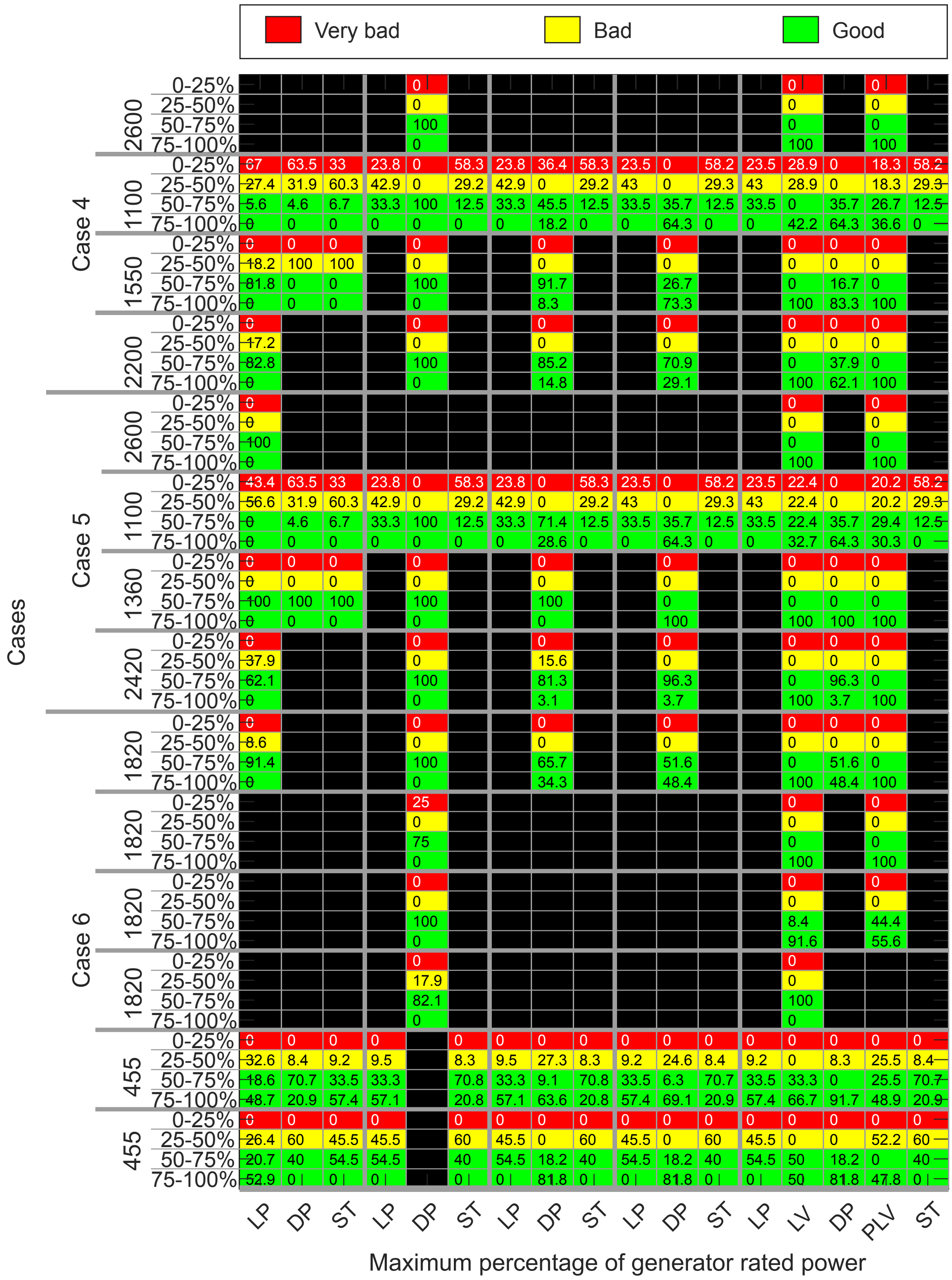


Figure 4.7 – Percentage of time that each generator is operating in each zone of operation.

Source: Author.

Finally, CASE5 has the 1100kW generator operating 100% of the time in this zone from 0% to 50%, the percentage for the 1550kW diesel generator is around 18.2%. To summarize, we have that CASE3 portrays the best results for a maximum percentage of 60%.

For a maximum percentage of 100%, cases 4 and 5 presented the best results. While

CASE3 operates around 5.3% in a range from 25% to 50%, the numbers for CASE1 and CASE 2 are respectively 24% and 37.6%, for an operation between 0% and 50% the numbers are the same for CASE1 and CASE3 but around 84.6% for CASE2. Cases 4 and 5 do not operate in this range from 0% to 50%.

Finally, when we analyze the results for CASE6, we can see the importance of auxiliary generators, these generators help the main generators to avoid operation under 25%. Moreover, for LV and PLV, the main generators operate only above 50%.

In terms of operation zone, CASE6 presents the best numbers, using auxiliary generators allows the operation on LP and ST above 25%, only in CASE6 it was possible. When we analyze the results for DP, cases 4 and 5 present good results, avoiding the operation under 50%. Moving the analysis to the voyages we can see that using auxiliary generators allow the operation to be above 25%. For partial load voyage, CASE3 also allows the operation above 25% for all generators. The battery dispatch in LP and ST may reduce the percentage of time that these generators are under 50%. It will be further investigated.

When we analyze the numbers for laden and partial load voyage we can see that CASE4 has the 1100kW generator operating about 57.8% of the time in a range from 0% to 50% during laden voyage, this number reduces to 36.6% for partial load voyage. For CASE5 these numbers are 44.4% for laden and 40.4% for partial load voyage. Since we want to avoid operation under 25%, the best results for the voyages are achieved with CASE3.

4.2 MTU Results

Now we can start to analyze the numbers for MTU generators. Firstly, it is important to highlight that neither the size of generators nor their fuel consumption curve are the same that was presented for CAT generators.

Another important point is regarding the fuel consumption, the best fuel consumption for CAT engines was 50351.28 liters, it was achieved by CASE4 operating without any restrictions of maximum power. For MTU generators, CASE1, which is the case that presented the highest fuel consumption, presented a fuel consumption of 50248.03 liters. So, the worst case presented for MTU engines consumes 103.24 liters less than the best case of CAT engines. For this reason, the reductions obtained for MTU generators are expected to be small.

The third point is that it was not found generators smaller than 1456kW for the MTU set of generators evaluated that can be applied for marine applications. By this reason, it was not possible to use one generator close to the value obtained in that evaluation regarding the average values between the first and third quartiles, which was around 1004 kW. Besides that, since the smallest generator for MTU is the 1456kW diesel generator, the loads that were under 728kW, 50% of the rated power, were not attended. So, as can be seen in Fig 4.8, only the analysis comprising a minimum percentage of 10% were done.

In the internal analysis of CASE1 we can see that a reduction of the maximum percentage of rated power also results in an increase of fuel consumption. When we compare this increase to the increase presented in Fig 4.1, we can see that the numbers for MTU generators are considerably smaller. We also can see that there is a pattern in both figures. When we compare the increase in fuel consumption from 100% to 90% to the increase from 90% to 80%, the second is more than two times the first. The same happens for both results, when we compare the increase of fuel consumption from 90% to 80% to the increase from 80% to 70%. Finally, a comparison of the increase from 80% to 70% to the increase from 70% to 60%, we see that the increase is much smaller.

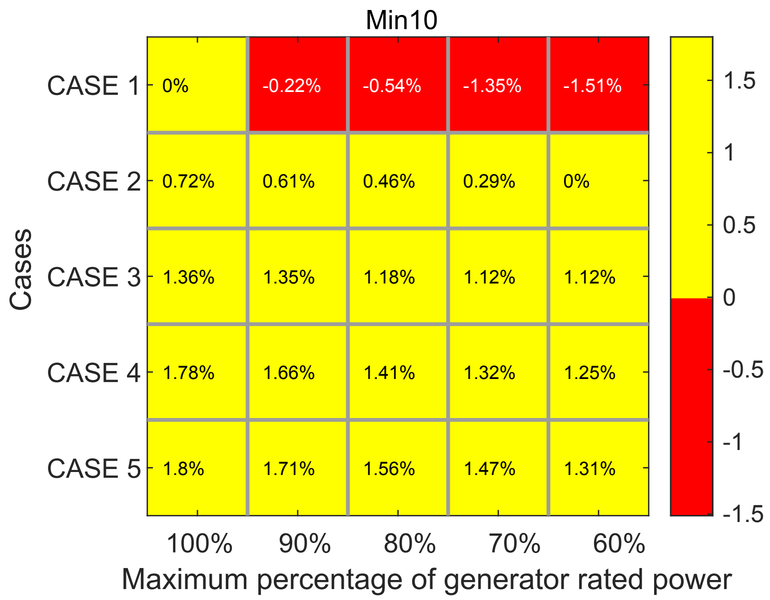


Figure 4.8 – Percentual reduction of all cases evaluated with MTU engines related to Case 1/Min10/Max100.

Source: Author.

We can see that the number of cases evaluated for MTU engines is smaller, five instead of six, mainly because no auxiliary engines are evaluated in this investigation. The biggest diesel engine evaluated for this part of the analysis is the 2424kW diesel engine. So CASE2 set of MTU generators considers both the biggest and the smallest diesel generators, as happened on CAT engines but with different numbers. These different numbers show a much different fuel consumption reduction. For a maximum percentage of 100% the reduction comparing CASE1 to CASE2 is close to 0.72%. Comparing all levels of maximum percentage from 90% to 60% to CASE1 with no restrictions of operation, we have the following reductions 0.61%, 0.46%, 0.29% and 0%. So, CASE2, operating with a maximum percentage of 60%, presents the same fuel consumption than CASE1 without restrictions.

Moving forward with this discussion, we can see that CASE3 presented similar results for both 100% and 90% of maximum percentage, the same occurs for 70% and 60%. The reduction obtained with CASE3 when no restriction was evaluated, is at a similar level to the reduction obtained with CASE4 with a restriction set to 70% of the maximum percentage of rated power.

The fuel reduction obtained with CASE4 operating without restrictions shows a value of around 1.78%, this number is close to CASE5. In terms of fuel consumption, the total reduction would be around 892.77 liters, this number is slightly higher than the reduction obtained only during ST with CAT generators.

Finally, we can evaluate CASE5, which is the case that had the highest fuel reductions, the number is around 1.8%. As can be seen, when the maximum percentage is set to 60% for this case, the reduction is similar to the one obtained with CASE4 when the maximum percentage is set to 70%. Moreover, the reduction of fuel consumed, when the restriction is set to 70%, is higher than the reduction obtained with CASE1, CASE2 and CASE3 without restrictions.

The results comprising the dispatch in each part of the mission for the MTU generators are available in Annex A.

4.3 Evaluation regarding emissions when using CAT generators

This section aims at evaluating the emission reductions obtained in each part of the mission.

4.3.1 LP Operation - Energy from the port x from diesel generators

Using generators of CASE1, the fuel consumed in LP is around 3,330.7 liters. If this mission was repeated throughout the whole year, the total consumption for one year would be around 249,807.8 liters, this value is equivalent to 657,743.8 kg of CO_2. Considering that, this emission occurred close to the coast, reducing it is highly recommended. Areas close to the port usually must respect the limits of emission control areas, it requires low-sulfur fuels, such as VLSFO.

One solution presented here, is the change of the generator set. When we use the generators available in CASE4, the amount of fuel consumed during one year would be equal to 202,130.3 liters. In emissions, this case will emit around 532,208.9 kg of CO_2. Then, the emission reduction would be around 125,534.9 kg.

In (BRAHIM; WIESE; MÜNSTER, 2019), the authors consider that a price of 350 - 450 €$_{2016}$ per ton of CO_2 would be necessary to induce the transition to achieve CO_2 neutrality by 2050 in compliance to Paris Agreement. Then, the reduction provided by CASE4 would save around €43.9 thousand. When we consider the prices per metric ton of CO_2 in Califórnia-US, Britain, Australia and Uruguay the values are around \$15,\$25, \$10 and \$137 (Statista, 2022; PLUMER, 2019). It leads to savings of around \$1.88 thousand, \$3.1 thousand, \$1.2 thousand and \$ 17.2 thousand.

According to (Ship and Bunker, 2023) the price of one liter of VLSFO is around \$0.498. If we consider the amount of fuel that is saved by the use of CASE4, we reach a value of \$23,743.39 in savings per year.

It is important to calculate the cost of the CO_2 emitted during LP, if we consider the use of CASE4 then the total CO_2 emissions, for one year, is around 532,208.95 kg. For one year, it would be equal to 7,096kg which would represent a cost that varies from \$70.96 to €2,483.64 considering the prices from \$10 to €350. The fuel cost would be equal to \$1,342.14

In (DOBROTKOVA; SURANA; AUDINET, 2018), the authors show the bid price of auctions of solar energy that happened in Brazil, the highest price is \$0.103/kWh and the lowest \$0.087/kWh. Considering that, the energy of the LP operation is around 10,120kWh. If we consider that the ships would be able to be powered during this operation from the port instead of being powered by the generators of the ship, the cost to buy the energy would be \$1042.36. Summing the fuel cost with the emission cost, we have a value close to \$1,413.10, it is \$370.74 higher than the cost to buy energy. Considering that, powering from the port using renewable sources, would not emit CO_2 we also have a social benefit by reducing emissions on port areas. The changes on ships to allow the powering from ports have costs that should be considered. The break-even point for this amount of fuel and emission cost would be a tariff of \$0.1396/kWh.

4.3.2 Other parts of the mission

When we move to the analysis of laden voyage, we can see that CASE1 consumed around 17196.19 liters, in one year it was equal to 1,289,714.25 liters. It is equivalent to about 3,395 tons of CO_2. Considering the lowest cost of carbon previously mentioned, \$10 per kg of CO_2 done in Australia, we will find that the total cost would be around \$33 thousand.

CASE3 is the one that provides the highest reduction in fuel consumption during LV, this reduction is around 658.07 liters per mission. In one year, the change in the generator set will provide a reduction of 49,355.25 liters. In emissions, the reduction is around 129.9 tons of CO_2.

Considering that voyages usually happen from the port to the platform, a part of this voyage will happen in these emission control areas mentioned previously. So, considering the use of VLSFO the money saved by the use of CASE3 generator set would be around \$24,578.91 per year. As can be seen, the savings during LV are higher than the savings during LP. Considering that for LP, we have used CASE4, if we use this generator set for LV the savings would be around \$15,195.10. Summing both savings, we reach to a value equal to \$38,092.76.

Moving the analysis to DP, the CO_2 emissions caused by the generator set of CASE1 are around 3,012.8 tons. Moreover, this emission would have a cost of \$30 thousand if we consider the carbon price applied in Australia.

For PLV, the case that provides the highest reduction is CASE3, the reduction is around 555.37 liters or 1,4 tons of CO_2 per mission. In one year the total fuel savings would be equal to 41,652.75 liters and more than 109 tons of CO_2 would not be emitted. For CASE4, the reductions in one year would be equal to 23,445 liters of diesel and 61 tons of CO_2.

Finally, for ST, the highest reductions are achieved in cases 2,4 and 5. This reduction was equal to 62,140 liters and 163.6 tons of CO_2 in one year.

4.3.3 Battery cost analysis

The reductions for the whole mission were already portrayed in Fig.4.1. As presented, the part of the mission that happens in port can be fed directly from renewable sources in port without consuming fuel. If we consider this alternative, the best solution would still be CASE4, now with a reduction of 4.55% for a maximum percentage of 100%, in liters the reduction was around 2,258.33 for one mission and 169,374.8 liters in one year. Financially speaking this change on the generator set would provide a total saving of \$88,808.26 of fuel not consumed and CO_2 not emitted in one year. If we consider that the LP operation would be fed by the diesel generators installed on the ship, the total savings would increase to \$113,807.01.

According to (HENZE, 2023), the average price for a lithium-ion battery pack was around \$151/kWh. So, without considering the cost for the whole battery solution (converters, control temperature equipments, etc) and installation costs, a 1MW battery pack would take 1.33 years to be paid by the savings obtained, considering the whole mission, by the generator set switch. If we consider that during LP the energy would come from the port, this 1MW battery pack would take around 1.7 years to be paid. It is important to highlight that we are considering here that the batteries would be used only as reserve, allowing a more optimal dispatch during DP.

Considering the Tesla megapack presented in (Tesla, 2021). It is sold in a solution that is equivalent to one and a half 20ft container but narrower. It has 3.9MWh/1.9MW and costs \$2,669,050 with an estimated maintenance cost of \$8,440 per year. It would have a cost of \$684.37/kWh for a solution that has fully integrated battery modules, inverters, and thermal systems. Considering that, the maintenance cost would reduce the previously calculated savings and we would install a 1MWh/1MW battery to operate as a reserve, this solution would be paid in 8.52 years when LP is fed by the port and in 6.5 years when the LP is fed by the generators.

4.4 Evaluation regarding emissions when using MTU generators

As presented before, the numbers of fuel consumption for MTU generators are smaller than those presented for CAT generators, therefore emissions will also be lower.

4.4.1 LP Operation - Energy from the port x from diesel generators

Analyzing the emissions for MTU engines, we can see that, for LP, the best cases are cases 3,4 and 5. In these cases, the reduction achieved is around 339.5 liters of diesel and 893.9 CO_2 emissions. As mentioned in the analysis for CAT generators, this operation could be fed by renewable energy from the port. The cost to buy the energy from the port, calculated for CAT generators, is equal to $1042.36. The cost of operating during LP with cases 3,4 and 5 should be a sum between the cost of fuel and the cost of emissions. For one mission the fuel cost would be equal to $1,276.14, and the cost of emissions would be around $67.47. So, the total costs would be equal to $1,343.62, and the break-even point for the energy tariff is equal to $0.1328/kWh.

4.4.2 Other parts of the mission

CASE5 achieved the highest reductions for LV. In one mission, the reduction is around 37.35 liters. In one year, the total reduction would be equal to 2,801.25 liters. It represents yearly savings of $1,395.02 . In terms of CO_2 emissions, the savings in one year would be equal 7,375.69 kg of CO_2, it represents $73.76 per year. The total consumption is equal to 16,587.38 liters, it costs $8,260.51 per mission. The total cost per mission for emissions is $436.74. Summing these costs we achieve a value of $8,697.26 per mission. In one year this total cost of emissions and fuel will be equal to $652,294.57.

In DP operation, CASE2 achieved the highest reductions, 91.78 liters per mission and 2141.25 liters per year. For reductions in CO_2 emissions, the values are 75.17 kg per mission and 5,637.91 kg per year. The total consumption of CASE2, per mission, is 14,391.07 liters, it leads to a cost of $7,166.75. The emission cost is around $ 378.91. If we consider CASE5, which is the case that achieved the highest reduction when the full mission is evaluated, the total consumption during DP is equal to 14,402.4 liters, we can see that the difference to CASE2 is minimal. The costs of using CASE5 are $7,172.39 for fuel, and $379.21 for CO_2 emissions.

For PLV operation, only CASE2 provides reduction of fuel consumed, it is around 21.05 liters per mission. The total reduction in one year is $ 827.79 . If we do not consider the cases that present an increase in fuel consumption, in comparison to CASE1, this reduction, in dollars, is the minor reduction achieved. From CAT and MTU generators results we may conclude that the use of more than one generator size, is not so beneficial for the voyages as it is for DP, LP and ST.

As presented for LP, cases 3,4 and 5 also presented the highest reductions for ST. Numerically, the reductions in ST are higher than those presented for LP. Per mission, around 464.2 liters are saved, it leads to a total reduction of 34,815 liters. The total reduction, in dollars, from fuel and CO_2 emissions is around $18,254.55. Moreover, the cost for the mission using one of these three cases is $1,016.04 for fuel and $53.72 for emissions. In one year, the total cost would be around $80,231.93.

4.4.3 Battery cost analysis

Finally, as evaluated for the CAT generator, we should consider what would happen if the LP operation was fed directly by the port, it would lead to a maximum reduction of 1.19%, which would be obtained also by CASE5. In this scenario, the total reduction obtained by using CASE5 instead of CASE1 would be around 562,93 liters per mission. Per year, the total fuel reduction would be 42,219.75 liters that provides a reduction of 111.1 tons of CO_2 emitted. In dollars, this change on the generator set would provide, per year, savings of around 22,137.08.

Considering that a 1MW battery would provide the reserve necessary to allow the optimized dispatch during the whole mission. These total savings would pay the buying of this battery in around 6.82 years, for a scenario in which the LP is fed by the port and around 4.25 years for a scenario without energy from the port. When we consider the Tesla megapack, the financial viability starts to deteriorate. For LP being fed by the port, the savings would require 32.44 years to pay the 1MWh battery, when LP is fed by the generators 19.28 years would be necessary to pay the battery. Since Tesla gives a 20-year warranty these numbers would not encourage the ship owner to buy the battery.

If we consider that value of €350 to tax carbon, the savings, considering LP being fed by the generators, would increase to $ 101,068.14, considering a currency of €1 equal to $1.08. Considering a scenario, in which LP is fed by the port, the savings would be around $62,003.29. So, considering these savings the 1MWh battery would be paid in 6.77 years when LP is fed by the generators and in 11.04 years when LP is fed by the port.

4.5 Lessons Learned

The previous analysis of the demand curve evaluating its values for mean and interquartile mean between the numbers from the first and third quartiles provided two generators that needed to be in the generator set, 1100kW and 2200kW, the only case that had these two generators was the case that provided the lowest fuel consumption for CAT generators.

For MTU, among the generators evaluated, there was no generator close to 1100kW but there was one close to 2200kW, the 2240kW generator. The generator closer to 1100kW was the 1456kW diesel generator. Two cases comprised both 1456kW and 2240kW, these cases had the highest reductions, but the case that provided the highest reduction was the case that had the other two generators different from each other and different from 1456kW and 2240kW.

Using different generator sizes in the generator-set can present a very good advantage for operations with a demand profile close to LP and ST. In terms of percentage, the numbers are above 19%.

For DP, the reductions are around 4%, when the diesel generators operate without restrictions. This reduction reaches 11.1% for CASE4, when the maximum percentage is reduced to 60%.

The numbers for LV and PLV are smaller than for DP in percentage when we compare to the other parts of the mission. But when we calculate the savings obtained in one year, the numbers for CASE3 are close to the levels of savings for DP obtained with CASE5 and CASE3. Savings for CASE3 are $ 21,839.79 and $ 26,586.28 for PLV and LV, respectively. On the other hand, CASE5 and CASE3 reached a reduction of $ 22,092.58 and $ 25,281.84, respectively.

These generator sets with different generator size are beneficial not only in terms of fuel consumption reduction but also considering the amount of time that the generators operate under 25% of its rated power. They also provide a gain in using generators more equally.

Despite the social benefits, feeding the ships during operation in port directly from the port using renewable energy show fuel and CO_2 emission reductions and a lower cost in comparison to the feeding the demand using the diesel generators of the ship. Moreover, the savings achieved by feeding the ship from the port, which were around $ 52,804.50, are higher than the savings achieved by using CASE6 instead of CASE1 without energy from the port, which were around $ 52,675.88 when there is no restriction on the maximum power of the generators.

If the energy is fed by the port, CASE3 becomes a solution that is as good as cases 4 and 5. For a maximum percentage of 80%, this case is the best solution. For the other levels of maximum percentage, CASE4 presented the best savings.

Chapter 5

Battery impact on generator sensitivity

In this chapter, we will evaluate the impact on fuel consumption, participation and operation zone of the generators. Two batteries are evaluated, 1MW and 2 MW. Moreover, the Round Trip Efficiency (RTE) evaluated varies from 92% to 98%. It is commonly known that three lithium-ion batteries, the ones most available commercially, have RTEs equal to 92, 95 and 96, Lithium Iron Phosphate (LFP), Lithium Nickel Manganese Cobalt (LNMC) and Lithium Titanate Oxide (LTO), respectively. So, this variation of RTE will comprise the most commercially available batteries. Moreover, four minimum levels of State of Charge (SOC) are evaluated, 30%, 50%, 70% and 90%. This minimum level impacts directly on the portion of the battery that is used for reserve.

The analysis of using batteries with the generator set of CASE1 may show a retrofit solution for existing ships. Considering that many of the existing ships will continue and that any regulation regarding taxation on ship emissions may enter into force in the following years, a solution for retrofit must be evaluated.

The results for the battery dispatch when the maximum percentage of rated power is set to 60% and 70% are presented in Annex B.

The results regarding the percentage reduction shown in Figs B.1, 5.1 and 5.4 are a comparison made to the base case, which is the CASE1 with maximum percentage equals to 100%.

5.1 Battery dispatch for a maximum percentage equals to 80% and 90%

Moving to the analysis of Fig. 5.1 we can see that, considering each scenario presented, most of them have higher numbers for reduction than those presented for a maximum percentage of 60% and 70% in Fig. B.1. For CASE1, the increase in the maximum percentage leads, once again, to an increase in the reductions obtained.

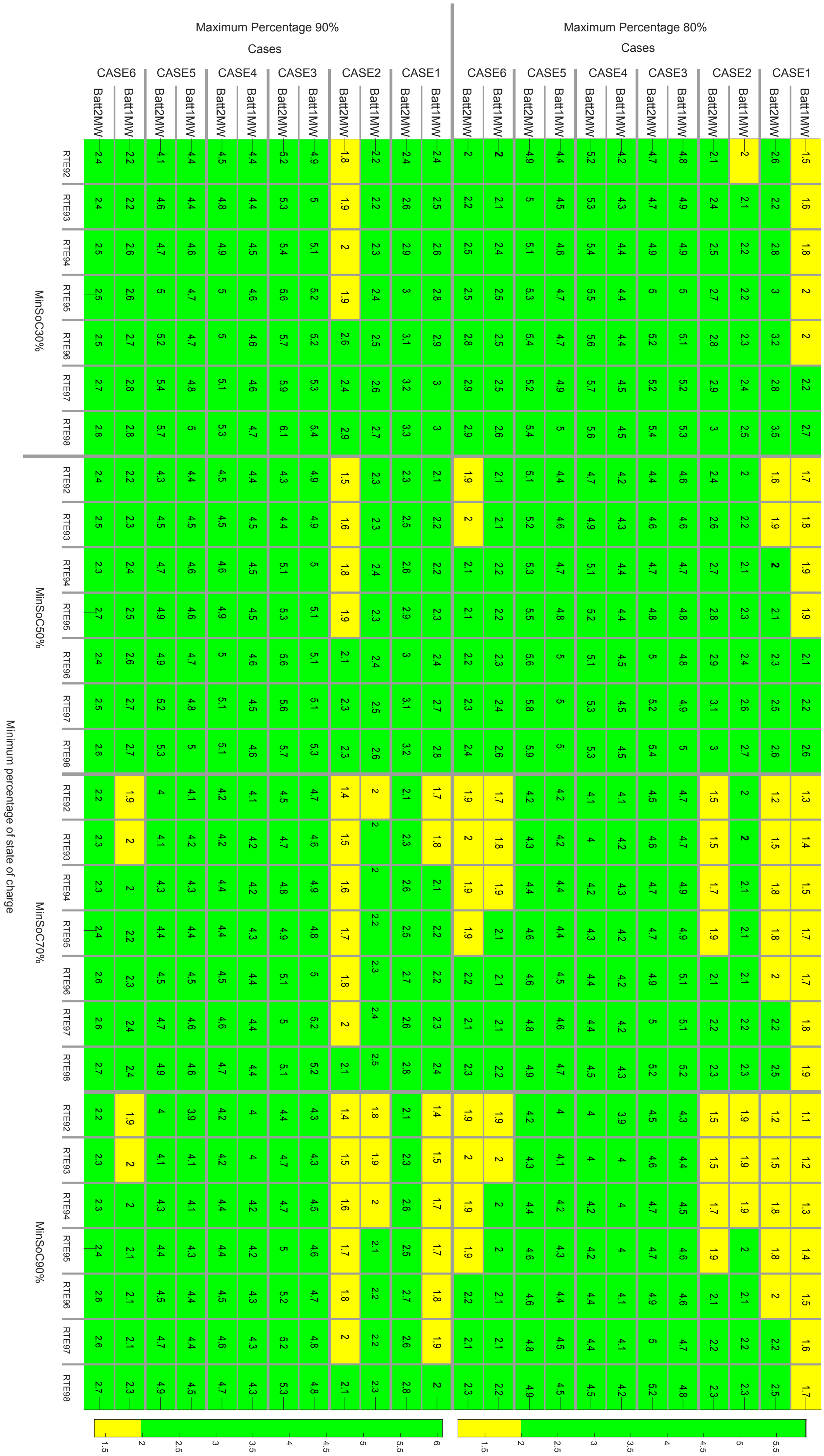


Figure 5.1 – Reduction Percentage obtained by dispatching the batteries in different levels of DoD. The cases analyzed have a restriction on the maximum percentage of the generators used set to 80% and 90%.

Source: Author.

It is interesting to see the considerable reduction that the battery dispatch provides when CASE1 is analyzed. In the last chapter, when battery was used only as a reserve, the fuel consumption increased 1.05% when the maximum percentage of the generators was reduced from 100% to 80%. When we look at the data provided in Fig. 5.1 we can see that for a minimum SoC of 90% the battery can provide an average reduction of 1.4% for the 1MW battery and 1.8% for the 2MW battery. When we reduce this minSoC to 30% we can see that the numbers for fuel reduction increase significantly to about 2% and 3% for the 1MW and 2MW battery, respectively.

When we have a closer look on the fuel reduction achieved in each part of the mission using CASE1 with battery we find that these reductions are mainly connected to the diminishing of fuel consumed during LP, ST and with a minor fuel reduction percentage, DP. During LP, the reductions for the 1MW battery are between 11.6% and 19.9%, whereas for the 2MW battery, the reductions are from 14.02% to 24.6%. For ST the percentages increase considerably. The 1MW battery achieves reductions that varies from 18.3% to 29.3%, whereas the 2MW battery can reduce the fuel consumption in percentages between 20.9% and 29.2%.

During laden voyage, CASE1 is the only case that, for some RTEs, achieves a reduction when battery is dispatched in comparison to the results when battery is used only as reserve. These reductions are minimal in comparison to the other parts of the mission, but this is the only case in which the dispatch of battery may be beneficial in terms of fuel consumption.

As will be presented for the other cases, the use of batteries in partial load voyages is not indicated. For this part of the mission, when the battery dispatch is evaluated we can see an average increase of 0.25% for both batteries. It is also fair to say that this increase is the lowest increase in comparison to the other cases for partial load voyage.

As happened for a maximum percentage of 60% and 70%, CASE2 provided a lower consumption reduction than the numbers presented in the last chapter. Moreover, it can be seen from the results for a maximum percentage of 90% and 100% that CASE2 provides better numbers when battery is used as a reserve. It is an interesting result, since it would be normal to think that the dispatch of batteries would provide an advantage in fuel consumption.

These numbers may result mainly from the increase in fuel consumption during laden voyage and partial load voyage. In comparison to the numbers of CASE2 using the battery as reserve, CASE2 presents numbers for partial load voyage with an average increase of 0.93% in fuel consumption for the 1MW battery and 1.36% for the 2MW battery in comparison to the number with battery using as a reserve. For laden voyage, this increase is around 0.9% for the 1MW battery and around 1.11% for the 2MW battery. On the other hand, using the 2MW battery in CASE2 for Standby can produce very interesting results. Discharging only 10% and 30% of the 2MW battery can achieve an average reduction of around 2.2%. When we increase the use of the battery to 50% and 70%, the reductions increase considerably to 6.26% and to 10.24%, respectively.

Analyzing the numbers for CASE2 when the operation analyzed is DP, we can see that as happened for laden voyage and partial load voyage the dispatch of batteries present worst numbers than the use of it only as a reserve. For the 1MW battery the increase was around 0.91%, whereas for the 2MW battery, the increase was about 1.21%. For LP operation, the only moment that the use of battery produces a reduction in the fuel consumption is when we have a reserve of 50%, for the 1MW battery the reduction is in average 0.45%, whereas for the 2MW battery, the reduction is about 5.87%. If we consider that the operation during loading in port will be fed directly from the port, using the dispatch of the 2MW battery only during standby operation can produce a small reduction of around 0.2% in the full mission.

The battery dispatch also provides a reduction in the fuel consumption when the CASE3 is analyzed. As can be seen, all levels of battery reserve provides a reduction in comparison to those results presented in the last chapter. Although the battery dispatch produces a reduction for the full mission, the analysis for the two voyages and DP show that the battery dispatch in these parts of the mission cause an increase in fuel consumption. For laden voyage, the average increase in fuel consumption is about 0.85% for the two battery sizes. For partial load voyage and for DP, the average increase is about 1.26% and 0.6%.

On the other hand, when CASE3 + Battery dispatch is evaluate for LP and ST, we can see that the reductions achieved are considerable. The average reductions for LP are smaller than those presented for ST. For the 1MW battery, the four levels of minimum SoC analyzed, 30%, 50%, 70% and 90%, achieve an average reduction of 5.57%, 4.06%, 5.29% and 3.04%, respectively. For the 2MW, the average reductions are 12.80%, 4.93%, 6.33% and 6.33%, respectively. For ST, following the same sequence of minimum SoC, for the 1MW battery the numbers are 14.93%, 13.06%, 11.59% and 11.24%, respectively. For the 2MW battery, the numbers are 11.03%, 12.39%, 13.59% and 13.59%, respectively.

For a maximum percentage of rated power of 60% and 70%, CASE4 presented worst numbers in comparison to the numbers of the last chapter, when we analyze the numbers for a maximum percentage of 80%, we can see that some numbers present higher reductions when the 2MW battery is used with a reserve of 30% for all RTEs and of 50% for RTEs higher than 94%. For the 1MW battery, the maximum reduction is about 4.5%, this number is around 0.6% lower than the reduction achieved without battery.

When we analyze the numbers in each part of the mission, we can see that during the voyages, the battery dispatch produce worst results than using it only as reserve. For partial load voyage the fuel consumption increase is, in average, around 1.14% for both battery sizes. For laden voyage, this increase is about 0.94% for both battery sizes. It is interesting to see that, increase the size of the battery for voyages reflects in an increase of the fuel consumption.

For DP operation, the battery dispatch increases the fuel consumption in the majority of the situations analyzed. The fuel consumption during DP operation is reduced only when the 2MW battery is used with a minimum SoC equals to 30% and 50%. For 30%, the RTEs that provide a fuel consumption reduction are above 94%, For 50%, the RTEs are 94%, 95%, 97% and 98%. For LP operation, the battery dispatch with CASE4 provides a reduction when the 2MW battery is operated with a minimum SoC under 50%, this reduction is around 5.87% for 50% and 9.64% for 30%. For the 1MW battery, the reduction is achieved only when the minimum SoC is set to 50% with an RTE above 95% also provides a reduction, in average, this reduction is about 0.24%. Finally, when the standby operation is analyzed we can see that for the majority of cases the 2MW battery dispatch achieves a reduction. For the 2MW battery with a minimum SoC of 90% the average reduction was around 1.72%, when the minimum SoC is 70%, 50% and 30% we have a reduction 2.18%, 6.26% and 10.24%, respectively.

Moving the analysis to the evaluation of CASE5, we can see that when the minimum SoC is under 50%, the use of the 2MW battery can achieve a reduction in comparison to the data available in the last chapter for most of the RTEs analyzed. Moreover, the highest reduction, when battery is dispatched, is achieved using CASE5, it was around 5.9%.

Considering the five parts of the mission, the use of the battery causes an increase in fuel consumption in the voyages. For partial load voyage the 1MW battery increases in around 1.09%, whereas for laden voyage this increase reaches 1.15%. For DP, the use of the battery dispatch with CASE5 produced a benefit when the minimum SoC was lower than 50%. For a minSoC of 30% the average fuel reduction for the 1MW battery was 0.73%, whereas for the 2MW battery it was higher, about 1.18%. For a minSoC of 50%, the average fuel reduction for the 1MW battery and for the 2MW battery were about 0.45% and 1.48%, respectively. On the other hand, the use of minSoC above 70% also can produce benefits, it will require an RTE above 95% for the two batteries but for these higher levels of reserve the fuel reduction achieved is minimal.

For LP the battery dispatch with CASE5 produced benefits only when the minSoC was set to 50% with a 2MW battery, then the fuel reduction was around 5.87%. For other levels of minSoC the average increase in fuel consumption for both battery sizes was around 2%. Finally, when we analyze the results for ST, we can see considerable reductions when the 2MW battery is analyzed. Considering the four levels of minimum SoC analyzed, 30%, 50%, 70% and 90%, the average fuel reduction achieved was around 10.24%, 6.26%, 2.18%, 2.18%.

Finally, when we analyze the results for CASE6 we can see that, when the minSoC is set under 50%, the battery dispatch can reduce the fuel consumption, in relation to the numbers presented in the last chapter. When we compare the fuel consumed in each part of the mission, when the battery is used only as a reserve, to the numbers, when battery is dispatched, we can see that for the voyages the fuel consumption increases when the battery is dispatched. For laden voyage, the average increase is circa 0.54% and 0.59 for 1MW and 2MW battery, respectively. For partial load voyage, these increments in fuel consumption are 0.71% and 0.69% for 1MW and 2MW battery, respectively.

One point about laden voyage and partial load voyage is that, the change on the minimum SoC do not present considerable differences on the amount of fuel consumption increase among each other for all cases. Moreover, as said before, the battery dispatch provides a fuel consumption reduction only when used in CASE1.

On the other hand, for CASE6, when we analyze the numbers for LP we can see that the 1MW battery achieves similar reductions for a minSoC of 70% and 90%, 1.33% and 1.27%, respectively. On the other hand, for 30% and 50%, the numbers are much higher 3.63% and 4.97%. For the 2MW battery, the results are more similar among the different minSoC, for 30%, 50%, 70% and 90% the average reductions are 3.24%, 3.63%, 3.24% and 3.24%.

For ST, the reductions for the 1MW battery are between 0.14% and 4.65%, this highest number was achieved for a minSoC of 70% and RTE equals to 96%, whereas the lowest reduction was found when the minSoC was 50% and the RTE equals to 92%. On the other hand, the reductions for 2MW battery vary from 0.54% to 5.89%, the minimum value was found with the same battery characteristics of the 1MW battery, whereas the highest number was obtained with minSoC of 30% and the RTE equals to 98%.

To summarize this analysis, Cases 2, 4 and 5 provide the highest reduction when the maximum percentage is set to 80%. For LP, the lowest fuel consumption is obtained with CASE4 operating with a 2MW battery with a minSoC of 30%. Although the fuel consumed for LV and PLV are higher than those presented in the last chapter, CASE3 with the 1MW battery achieves the lowest fuel consumption for LV, the numbers are similar among the four minSoC evaluated, whereas for PLV the lowest consumption is obtained with CASE3, the numbers are similar for the two batteries with all four minSoC analyzed. For DP, the lowest reduction is achieved with CASE5 with the 2MW battery and the minSoC under 50%. For ST, the cases 2, 4 and 5, that have the 1100kW generators, provide the lowest fuel consumption using the 2MW battery with the minSoC of 30%.

At the lower part of Fig. 5.1 we can see the reductions obtained with a maximum percentage of 90%. This level of maximum percentage will achieve the highest reductions for CASE3 when the 2MW battery is analyzed. It is also the highest reduction among all levels of maximum percentage analyzed.

For CASE1, the 1MW battery achieves an average reduction of 2.23%, whereas for the 2MW battery it is around 2.68%. The maximum reduction occurs when the minimum SoC is set to 30% and the RTE is 98%, it is around 3.3%. In the last chapter, it was presented that changing the maximum percentage from 100% to 90% increases the fuel consumption in 0.37%. As can be seen, the reductions, when the battery dispatch is considered, are much higher. Comparing to the reductions presented in the last chapter, cases 3 and 6 also presented numbers for fuel consumption reduction higher when the battery dispatch is analyzed. In the last chapter the reductions for these two cases were 4.72% and 2.39%.

Analyzing each part of the mission for all cases, we can see that for partial load voyage, no case has provided a reduction in the fuel consumption, the highest increase occurs for CASE2 with the 2MW battery, in average it was around 1.3%. For laden voyage, the highest increase is found in cases 2 and 3 when the 2MW battery is used, the average increase is about 1.11%. As happened for the maximum percentage of 80%, the use of battery in loading in port and standby can provide considerable reductions for cases 1, 3 and 6, in average, it was around 16%, 7.23% and 3.07%, respectively, for ST, the reductions are, in average, 25.2%, 14.7 and 2.6%, for these three cases, respectively. For DP, when the battery dispatch is considered, the only cases that provided reduction are cases 1 and 6, the average reductions are 1.51% and 0.29%, respectively.

One point that is interesting to mention is that the battery dispatch allow the generators to operate at lower maximum percentages in the voyages, the cost of it is the increase in fuel consumption.

5.2 Battery cycles for a maximum percentage equals to 80% and 90%

Battery degradation can be measured in two ways, by calendar and by number of cycles. Other aspects of battery operation can accelerate the battery aging such as operation at extreme temperatures and high charge or discharge rates. Moreover, the depth of discharge play an important role on the number of cycles that one battery can do.

When the battery completes these amount of cycles provided in Fig.5.2, the battery do not finish its lifetime, usually it represents that at the end of these cycles the battery remains with 80% of its initial capacity, but the battery can still be used.

In (MALLON; ASSADIAN; FU, 2017), the authors have portrayed a discussion regarding the number of cycles vs depth of discharge. Moreover, the authors present equation 2 that describes this relation. The values for the constants are β_0=2731.7, β_1=0.679 and β_2=1.614.

$$Cycles = \beta_0 * DOD^{-\beta_1} * exp(\beta_2 * (1 - DOD)) \tag{2}$$

For a DOD that varies from 10% and 100%, the curve considering the number of cycles, adapted from (MALLON; ASSADIAN; FU, 2017), is presented in Fig.5.2. Considering the four DOD analyzed in this work, 10%, 30%, 50% and 70%, we can assume that the number of cycles is 96800, 39100, 23500 and 15900, respectively.

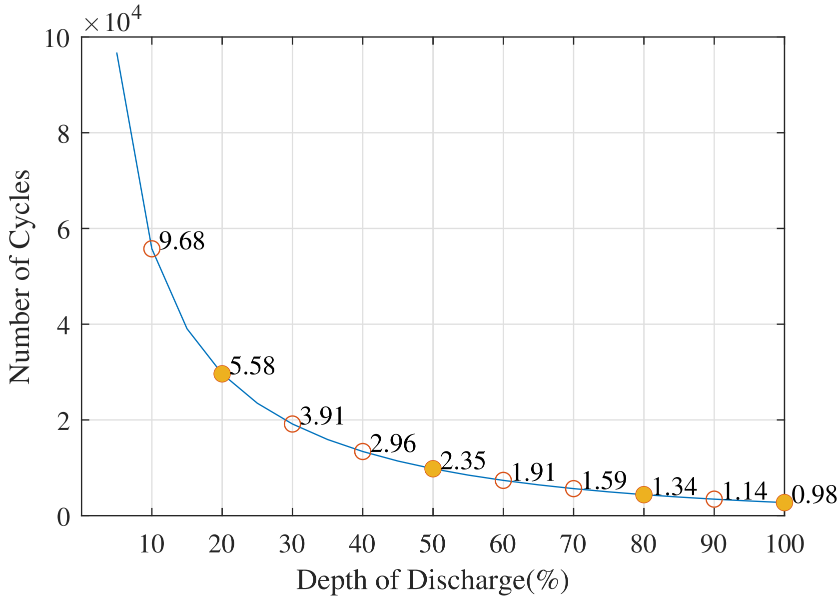


Figure 5.2 – Relation between number of cycles and depth of discharge.

Source: Adapted from (MALLON; ASSADIAN; FU, 2017).

So, considering the battery dispatch, the minimum SoC and the number of cycles presented in Fig.5.2, we can determine how many years the battery can last pursuing this dispatch. This analysis does not considers the fade in battery health caused by the aging of the battery which could reduce the amount of energy available to be dispatch.

As can be seen in 5.3 the change in the generator set also provides an increase in the number of years that the battery would last. Moreover, the use of auxiliary generators provide a considerable increase in the number of years, reaching almost 18 years when the minSoC was set to 50% and 70% with a 2MW battery.

For cases 3, 4 and 5 the increase of the battery size from 1MW to 2MW also improves the amount of years that the battery lasts. It is interesting to see that the highest number of years are achieved with the minSoC equals to 70%. On the other hand, the lowest number of years for all cases occurs for minSoC equals to 90%. CASE5 operating with a 1MW battery.

It is also interesting to see that, for cases 2, 4 and 5, the increase in the RTE results in a reduction of the number of years that the battery lasts. For cases 1,3 and 6 the change in the RTE do not impact in the number of years.

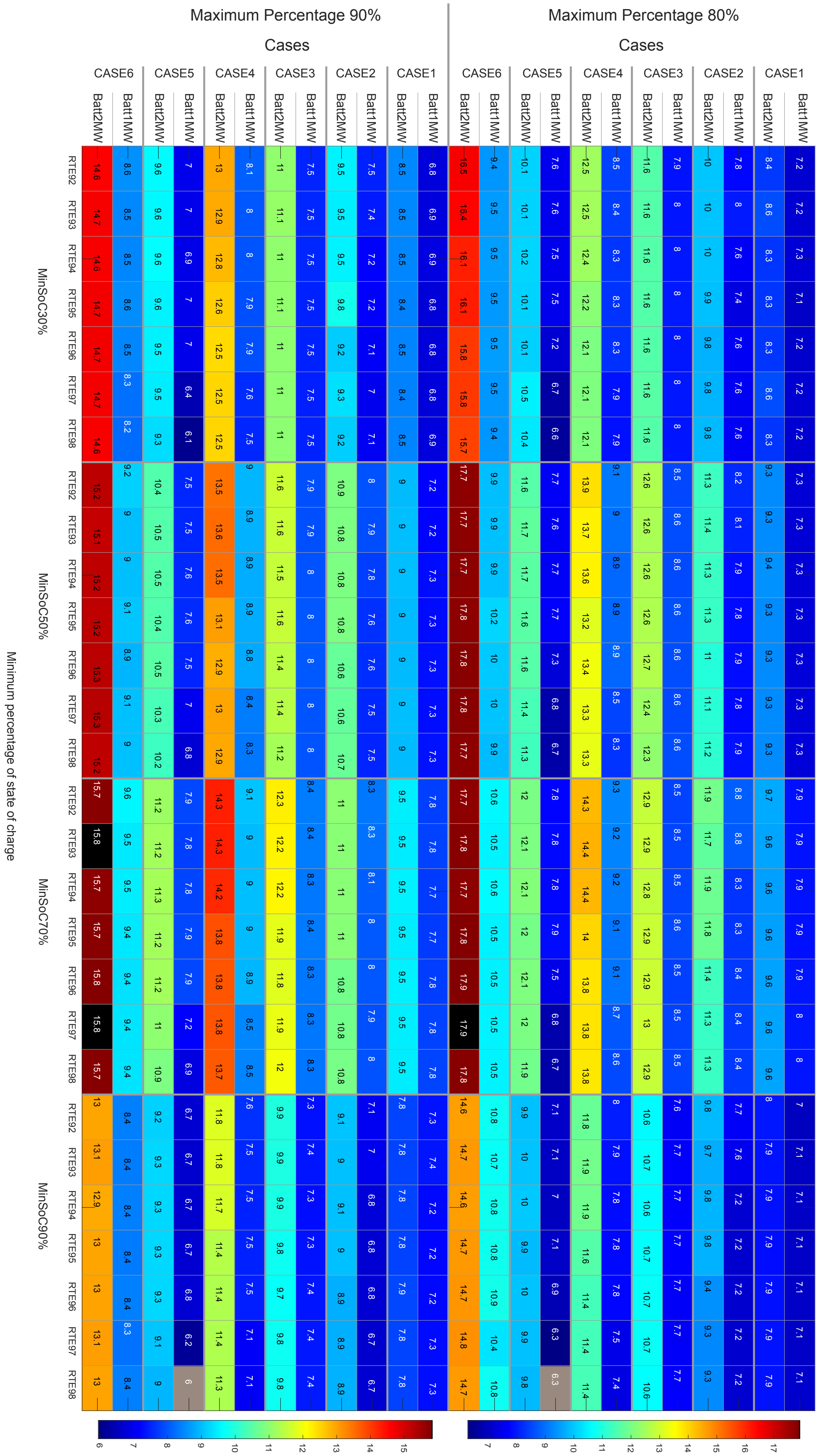


Figure 5.3 – Number of years that the battery will last for a maximum percentage of the rated power of the generators of 80% and 90%.

Source: Author.

Considering the data provided in the analysis of fuel consumption reduction, it was shown that the use of battery in voyages do not result in fuel consumption reduction. So, removing the number of cycles that occurred in these voyages we have some differences. For CASE1, the number of years increase in average 1.1 years for 1MW battery and 2 years for 2MW battery. For cases 2 and 3 the increase is around 1.8 years and 3.4 years for 1MW and 2 MW battery, respectively.

For CASE5 it is about 1.6 years for the 1MW battery and 3 years for the 2MW battery. When CASE4 is analyzed the increase for the 1MW battery and for the 2MW battery was 1.5 and 3 years, respectively. For CASE6 the increase was around 3 years for the 1MW battery and 6 years for the 2MW battery.

Analyzing the numbers for the maximum percentage of 90%, we can see that the numbers are slightly smaller than those presented for 80%. The highest reductions in terms of years occur for CASE6. The only case that has an increase in the number of years that the battery last is CASE4 operating with a 2MW battery with the minSoC of 30%. As can be seen this increase is around 0.5 years.

5.3 Battery dispatch for a maximum percentage equals to 100%

Moving the analysis to the maximum percentage of 100%, we can see that only CASE3 presents a global reduction higher than the one presented in the last chapter. In most of the cases it happens when the RTE is above 95% for all levels of minSoC analyzed.

We should note that, for some cases, the reduction achieved, without restrictions for the generator operation, is lower than the reduction achieved with the maximum percentage set to 90%.

When we consider the parts of the mission, we can see that, for the maximum percentage of 100%, the results are similar to those presented for 80% and 90%. The battery dispatch reduces the fuel consumption for LP in cases 1, 3 and 6 for both batteries in all levels of minSoC. These reduction are, in average, around 15%, 6.4% and 3% for cases 1, 3 and 6, respectively. Moreover, cases 2, 4 and 5 can reduce the fuel consumption when a 2MW battery is used and the minSoC is set to 30%, these reductions are, respectively, 5.2%, 5.2% and 3.6%.

For LV and PLV, the use of battery increases the fuel consumption in most of the cases. As happened before, CASE1 has minor reductions when the battery RTE is above 94%. For DP, we only have a reduction with cases 1 and 6. The average reduction for CASE1 is 1.02%. For CASE6, the fuel consumption reduction occurs when the minSoC is set to 30%, in average, the reduction is around 1.2%.

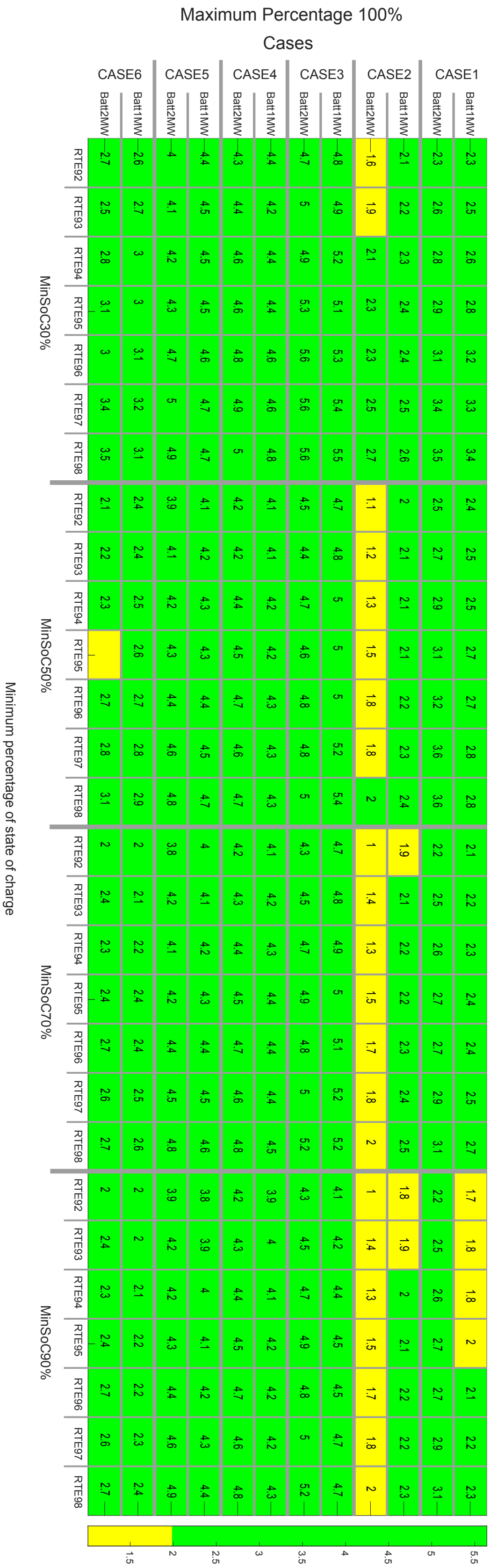


Figure 5.4 – Reduction Percentage obtained by dispatching the batteries in different levels of DoD. The cases analyzed do not have a restriction on the maximum percentage of the generators used.

Source: Author.

Finally, when we analyze the data of ST, we can see that increase of the maximum percentage helps the battery dispatch to achieve lower levels of fuel consumption. This reduction occurs for cases 1,3 and 6. In average, CASE1 reduces the fuel consumption in 25.5%, for cases 3 and 6, the numbers are 14.8% and 3.1%, respectively.

Contrasting the numbers of fuel consumed with the maximum percentage of 100% presented in the last chapter to the ones obtained here, we can see that if we consider only the parts of the mission that the battery produces benefits, all cases have a lower amount of fuel consumed. The lowest differences occur with cases 2, 4 and 5 when the 1MW battery is dispatched, the reductions are minimal, around 0.03%. For the 2MW battery, it increases slightly to 0.31%, 0.32% and 0.14% for these three cases, respectively. CASE1 reduces in around 3.29% for the 1MW battery and 2.81% for the 2MW battery. Cases 3 and 6 also have reductions for the 1MW and 2MW battery, their numbers are 1.52% and 1.67% for CASE3 and 0.66% and 0.38% for CASE6.

For the 1MW battery and the 2MW battery with a minSoC of 30% and an RTE of 96%, we have a fuel reduction during LP and ST. Considering that the battery will be dispatched only in the moments in which we have a fuel reduction we have a change in the case that achieves the highest reduction. CASE3 achieves a reduction of 6.24% and 6.37% for 1MW and 2MW battery, respectively.

For the 2MW battery, Considering the amount of fuel saved, it is around 253,286 liters per year. For the same price of $0.498 per liter of VLSFO, the savings due to fuel reduction are about $126,136.00, considering the cost of CO_2 as $10 per ton we can save around $6,669 which implies in a total saving of $132,805.00. For a battery cost of $684.37 per kWh, 10.3 years would be necessary to payback the battery cost with the fuel and CO_2 emissions savings.

For the 1MW battery, the total savings would be close to the number shown for the 2MW battery, around $130,014.59. Then, the amount of time required to payback a 1MW battery would be around 5.26 years.

Considering the savings achieved for connecting and dispatching a 1MW battery in CASE1, it would be around $68,599.01. Then to have the battery paid by the savings, 10 years would be required.

5.4 Battery cycles for a maximum percentage equals to 100%

With this analysis of payback previously done, we now can contrast it to the battery life due to its cycling. As can be seen, for CASE3, the 1MW battery is expected to last around 7.3 years, whereas the payback calculated is around 5.26 years. It gives 2 years of savings that will go directly to the shipowner.

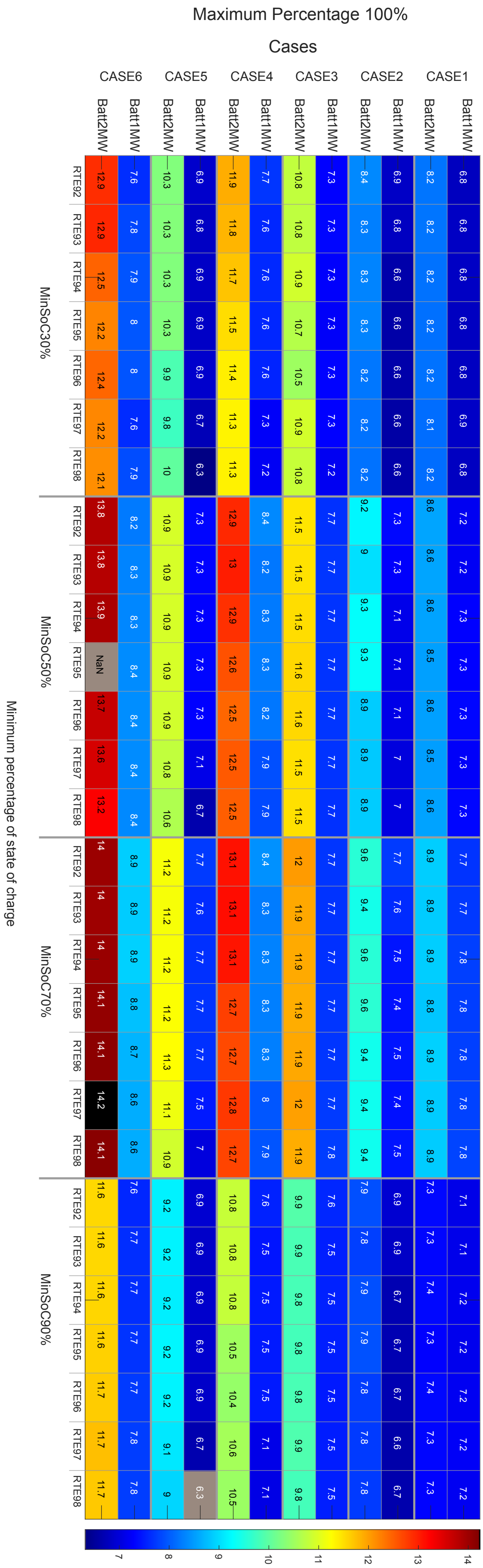


Figure 5.5 – Number of years that the battery will last for a maximum percentage of the rated power of the generators of 100%.

Source: Author.

Considering the amount of $130,014.58 calculated previously as the savings for one year, the total amount that the owner would receive would be around $260,029.16. On the other hand, the 2MW battery is expected to last around 10.5 years whereas its payback would need 10.3 years. Then for this situation the owner would receive a much smaller amount. It would be around $26,561.

Considering only the cycles in LP, DP and ST, the earnings of the owner increases considerably. For this situation, the 1MW battery is expected to last around 8.8 years, whereas the 2MW battery, 12.9 years. Then the owner would have 3.54 years of savings after the battery payment, the total amount would be $460,251.64. For the 2MW battery, this period would be 2.6 years and the total amount $345,293.01.

On the other hand, the use of CASE1, in comparison to the CASE1 with battery only as a reserve does not present a viability. The payback for the 1MW battery is 10 years, whereas the battery is expected to last 6.8 years when the cycles in all parts of the mission are considered and 7.7 years when only the cycles in LP, DP and ST are considered.

One way to help CASE1 achieve the viability is if we consider the fuel consumed in DP with the open bus-tie instead of considering the fuel consumed with the bus-tie closed, which is the optimized dispatch. Then for this situation, the total savings increase considerably, it reaches $341,011.4, which implies in a much shorter payback of 2 years. Then the shipowner would have at least 5.7 years of savings after the battery payment, leading to a huge amount of $1,943,764.9. For this situation, the viability for this retrofit is guaranteed with the lower cost of CO_2 emission.

5.5 Lessons Learned

To conclude, this chapter shows the fuel reductions achieved by the use of batteries in each case analyzed previously. The use of batteries in voyages do not present any benefit, then it can be recommended to set the BMS to not dispatch the battery during these parts of the mission. One potential benefit of using battery in these voyages is the possibility of fixing the operation of the diesel generators at their highest efficient point and using the batteries in a peak shaving mode. It could avoid the operation of diesel generators under 50% of its rated power.

Considering only the battery dispatch in parts of the mission that the battery provide fuel consumption reduction, the battery dispatch provides minor fuel consumption than those presented in the last chapter.

The use of auxiliary generators provides a considerable increase in the number of years that the battery lasts. Moreover, comparing CASE1 to the other cases analyzed we can see that the use of generator sets that comprise different generator sizes also increase the number of years that the battery lasts.

Since it was presented in the last chapter that the use of energy from the port, during

LP, has a lower cost. Batteries can be a solution to reduce the fuel consumption and the CO_2 emissions during ST in a retrofit or if CASE3 is considered for a new ship.

When the battery dispatch is considered, the highest reduction is achieved with CASE3. Moreover, it was presented that the acquisition of both 1MW and 2MW battery is feasible.

Legislation regarding the operation with the bus-tie closed during DP using battery as a reserve must be signed, presenting the amount of time that the battery has to supply the ship in a situation without generators. As presented in the last chapter, pursuing the DP operation with optimal dispatch provides a huge emission and fuel consumption reduction. For CASE1, when we consider the fuel consumed for DP operating with bus-tie open, and compare it to the fuel consumed with the battery dispatch, the acquisition of the 1MW battery becomes feasible by contrasting the years required for the payback and the years that the battery would last due to cycling.

Chapter 6

Evaluating the effect of ship speed reduction on emissions

The power required from the propellers varies with changes in environmental conditions, but the biggest impacts are changes in ship speed. Considering that, for some ships, including the PSVs the power demand required from the propellers represents a huge part of the total ship demand, reducing it may have considerable reductions on ship fuel consumption and emissions.

To analyze it, we have created some curves of demand vs ship speed. From these curves, we could evaluate the impact that different reductions would have, considering the same linear trajectory. The reduction in speed impacted in the duration of the voyage. The first two curves were based on the author's work (BERTHELSEN; NIELSEN, 2021), where a curve is presented contrasting the power and speed of tanker ships of different sizes. Even though tanker ships are much larger than PSVs, their curve was used as a reference to evaluate possible reductions that can be obtained for this level of constant. This constant will be further explained.

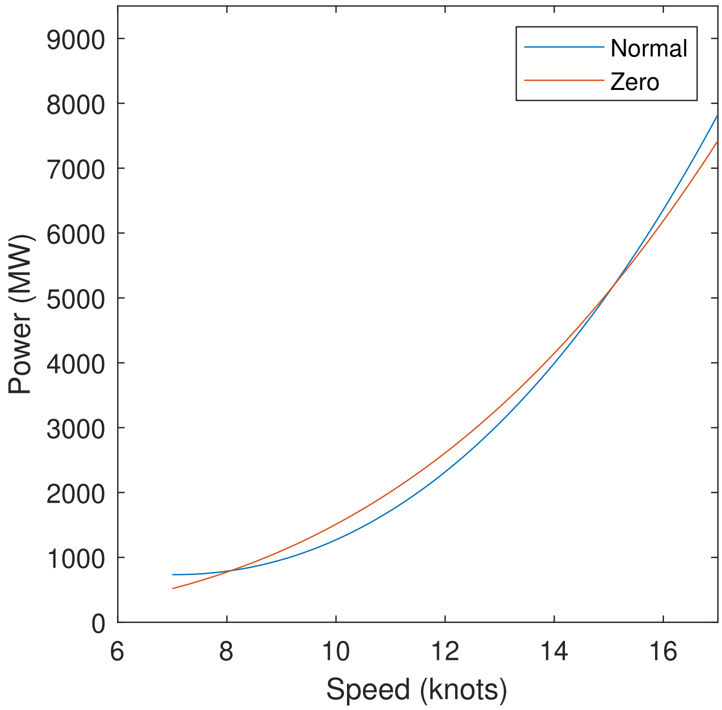
Fig. 6.1 presents these two curves (BERTHELSEN; NIELSEN, 2021). As can be seen, curves are named "Normal" and "Zero". These names are related to the fit curve method used to determine the power vs. speed curve that would meet the power and speed values obtained (BERTHELSEN; NIELSEN, 2021).

$$Power(speed) = p1 * speed^3 + p2 * speed^2 + p3 * speed + p4 \tag{3}$$

The "Normal" curve was obtained using the fit function of Matlab; the fitType was set to "poly3" which traces a curve considering the function presented in Eq.3. For this scenario, the values of p1, p2, p3 and p4 were set to vary from -inf to inf. Considering this range, matlab set p1 equals to 1.386, p2 as 28.65, p3 and p4 equal to -611.6 and 3137, respectively. On the other hand, the "Zero" curve was found using the same fit function and the same fitType of "Normal" curve, but for this curve values of p2, p3 and p4 were set to zero.

As can be seen in Fig. 6.1, this variation on the fit function of MATLAB does not provide a considerable variation on the values of power for the same speed.

Figure 6.1 – Power vs Speed curves based on (BERTHELSEN; NIELSEN, 2021).



6.1 Curve calculated from PSV measurements

Besides considering the curves presented in the literature, another way to find a curve that relates power and speed is through the calculation of the constant that associates these parameters. As presented in Eq.4 this constant is $\frac{1}{2} * \rho_w * S_W * C_T$. This equation is obtained from (BERTHELSEN; NIELSEN, 2021). As can be seen, it introduces some parameters that change the standard association between power and ship speed. In many papers, this relation is considered as P$\approx V^3$. The use of this constant turns this equation becoming dependent on temperature, ship's size and ship speed.

$$P_e = \frac{1}{2} * \rho_w * S_W * C_T * V^3 \quad (4)$$

Where: P_e = Electrical Power
ρ_w = Water density
S_W = Wetted Surface Area
C_T = coefficient of total hull resistance
V = Ship speed

As can be seen, Eq.4 is composed of two constants (ρ_w and S_W), the first constant is related to the environment, the water density. The second constant is related to the ship size. The other parameter of the curve is the coefficient of total hull resistance C_T, this parameter is described in Eq. 5. C_T results from the sum of C_v and C_w. Further, these last two parameters are presented.

$$C_T = C_V + C_W \tag{5}$$

Where: C_T = coefficient of total hull resistance
C_V = coefficient of viscous resistance
C_W = wave making resistance

Eq. 6 displays how the reynolds number is calculated. As can be seen, this parameter varies according to the ship's speed. L is a constant term that depends on each ship. Moreover, υ is the kinematic viscosity of water.

$$R_n = \frac{L * V}{\upsilon} \tag{6}$$

Where: R_n = Reynolds Number
L = Overall length of the ship (ft)
V = Ship velocity (ft/s)
υ = kinematic viscosity of water (ft^2/sec)

C_F is dependent on the reynolds number as presented in Eq. 7. In Eq. 8, it is shown that C_V, one of the terms of Eq.5 is reliant on C_F and K.

$$C_F = 0.075/[(log_{10} R_n) - 2]^2 \tag{7}$$

Where: C_F = Tangential component of viscous resistance

$$C_V = C_F + K * C_F \tag{8}$$

Where: K*C_F = normal component of viscous resistance

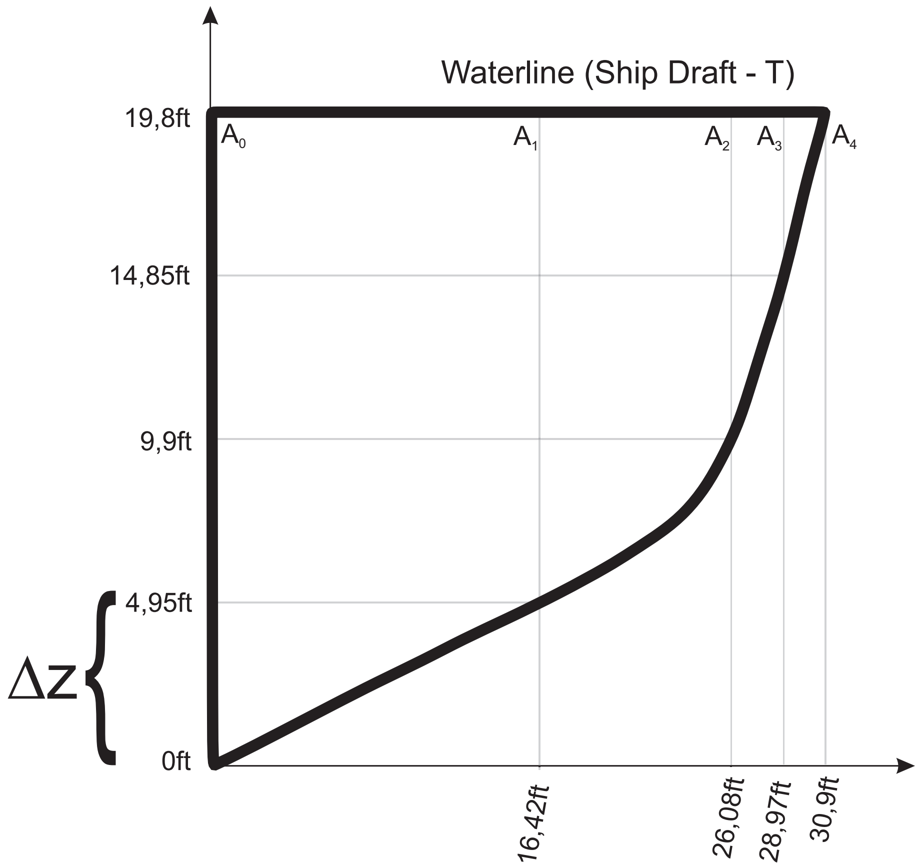
K is obtained from Eq.9. As presented, this equation is based on various structural parameters of the given ship.

$$K = 19 * (\frac{\nabla}{LWL * B * T} * \frac{B}{LWL}) \tag{9}$$

Where: ∇ = Underwater volume of the ship
LWL = Ship lenght at the waterline(ft)
B = Ship beam (ft)
T = Ship draft (ft)

Equations 5 to 9 were obtained in (United States Naval Academy, b). In these equations and in Eq.4, there are parameters that are not given in a ship datasheet and must be calculated, in Fig. 6.2, the frontal half area of the ship is provided. The calculation of the total wetted area (S_w), based on this figure is possible due to Eq.10, which is provided by (United States Naval Academy, a).

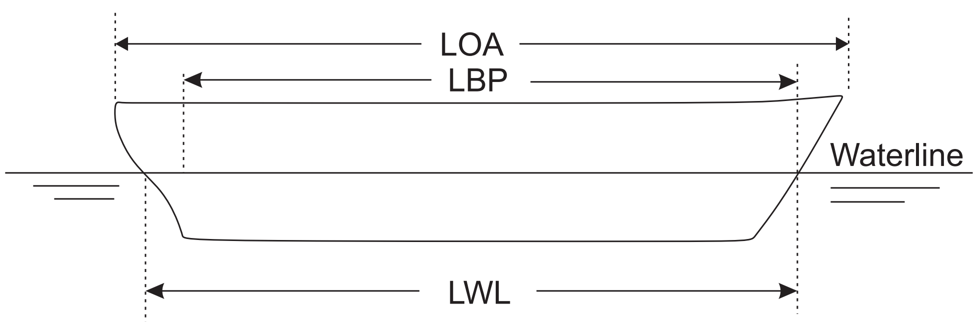
Figure 6.2 – Frontal Half Area of a PSV.



Frontal and Back areas can be determined as 2*A_{sect}. A_{sect} is determined from Eq. 10. Lateral areas can be determined as 2*$A_{lateral}$ which is presented in Eq. 11.

$$A_{sect} = \frac{1}{3} * \Delta z[A_0 + 4A_1 + 2A_2 + 4A_3 + A_4] \tag{10}$$

Figure 6.3 – Lateral of a PSV.



$$A_{lateral} = LBP * Waterline \tag{11}$$

Total Wetted Area (S_w) is then calculated according to Eq. 12.

$$S_W = 2 * A_{lateral} + 2 * A_{sect} \tag{12}$$

In Eq.13 the calculation of the underwater volume of the ship is portrayed. In (MOSER et al., 2016) the terms of this equation are in meters, after the calculation, it is possible to convert to ft^3 by multiplying the results by 35.3147. It can be seen that the volume is dependent on the wetted surface, the ship length, the ship draught and a constant value of 1.7.

$$\nabla = T * (S_W - 1.7 * L_{BP} * T) \tag{13}$$

Table 6.1 shows the constant values used to calculate the parameters that are applied to the equations shown before. As can be seen, there are constant values related to the environment, such as gravity, water viscosity and water density. Moreover, there are constant values linked to the ship's structure, which are presented as ship beam, draft and length between parallels (LBP). As calculated values that do not vary with the ship's speed, we can see the wetted surface area, the underwater volume of the ship and the factor K.

It is interesting to note that, the value calculated to the wetted surface is close to the value presented in (MOSER et al., 2016). In this reference, the authors collected the wetted surface areas of various ships and separated them according to the ship type. PSVs are in the group of tugs and supply vessels. Considering this group, it is possible to say that the PSVs would have the biggest wetted surface areas due to their size in comparison to tugs. Figure 3 of this reference presents that the maximum values are around $1*10^3$ and $1.5*10^3$ m^2. In ft^2, these numbers would be around $10.76*10^3$ and $16.14*10^3$. Furthermore, the value of $12.53*10^3$ is plausible for a PSV.

Table 6.1 – Constant and calculated values that do not vary with the ship speed.

Constant Values			
Gravity (ft/s^2)	32.1741[3]	Ship Beam (ft)	68.9[1]
υ (ft^2/s) (T=26.7°C)	9.26E-6[2]	Ship Draft (ft)	19.8[1]
Water Density	62.217[2]	LBP (ft)	272.31[1]

Calculated Values	
Wetted Surface (S_W) Eqs. 10, 11 and 12 (ft^2)	12534.16
Underwater Volume of the Ship (∇) (ft^3)	68388.53
K Eq. 9	0.0425

Source: Data collected from various sources. [1] (TIDEWATER, 2016), [2] (Engineers Edge,), [3] (The Engineering Toolbox,) .

Table 6.2 – Calculated values that varies according to the ship speed

Ship Speed (knots)	Ship Speed (ft/s)	Reynolds Number (R_n) Eq. 6	C_f Eq.7	C_V Eq. 8	Froude Number [1]	C_W [2]	C_t Eq. 5
1	1.69	5.21E+07	0.002295	0.002388	0.0176011		0.002388
2	3.38	1.04E+08	0.002071	0.002155	0.0352022		0.002155
3	5.06	1.56E+08	0.001955	0.002034	0.0528032		0.002034
4	6.75	2.08E+08	0.001878	0.001955	0.0704043		0.001955
5	8.44	2.60E+08	0.001822	0.001896	0.0880054		0.001896
6	10.13	3.13E+08	0.001778	0.00185	0.1056065		0.00185
7	11.81	3.65E+08	0.001742	0.001813	0.1232075		0.001813
8	13.50	4.17E+08	0.001711	0.001781	0.1408086	5.00E-05	0.001831
9	15.19	4.69E+08	0.001685	0.001754	0.1584097	6.00E-05	0.001814
10	16.88	5.21E+08	0.001662	0.00173	0.1760108	8.00E-05	0.00181
11	18.57	5.73E+08	0.001642	0.001709	0.1936118	9.00E-05	0.001799
12	20.25	6.25E+08	0.001624	0.00169	0.2112129	1.00E-04	0.00179
13	21.94	6.77E+08	0.001607	0.001673	0.228814	1.10E-04	0.001783
14	23.63	7.29E+08	0.001592	0.001657	0.2464151	2.20E-04	0.001877
15	25.32	7.81E+08	0.001579	0.001643	0.2640162	2.50E-04	0.001893
16	27.00	8.33E+08	0.001566	0.001629	0.2816172	3.00E-04	0.001929

Source: [1] and [2] Data collected from (United States Naval Academy, b) and (SUN et al., 2012), respectively.

In Table 6.2, the terms that needed to be calculated and varied with the ship's speed are presented. As can be seen the first two columns are the ship'S speed in knots and ft.s, then on the third column we can see the reynolds number, which equation was presented on Eq.6. These values are used to calculate C_f as portrayed on Eq.7, the results of this equation is shown on the fourth column of Table 6.2. Then, on the fifth column, we have C_v that as presented on Eq. 8, and is calculated based on C_f and K. The second is not dependent on ship's speed an is presented in Table 6.1. Besides them, on the sixth column, the froude number is presented. It is calculated according to Eq. 14 and was used to determine the values of C_W from (SUN et al., 2012). In this reference, a curve comparing the froude number and C_W is portrayed in the fourth figure of this reference in which it is not possible to see the values of C_W for froude numbers lower than 0.14, since the values were already much smaller than C_V, it was considered that for froude numbers smaller than 0.14, C_W would be zero. Finally, we can see the C_T values in the last column. As presented on Eq. 5, these values are the results of a sum between C_V and C_W.

$$F_N = \frac{V}{\sqrt{g * L}} \tag{14}$$

Where: F_N = Froude Number
V = Ship speed (ft/s)
g = gravity (ft/s^2)
L= Ship length (ft)

Table 6.3 presents the parameters that are used in Eq.4 to calculate the electrical power based on the ship's speed.

Table 6.3 – Parameters to calculate the electrical power according to Eq.4.

Ship Speed (knots)	Ship Speed (ft.s)	Constant $\frac{1}{2} * \rho_w * S_W * C_T$	Cubic Ship Speed $(ft/s)^3$	P_e (kW) Eq. 4
1	1.69	9.31E+02	4.81E+00	4.47
2	3.38	8.40E+02	3.85E+01	32.32
3	5.06	7.93E+02	1.30E+02	102.98
4	6.75	7.62E+02	3.08E+02	234.55
5	8.44	7.39E+02	6.01E+02	444.36
6	10.13	7.21E+02	1.04E+03	749.25
7	11.81	7.07E+02	1.65E+03	1,165.63
8	13.50	7.14E+02	2.46E+03	1,757.59
9	15.19	7.07E+02	3.51E+03	2,478.99
10	16.88	7.06E+02	4.81E+03	3,393.38
11	18.57	7.01E+02	6.40E+03	4,488.83
12	20.25	6.98E+02	8.31E+03	5,798.72
13	21.94	6.95E+02	1.06E+04	7,343.08
14	23.63	7.32E+02	1.32E+04	9,656.69
15	25.32	7.38E+02	1.62E+04	11,976.16
16	27.00	7.52E+02	1.97E+04	14,816.60

Fig 6.4 presents the demand curve. The focus will be on the voyage parts of the demand curve highlighted in black and blue. These curves are considered the base case.

Tracing the curve power vs. speed with the values presented in Table 6.3 and adding it to one figure with the other curves presented in Fig 6.1, we have these three curves portrayed in Fig 6.5.

From these two figures, we can start the analysis. The first step of the analysis is the conversion of power from speed using the curves presented in Fig 6.5. Then, the second step is the percentage reduction of the speed. Considering that, the ship's trajectory is linear and is the same for all analysis; when the speed is reduced, the ship's speed summation reduces. Because of this, these scenarios with reduced speed may have more hours than the base case scenario. One premise considered is that these added speeds must be smaller than the maximum speed of the original hours. After that, the third step is the conversion backwards to power to create the demand curve to be analyzed on Homer.

As can be seen by contrasting the voyage parts of the power demand curve presented in Fig 6.4 to the power of Fig 6.5. For a maximum power of 6740kW, the maximum speed for the calculated curve is around 12.5 knots; for the blue curve, the maximum speed is around 16.2 knots and for the red curve it is about 16.4 knots.

The analysis performed will evaluate reductions from 5 to 15% with a 1% step rate for laden and partial load voyages using each power and speed correlation curve presented. From one curve of demand presented in Fig6.4, this analysis will have 22 demand curves (laden + partial load) for each correlation curve. These demand curves and their respective speeds are presented from Table 6.7 to Table C.4.

Figure 6.4 – Power Demand Curve.

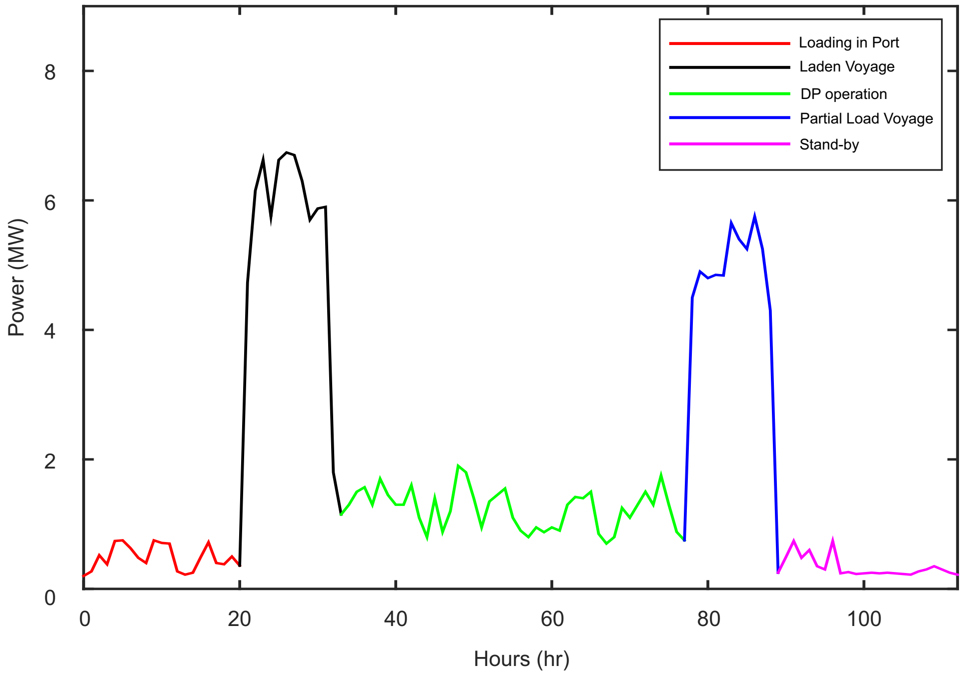
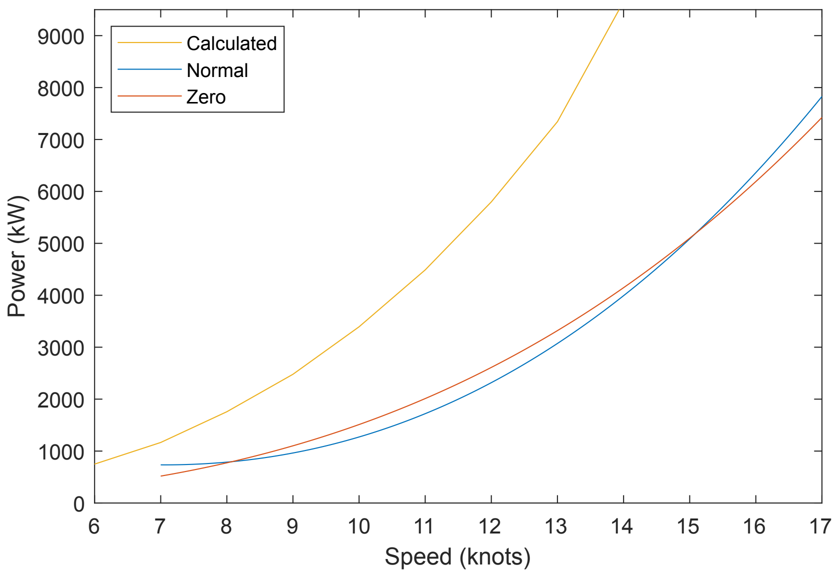


Figure 6.5 – All Power vs Speed curves analyzed.



For both voyage missions, the original demand curve has 11 hours. As mentioned before, the focus here is to analyze missions with the same distance, and as can be seen, each correlation curve produces a different distance traveled in each type of voyage. It is possible to compare these correlation curves if, at the end of all simulations, we divide the total amount of fuel reduced per mile traveled.

Firstly, the idea was to find a comparison inside each correlation curve, so the summation of miles traveled in each voyage was set to be the same for the original curve and for all the other curves with speed reduction. It implied in extra hours for some curves, 12th and/or 13th hours were required. To define the number of extra hours required, some steps were taken. Firstly, considering only the first 11 hours, the quantity of miles traveled on the original curve was reduced from the quantity of miles traveled using a given reduction. It resulted in a number that was, at a first moment, considered as a speed of one hour, named as speed A. This speed A was then compared to the maximum speed of the eleven-hour speed curve for the same given reduction. If speed A was higher, then it was divided by half since it does not make sense to reduce the speed, if the ship would need to operate at a higher speed to achieve the same distance in this extra hour. So, in this case, with speed A higher than maximum speed, we would have two extra hours, with $\frac{speedA}{2}$ in each extra hour. The other possible solution is if speed A was lower than the maximum speed; then in this case, we would have only one extra hour with the ship operating at speed A.

6.2 Ship Power System

To estimate the consumption reduction and ship emission reduction that could be obtained with the reduction of ship speed, we first need to determine the generators that will compose the ship power system.

The generators used in these analyses are the same as those used in Chapter 4. One more time, these generators are presented in Tables 6.4 and 6.5.

Table 6.4 – Cases including Caterpillar generators.

Cases	Sum of Power	Side A			Side B			Sum of Power	
	Sum Side A	**Aux Gen A**	**Main Gen A**	**Main Gen B**	**Main Gen C**	**Main Gen D**	**Aux Gen B**	Sum Side B	Total Sum
Case 1	3640		**1820**	**1820**	**1820**	**1820**		3640	7280
Case 2	3700		**2600**	**1100**	**1100**	**2600**		3700	7400
Case 3	3750		**2200**	**1550**	**1360**	**2420**		3780	7530
Case 4	3700		**2600**	**1100**	**1550**	**2200**		3750	7450
Case 5	3700		**2600**	**1100**	**1360**	**2420**		3780	7480
Case 6	4095	**455**	**1820**	**1820**	**1820**	**1820**	**455**	4095	8190

As can be seen, eight caterpillar generators were chosen. The generator's power is highlighted in bold. These generators were divided into six cases, the first two differ on the use of auxiliary generators, which are much smaller than the main generators. For the other cases, generators of different sizes are selected. The base case includes four 1820 kW generators, the fuel consumption and emissions from this case will be used to determine the percentage reduction or increase obtained from the other cases.

For the analysis of MTU generators, five engines were chosen to form five cases; in this analysis, auxiliary generators were not used, The base case that will be used as a comparison is Case 1. Different from the Caterpillar base case, here the generator size is 1840kW.

Table 6.5 – Cases including MTU generators.

Cases	Sum of Power	Side A		Side B		Sum of Power	
	Sum Side A	**Main Gen A**	**Main Gen B**	**Main Gen C**	**Main Gen D**	Sum Side B	Total Sum
Case 1	3680	**1840**	**1840**	**1840**	**1840**	3680	7360
Case 2	3880	**2424**	**1456**	**1456**	**2424**	3880	7760
Case 3	3864	**2240**	**1624**	**1624**	**2240**	3864	7728
Case 4	3696	**2240**	**1456**	**1624**	**2240**	3864	7560
Case 5	3880	**2424**	**1456**	**1624**	**2240**	3864	7744

The base case used is the same as presented in Chapter 4, CASE1 of CAT and MTU generators, with all generators having the same amount of power. Replacing the amount of fuel consumed in the original voyages with the fuel consumed in these voyages at reduced speed allows for the measurement of the percentage reduction of the full curve caused by the speed reduction.

Table 6.6 – Total miles traveled in each voyage for the different correlation curves.

Correlation Curve	Voyage	Miles traveled
Calculated	Laden	133.5088
	Partial Load	125.78
Ref Normal	Laden	173.712
	Partial Load	164.4962
Ref Zero	Laden	174.9596
	Partial Load	164.2619

In Table 6.6 the number of miles traveled using each curve is shown. All distances were determined based on the same power demand curve for the original laden and partial load voyage. As presented in Fig. 6.5, the curves have a relation between power and speed that is different from each other. As shown in Table 6.6, it results in different amounts of miles traveled. As explained before, these distances are maintained when the ship's speed is reduced by increasing the number of hours that the voyages last with the ship traveling at different speeds.

In the following pages, Tables 6.7, 6.8 containing the speed and power for each level of speed reduction are presented.

Table 6.7 – Comparison between the original demand and speed of the laden voyage and the speed and demand obtained for reductions from 0.15 to 0.05% using the calculated curve to correlate speed and power.

% reduction	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13
Original	Original Speed	11.21	12.18	12.47	11.93	12.47	12.54	12.51	12.27	11.89	12.01	12.02	0.00	0
	Original Demand	4730	6150	6625	5750	6625	6740	6700	6300	5700	5875	5900	0	0
15%	Reduced Speed	9.53	10.35	10.60	10.14	10.60	10.66	10.64	10.43	10.11	10.21	10.22	10.01	10.01
	New Demand	2850.64	3683.24	3961.91	3448.62	3961.91	4029.40	4005.93	3771.23	3419.31	3521.93	3536.59	3318.92	3318.92
14%	Reduced Speed	9.64	10.48	10.72	10.26	10.72	10.78	10.76	10.56	10.23	10.33	10.34	9.35	9.35
	New Demand	2954.95	3820.20	4109.80	3576.38	4109.80	4179.93	4155.53	3911.64	3545.92	3652.57	3667.80	2683.88	2683.88
13%	Reduced Speed	9.76	10.60	10.85	10.38	10.85	10.91	10.89	10.68	10.35	10.45	10.46	8.68	8.68
	New Demand	3062.071	3960.845	4261.668	3707.591	4261.668	4334.516	4309.174	4055.825	3675.943	3786.728	3802.549	2144.561	2144.561
12%	Reduced Speed	9.87	10.72	10.97	10.50	10.97	11.03	11.01	10.80	10.47	10.57	10.58	8.01	8.01
	New Demand	3172.053	4105.238	4417.576	3842.294	4417.576	4493.212	4466.902	4203.856	3809.433	3924.46	3940.887	1692.02	1692.02
11%	Reduced Speed	9.98	10.84	11.10	10.61	11.10	11.16	11.14	10.92	10.59	10.69	10.70	7.34	7.34
	New Demand	3284.92	4253.44	4577.58	3980.54	4577.58	4656.07	4628.77	4355.79	3946.44	4065.82	4082.87	1317.29	1317.29
10%	Reduced Speed	10.09	10.96	11.22	10.73	11.22	11.28	11.26	11.05	10.70	10.81	10.82	6.68	6.68
	New Demand	3400.75	4405.50	4741.75	4122.39	4741.75	4823.18	4794.85	4511.67	4087.01	4210.86	4228.54	1011.45	1011.45
9%	Reduced Speed	10.20	11.09	11.35	10.85	11.35	11.41	11.39	11.17	10.82	10.93	10.94	6.01	6.01
	New Demand	3519.55	4561.46	4910.14	4267.89	4910.14	4994.57	4965.20	4671.56	4231.20	4359.62	4377.97	765.54	765.54
8%	Reduced Speed	10.32	11.21	11.47	10.97	11.47	11.53	11.51	11.29	10.94	11.05	11.06	10.68	
	New Demand	3641.37	4721.39	5082.80	4417.09	5082.80	5170.32	5139.87	4835.51	4379.05	4512.17	4531.19	4058.60	
7%	Reduced Speed	10.43	11.33	11.60	11.09	11.60	11.66	11.64	11.41	11.06	11.17	11.18	9.35	
	New Demand	3766.27	4885.33	5259.79	4570.04	5259.79	5350.46	5318.92	5003.57	4530.62	4668.56	4688.26	2683.88	
6%	Reduced Speed	10.54	11.45	11.72	11.21	11.72	11.78	11.76	11.54	11.18	11.29	11.30	8.01	
	New Demand	3894.27	5053.35	5441.17	4726.79	5441.17	5535.09	5502.42	5175.80	4685.96	4828.83	4849.24	1692.02	
5%	Reduced Speed	10.65	11.57	11.85	11.33	11.85	11.91	11.89	11.66	11.30	11.41	11.42	6.68	
	New Demand	4025.43	5225.49	5627.02	4887.39	5627.02	5724.25	5690.42	5352.27	4845.12	4993.04	5014.17	1011.45	

Table 6.8 – Comparison between the original demand and speed of the partial load voyage and the speed and demand obtained for reductions from 0.15 to 0.05% using the calculated curve to correlate speed and power.

% reduction	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13
Original	Original Speed	11.04	11.34	11.27	11.30	11.30	11.86	11.69	11.59	11.93	11.59	10.88	0.00	0.00
	Original Demand	4500	4900	4800	4850	4840	5650	5400	5250	5750	5250	4300	0	0
15%	Reduced Speed	9.38	9.64	9.58	9.61	9.60	10.08	9.94	9.85	10.14	9.85	9.25	9.43	9.43
	New Demand	2715.84	2950.28	2891.67	2920.98	2915.11	3389.98	3243.39	3155.45	3448.62	3155.45	2598.64	2761.80	2761.80
14%	Reduced Speed	9.49	9.75	9.69	9.72	9.71	10.20	10.06	9.97	10.26	9.97	9.36	8.80	8.80
	New Demand	2814.87	3058.51	2997.59	3028.04	3021.95	3515.44	3363.11	3271.72	3576.38	3271.72	2693.06	2239.83	2239.83
13%	Reduced Speed	9.60	9.87	9.80	9.83	9.83	10.32	10.17	10.08	10.38	10.08	9.46	8.18	8.18
	New Demand	2916.56	3169.64	3106.36	3138.00	3131.67	3644.29	3486.05	3391.11	3707.59	3391.11	2790.04	1796.39	1796.39
12%	Reduced Speed	9.71	9.98	9.91	9.95	9.94	10.44	10.29	10.20	10.50	10.20	9.57	7.55	7.55
	New Demand	3020.97	3283.73	3218.04	3250.89	3244.31	3776.57	3612.27	3513.69	3842.29	3513.69	2889.60	1423.98	1423.98
11%	Reduced Speed	9.82	10.09	10.03	10.06	10.05	10.56	10.41	10.31	10.61	10.31	9.68	6.92	6.92
	New Demand	3128.12	3400.85	3332.66	3366.74	3359.93	3912.34	3741.81	3639.51	3980.54	3639.51	2991.78	1115.13	1115.13
10%	Reduced Speed	9.93	10.21	10.14	10.17	10.17	10.67	10.52	10.43	10.73	10.43	9.79	6.29	6.29
	New Demand	3238.07	3521.01	3450.25	3485.63	3478.56	4051.63	3874.73	3768.60	4122.39	3768.60	3096.63	862.36	862.36
9%	Reduced Speed	10.04	10.32	10.25	10.29	10.28	10.79	10.64	10.55	10.85	10.55	9.90	5.66	5.66
	New Demand	3350.85	3644.25	3570.90	3607.58	3600.23	4194.52	4011.06	3901.01	4267.89	3901.01	3204.16	658.18	658.18
8%	Reduced Speed	10.15	10.43	10.36	10.40	10.39	10.91	10.76	10.66	10.97	10.66	10.01	10.06	
	New Demand	3466.51	3770.65	3694.60	3732.62	3725.02	4341.03	4150.87	4036.79	4417.09	4036.79	3314.46	3369.76	
7%	Reduced Speed	10.26	10.55	10.48	10.51	10.50	11.03	10.87	10.78	11.09	10.78	10.12	8.80	
	New Demand	3585.07	3900.22	3821.42	3860.82	3852.94	4491.23	4294.20	4175.99	4570.04	4175.99	3427.51	2239.83	
6%	Reduced Speed	10.38	10.66	10.59	10.62	10.62	11.15	10.99	10.89	11.21	10.89	10.23	7.55	
	New Demand	3706.59	4033.01	3951.40	3992.21	3984.04	4645.17	4441.09	4318.66	4726.79	4318.66	3543.40	1423.98	
5%	Reduced Speed	10.49	10.77	10.70	10.74	10.73	11.27	11.11	11.01	11.33	11.01	10.34	6.29	
	New Demand	3831.11	4169.09	4084.58	4126.83	4118.38	4802.89	4591.60	4464.83	4887.39	4464.83	3662.13	862.36	

6.3 Results for CAT generators using calculated curves

This section aims at presenting the percentage reductions obtained by comparing the fuel consumed when using CASE1 generators operating in the original laden and partial load voyage to each case operating in the demands of each percentage reduced speed. It is important to mention that 85% refers to 85% of the speed for the original voyage operation; in other words, it means 15% of speed reduction.

6.3.1 Laden Voyage

Fig 6.6 presents the fuel savings obtained for each level of speed reduction. As can be seen, the numbers for a minimum percentage to turn on the generators of 10% are very similar to those presented for 50%. A 5% speed reduction leads to fuel reductions of at least 13.8%. The highest fuel reduction achieved for this level of speed reduction is achieved with CASE3, which presented values of around 16.8%. This number represents a considerable reduction for such small reduction in speed. Cases 4 and 5 present numbers around 15.5% and 16.5%, respectively. For cases 1 and 2, this level of fuel reduction, close to 16%, is obtained only with a speed reduction of 6%.

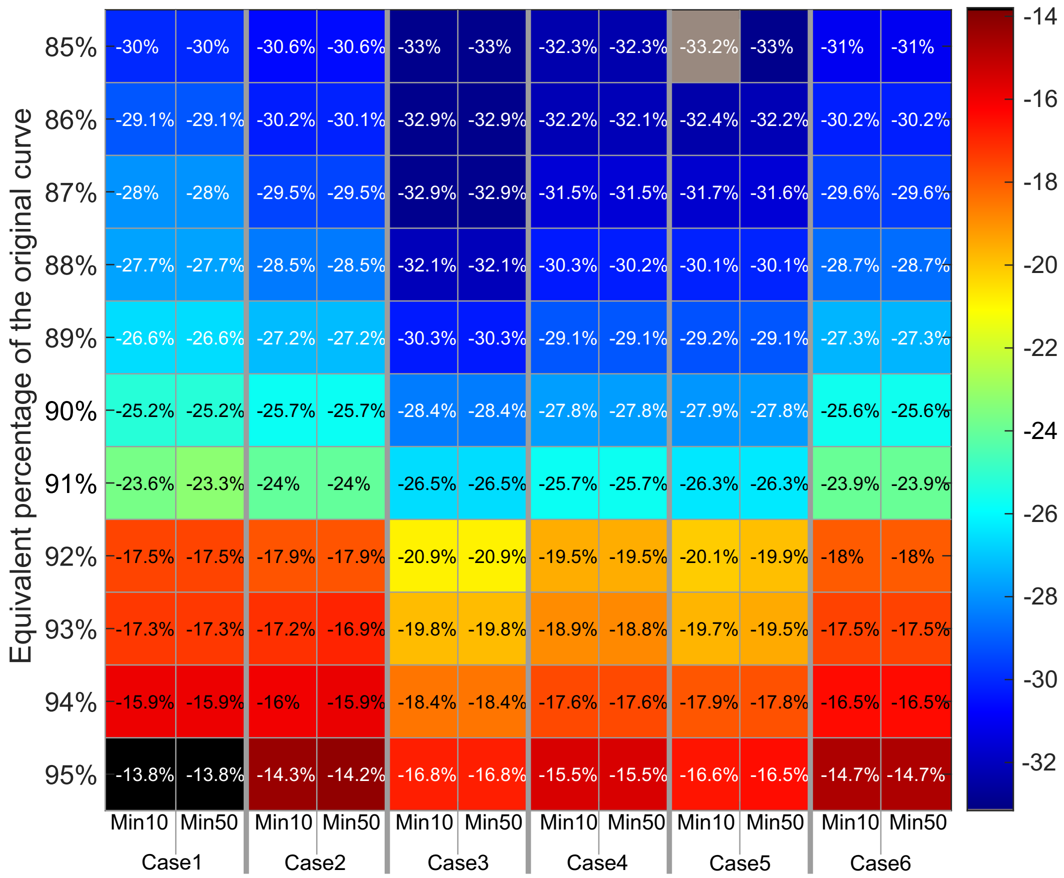


Figure 6.6 – Percentage reduction of fuel consumed by varying the speed reduction during the laden voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the calculated curve.

The increase in speed reduction from 5% to 8% does not provide a linear reduction in fuel consumption. As can be seen, from 5% to 6%, the fuel reduction, on average, varies around 1.7%. The lowest variation is 1.3%, which is obtained with CASE5, whereas the highest variation, 2.1%, was obtained with CASE4 and CASE1. Analyzing the speed reduction increase from 6% to 7% provides a small fuel reduction variation. On average, this speed variation results in a fuel variation of 1.4%. From 6% to 7%, CASE5 fuel reduction variation was 1.8%, whereas from 5% to 6%, this variation was only 1.3%. CASE5 was the only case that had a higher number of fuel reductions from 6% to 7% than from 5% to 6%. Moving the speed reduction from 7% to 8% provides a much smaller fuel reduction variation. On average, this number is around 0.6%. Commonly, the same speed reduction variation of 1% did not provide similar results. This discussion highlights the non-linear relation between fuel and speed reduction.

When the speed reduction is above 9%, two extra hours of operation are required to meet the same trajectory of the original demand. At this level of speed reduction, we have a considerable increase in fuel consumption reduction in comparison to the 8% speed reduction. The variation in fuel consumption reduction is around 6%. CASE3 reaches around 26.5% fuel reduction; cases 4 and 5 have reductions of 25.7% and 26.3%. CASE1 achieves this level of reduction of about 26.5% only when speed is reduced by 11%.

CASE3 presents a saturation of fuel consumption reduction after a speed reduction of 13%. This saturation is also seen in cases 4 and 5 when speed reduction is above 14%. The other cases do not portray saturation.

6.3.2 Partial Load Voyage

Fig. 6.7 presents the fuel reductions that can be obtained when the ship's speed is reduced during partial load voyage. As can be seen, in the majority of cases, the numbers are smaller. As exceptions, we have the reductions obtained for a variation between 5% and 8% for cases 3 and 5. Comparing both voyages, we can see that, for this level of demand, the change in the generator set, represented here by the cases from 1 to 6, has a much higher impact on fuel consumption. For Fig 6.6, the biggest difference in fuel reduction for a speed reduction of 5% happened comparing CASE1 and CASE3, it was around 3%. For Fig. 6.7, this difference was 4.9%, and was obtained comparing the same cases.

The fuel percentage decrease for a speed reduction of 5% is higher than 12.4%. This number was reached for CASE1. CASE3 has the higher fuel consumption reduction, it is around 17.3%. As presented for laden voyage, the fuel percentage reduction jumps considerably from 8% to 9%.

For a speed reduction of 8%, the fuel consumption reduction reaches almost 20% for CASE3. This number is much higher than the one obtained when CASE1 is used, around 14.7%. It is interesting to note that, for CASE1 reducing the speed by 7% is slightly better than reducing it by 8%. Comparing these speed reductions, CASE3 portrays the same numbers for both. CASE5 is the case that presents the highest difference, around 1.1%.

Comparing the minimal percentage to turn on the generator, we can see that most of the fuel reductions are the same for a given case at a given speed reduction. As introduced in Fig 6.6, the fuel reductions may present a saturation. For partial load voyage, it results in a smaller speed reduction in most cases. For CASE3, whereas the results for laden voyage presented a saturation in speed reductions above 13%, for partial load voyage this saturation appeared after 12%. For cases 4 and 5, this saturation appears after 13% in Fig. 6.7. For cases 1 and 2, this saturation occurred after 14%, and for CASE6 after 13%.

It is interesting to compare CASE1 and CASE6 to evaluate which speed reduction level the auxiliary generators may be the most beneficial at. For speed reductions higher than 14%, the numbers are similar. These similar results have not occurred for laden voyage; there CASE6 presented numbers higher for all levels of speed reduction.

Besides that CASE5 starts to have a higher fuel consumption reduction than CASE3 only for a speed reduction higher than 10%. For this case, there are two considerable jumps in fuel speed reduction; for a variation of 1% from 8% to 9% of speed reduction, this jump was around 6.3%. From 9% to 10%, this jump was 2%.

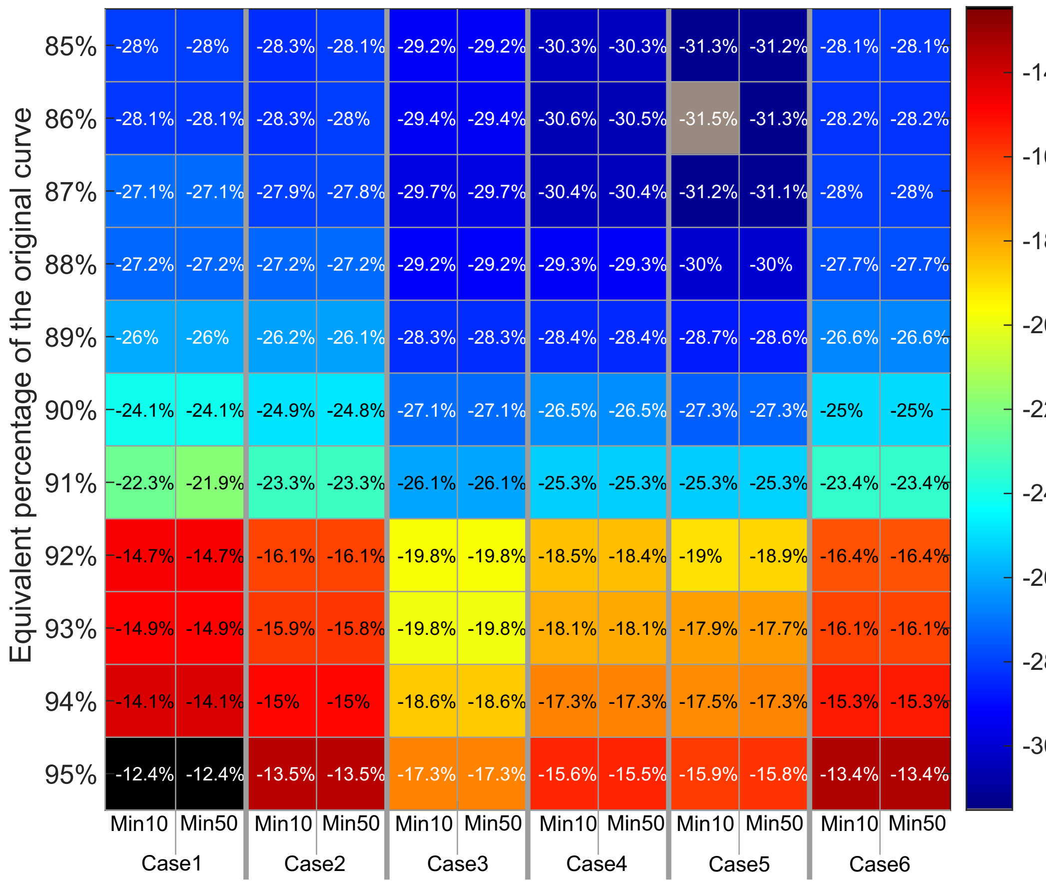


Figure 6.7 – Percentage reduction of fuel consumed by varying the speed reduction during partial load voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the calculated curve.

Finally, we can discuss the highest fuel reductions achieved in each case. As displayed for laden voyage; CASE5 presents the highest fuel reductions, the difference is that for partial load voyage the highest fuel reduction was achieved for a speed reduction of 14%, whereas for laden it was obtained with a speed reduction of 15%. The highest fuel reduction obtained with CASE1 was 28.1% also reached 14%. CASE2 had a reduction of 28.3% for 14% and 15%. CASE4 reached 30.6% for a speed reduction of 14%. A fuel consumption decrease of 28.2% was found for a speed reduction of 14%.

If we consider that, the relation between speed and power for a PSV would be more similar to that of a tanker, as presented in the normal and zero curves. We can see that for the normal curve, the numbers of reduction are slightly higher when compared to Fig 6.6.

6.3.3 Impact of speed reduction on the full demand curve

To conclude the evaluation regarding CAT generators, Fig. 6.8 presents the total reductions considering three levels of speed reduction. This figure considers the reduction for both laden and partial load voyage. The percentage reduction presented is in relation to CASE1 consumption without restrictions on maximum percentage, without speed reduction, and operating in DP with an optimized dispatch. The values presented in this figure consider the fuel consumption for the voyages achieved by the use of the calculated curve.

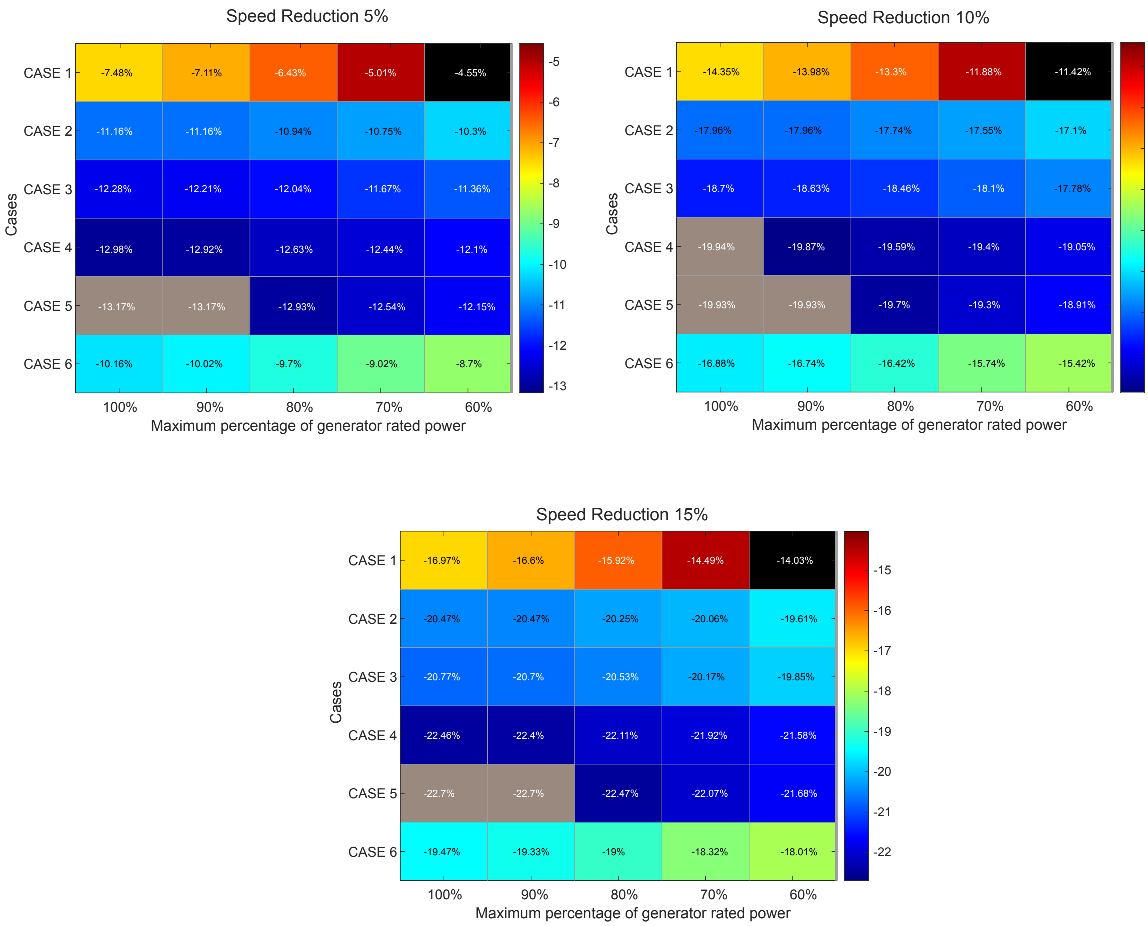


Figure 6.8 – Percentage reduction of fuel consumed for the complete mission, considering three levels of speed reduction.

Analyzing these results in terms of fuel consumption we find that the change from CASE1 to CASE5, summed to a speed reduction of 5%, presents a total reduction of 6974.58 liters per mission. In one year, the total savings in one year will be $274,273.46 for a cost of $10 per ton of CO_2 and $0.498 per liter of diesel. If we increase the speed reduction to 10%, which is the number desired by IMO, the fuel consumption reduction in one mission increases to 10,558.75 liters. Moreover, the savings reach a value close to $415,220.16 in one year. This value is 51.39% higher than the number presented for a speed reduction of 5%. Finally, when the speed reduction is set as 15%, the fuel saved is around 12,027.24 liters, and the money saved in one year will be around $472,968.42, which is only 13.9% higher than the value for a speed reduction of 10%.

If we consider that the money saved would be totally used to pay for the battery, assuming a price of $684.37/kWh, we can find that the payback for a 1MWh battery will be 2.49 years, 1.65 years and 1.45 years for the speed reduction of 5%, 10% and 15%, respectively. Moreover, for a 2MWh battery, the payback will be 5 years, 3.30 years, and 2.89 years for speed reductions of 5%, 10%, and 15%, respectively. It is interesting to note that, if the shipping sector starts to reduce its operational speed, the payback time for batteries would reduce considerably even if we consider a low taxation of CO_2, such as $10 per ton.

Considering the LP operation being fed through renewable energy from the port, at a price of $0.103 /kWh. It would cost of $78,177 per year. On the other hand, the fuel saved would increase to 9,669.65 liters, 13,253.82 liters, and 14,722.32 liters for speed reductions of 5%, 10%, and 15%, respectively. Then the total savings, considering the cost of buying the energy from the port, would be, for speed reductions of 5%, 10%, and 15%, around $302,079.49, $443,026.19, and $500,774.45, respectively. Calculating the payback period for the 1MWh and 2MWh batteries would be 2.26 years and 4.53 years, respectively, for a speed reduction of 5%. Moreover, for a speed reduction of 10%, these values would be 1.54 and 3.09 years, and for a 15% reduction, 1.37 and 2.73 years.

6.4 Results for MTU Engines

A compilation showing the total reduction achieved by the whole curve as done for CAT generators is provided in Fig.6.9. As happened in Chapter 4 the results comprising MTU generators show a lower reduction.

For the results comprising no speed reduction, CASE5 also portrayed the highest reduction. In those results, the maximum reduction was around 1.74%. It can be seen in Fig.6.9 that a small reduction of 5% in speed reduction provides a considerable increase in fuel reduction. The reduction reaches 10.11%.

Then for the 10% of speed reduction, we can see that the numbers increase significantly. The fuel consumed using CASE1 is almost 15% lower than the fuel consumed without any speed reduction. Moreover, CASE5 achieves a reduction slightly higher than 17%.

For a speed reduction of 15%, the reduction increases, but not as much it occurred in the variation from 5% to 10%. The fuel consumed by cases 4 and 5 for this speed reduction are almost the same: 19.45% for CASE4 and 19.47% for CASE5.

Discussing the real amount of fuel saved, we will find that for a speed reduction of 5% using CASE5 in comparison to CASE1 without any speed reduction, the amount of fuel saved in one year is 380,997.47 liters. For a speed reduction of 10%, this quantity increases to 643,406.59 liters. Finally, for a speed reduction of 15% it reaches 733,582.12 liters.

Then, considering the same prices of diesel and the same taxation on CO2 emissions, we will find the following payback times to buy a 2MW battery 6.85, 4.06, and 3.56 years for the speed reductions of 5%, 10%, and 15%, respectively.

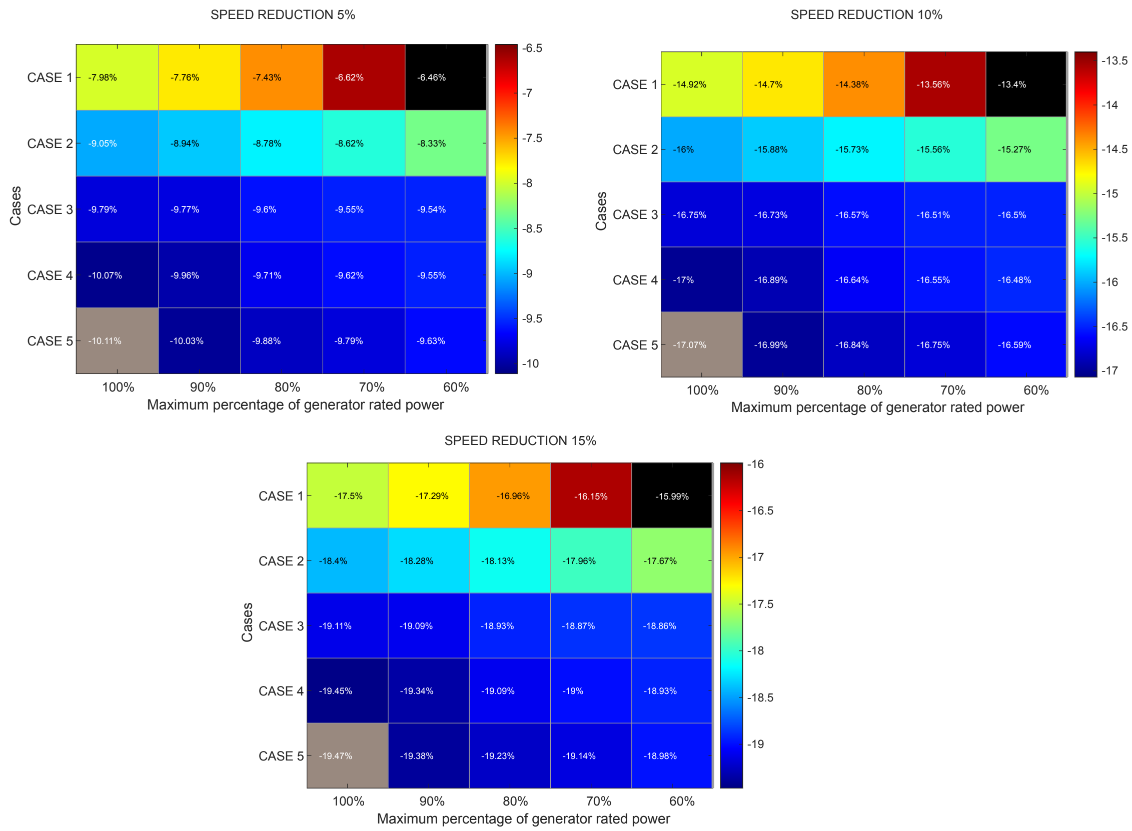


Figure 6.9 – Percentage reduction of fuel consumed for the complete mission considering three levels of speed reduction.

If we consider that the LP operation will be fed by the port using renewable energy such as solar. In one year, the amount of fuel reduced, will be 573,188.02, 835,597.14 and 925,772.66 liters for the speed reductions of 5%, 10%, and 15%, respectively. Then the money saved by the solutions used in this scenario will be \$222,362.67, \$359,951.65, and \$407,233.38.

The payback to buy a 2MW battery for the speed reductions of 5%, 10% and 15%, considering the cost of buying the energy from the port, is equal to 6.16, 3.80 and 3.36 years.

6.5 Partial Conclusions

Reducing speed is the most promising solution to reduce CO_2 emissions and fuel consumption during voyages.

For CAT and MTU generators, the speed reduction resulted in savings that allowed the acquisition of batteries with a feasible payback time without requiring a harder taxation.

Chapter 7

Conclusions

The methodology implemented in this work first evaluated different sets of generators. By pursuing a sensitivity analysis on various generators, we could find which set of generators provided the lowest fuel consumption and, therefore, the lowest CO_2 emissions. Moreover, it was presented that, considering the linear pattern between fuel consumption and power for an identical brand of generators, the case that provided the lowest consumption could be predicted by statistically analyzing the demand curve. In this first part of the methodology, the battery was considered only as an additional power source, allowing an optimized dispatch during DP operation. So, the state of charge remained intact during the whole mission.

Then, the second step of the methodology considered the battery dispatch. In this phase, more than just allowing an optimized dispatch, the battery allowed the diesel generators to be turned off when the loads were too small. In other moments of the mission, diesel generators must operate above the demand level to charge the batteries. In some cases, it increased fuel consumption even though there was a reduction in the time that the generators operate at low loads.

Finally, the third step of the methodology evaluated the ship speed reduction during voyages. It was analyzed due to an indication of IMO considering a 10% reduction of ship speed as a solution to reduce fuel consumption and emissions. This methodology calculated the relation between ship speed and power using ship equations.

Presenting a discussion regarding all results, on the analysis of dispatching the battery, it was shown that the reductions are not directly connected to the depth of discharge since, for some scenarios, the reduction achieved with a minSoC of 50% was higher than the reduction obtained with a reserve of 30%. Moreover, the results showed that batteries can be a good alternative for ship retrofits. Considering that, on most of the existing ships, a complete change of the generator set is not possible. The use of batteries in CASE1 provided good reductions reaching numbers around 3.2% for RTEs available in commercial batteries.

Moreover, it was presented that, if we consider only the parts of the mission, in which the use of battery is beneficial in terms of fuel consumption reduction, all cases can have a fuel consumption reduction when a battery with a commercial RTE is analyzed.

The battery dispatch also changed the case that provided the lowest fuel consumption, in this scenario CASE3 reaches a reduction that is around 6.24% and 6.37% for the 1MW and 2MW battery, respectively.

Chapter 5 also presented a financial evaluation considering the years to payback the investment required to acquire the battery and the lifespan of the battery. This analysis considered CASE1 as a retrofit solution and CASE3 for a new ship.

From the battery lifespan analysis we could see that besides helping to reduce the fuel consumption, the use of a generator set that comprises different generator sizes also helps to increase the amount of years that the battery lasts.

It is interesting to note that the greater gain in fuel consumption during DP is achieved by the change from operation with the bus-tie opened to the bus-tie closed. A regulation stating the minimal reserve required to pursue this operation safely and allowing batteries to be used as a reserve to enable the use of closed bus-tie is necessary.

Then, considering that the two first steps of the methodology have not achieved considerable reductions during voyages, another step should be considered. This step was based on one of the solutions proposed by IMO, this organization encourages the speed reduction in 10%. So, we aim at evaluating various levels of speed reduction, including 10%, to understand why IMO specifically indicated this number.

The speed reduction showed that this solution can provide considerable reductions of fuel and CO_2 emission. The analysis of different curves provided that speed reductions of around 10% achieved a reduction of fuel and CO_2 emission above 20%.

7.1 Future Studies

Future studies should evaluate some solutions that will become more commercial and financially available in the next years. As these solutions-fuel cells, variable speed generators and green fuels produced from renewable energy-are the most promising.

These studies regarding fuel cells should comprise different sizes of fuel cells. It is necessary since there are developments of fuel cells around 3MW from a partnership between ABB and Ballard.

Moreover, advanced models that comprise the fading effect of the batteries through the years should be developed to investigate if the change in the lifespan would make the use of battery impracticable.

Further analysis on battery dispatch should be done considering these new demands resulted from the reduced speed, it is necessary, since for our analysis on the standard demand, the battery dispatch in voyages do not provide benefits in terms of fuel consumption.

An evaluation that was not shown in this work is the analysis of how the battery dispatch change the point of operation of the generators. Besides reducing the fuel consumption, these batteries can also be playing another important role.

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Annexes

ANNEX A

MTU Generators

In this annex, we will present the same evaluation pursued for CAT generators but now for the MTU generators. The results presented here will comprise each part of the mission.

In the following figures we have the amount of fuel consumed by each one of the four diesel generators. For CASE1, we have four 1840kW diesel generators, in CASE2 we have as gen 1 and gen 2 the two 2424kW diesel generators, for gen 3 and gen 4 we have two 1456kW diesel generators. CASE3 has as generators 1 and 2 the two 2240kW diesel generators, as generators 3 and 4 we have the two 1624kW. Finally, we have as gen 1 for CASE4 and CASE5 the 2240kW and the 2424kW diesel generators, respectively. As gen 2, 3 and 4 we have for both cases the 2240kW, 1624kW and 1456kW, respectively.

A.1 Loading in Port (LP)

As happened in the analysis of the CAT generators, the use of different generators in a generator set also presented considerable reductions when we analyze LP operation. Differently from what happened in Fig.A.1, here CASE2 that comprises 2 generators with 2 different sizes (2424kW and 1456kW) did not provide the best results.

It is interesting to analyze that by comparing cases 2 and 3 we can see that the use of 1624kW diesel generator produced a lower consumption than using the 1456kW diesel generator. It is related to the fuel consumption curve of both generators. Moreover, it is strengthened in cases 4 and 5 that comprises both generators but the optimized dispatch chooses the 1624kW.

By comparing CASE1 to the ones that use the 1624kW diesel generator, we can see that this change leads to a reduction of around 339.5 liters of fuel.

The percentage reduction obtained by the CASE2 in comparison to CASE1 is around 3.5%. For cases 3, 4 and 5 this percentage is much higher, around 11.7%.

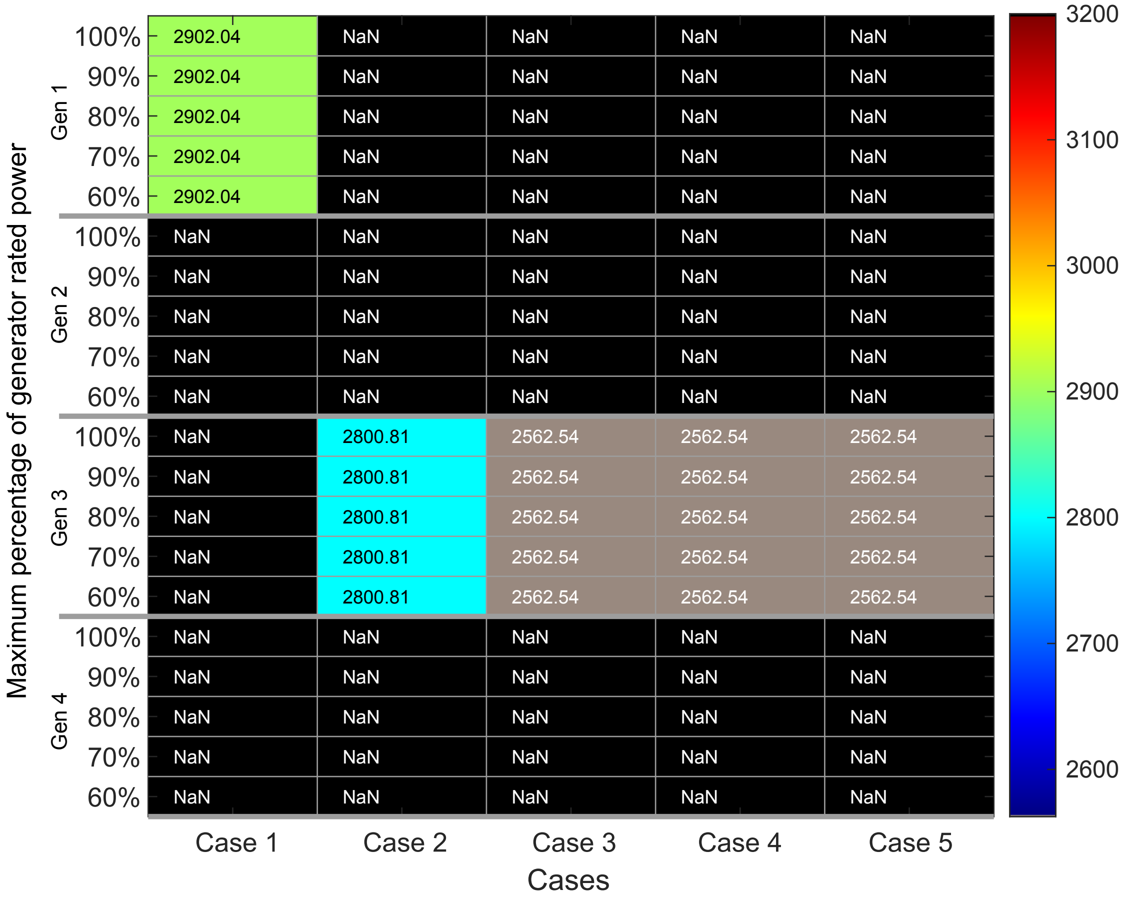

Figure A.1 – Fuel Consumed during LP operation in liters per generator in each case for different maximum percentage of generator rated power. The minimum load of generators was set to 10% for LP operation.

Source: Author.

A.2 Voyages - Laden and Partial Load Voyage

As presented in Fig.4.3 the reductions are much smaller than the reductions that happened for the other parts of the mission. As expected due to the results presented in Fig.4.8, the level of percentage of the reductions in Fig. A.2 will be also smaller than the ones presented in Fig. 4.3.

CASE2 achieved a reduction of 0.17% in comparison to CASE1, in liters it was equivalent to 28.55 liters. CASE4 and CASE5 also presented a reduction in fuel consumption, these reductions were around 0.2%, in liters these numbers were close to 32.63 and 37.35, respectively. The set of generators used in CASE3 provided an increase of 0.3% in fuel consumption. This case consumed around 48.13 liters more than CASE1. As can be seen these numbers are very small in comparison to the ones presented for CAT generators.

For partial load voyage, the numbers are worst, comparing all cases to CASE1, only CASE2 provides fuel reduction, it was around 0.15%, in liters, around 21.05 liters. All other cases increased the fuel consumption in comparison to CASE1, CASE4 and CASE5 incremented the fuel consumption by 0.2% and 0.1%, respectively. CASE3 increased by 0.72%, which is equivalent to almost 99.49 liters more.

When we compare the numbers for the minimum percentage to use the generator, we can see that the variation from 10% to 50% does not present a difference when partial load voyage is evaluated. When we evaluate laden voyage, we can see that the numbers for cases 1,2 and 3 are the same for both minimum percentages, for CASE4 and CASE5, the minimum percentage of 50% provides an increase of around 25 liters for both cases.

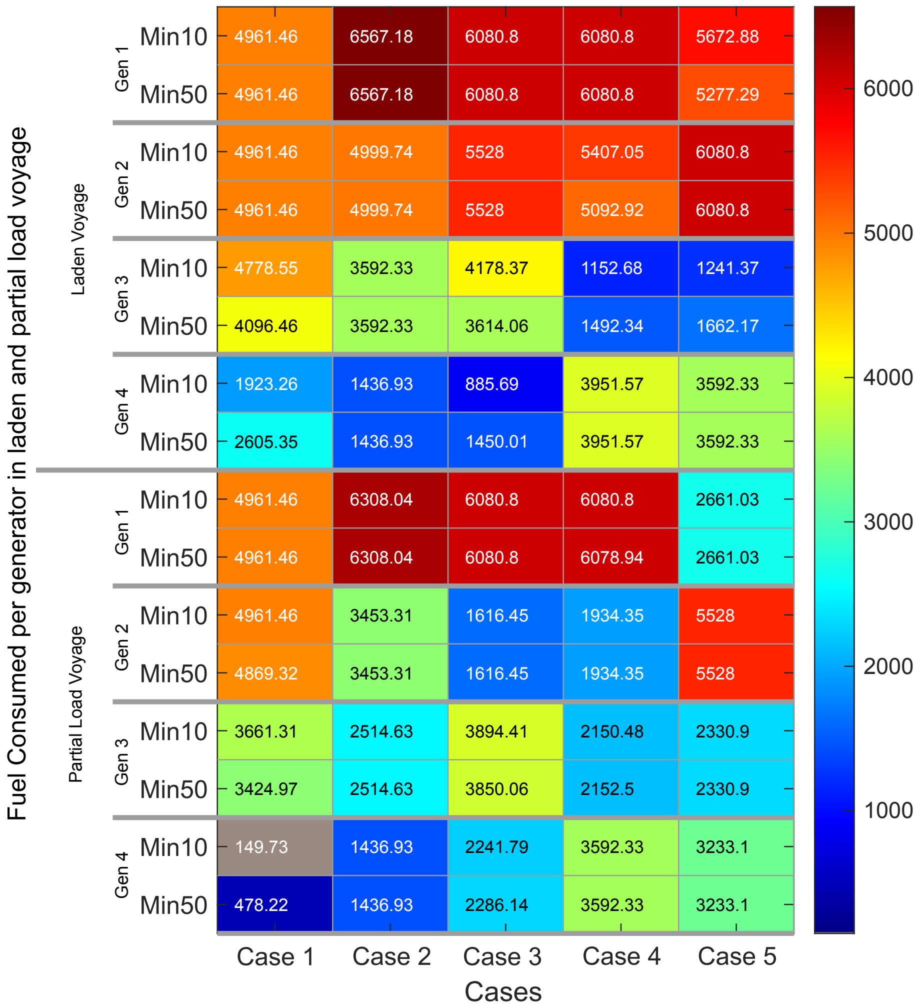

Figure A.2 – Fuel Consumed during LV and PLV operation in liters for each generator in each case for a maximum percentage of generator rated power equal to 100%. The minimum load of generators was set to 10% and 50% for LV and PLV operation.

Source: Author.

A.3 Dynamic Positioning (DP)

Moving the analysis to Fig. A.3, we can see that there are very different reductions among the maximum levels of percentage. Comparing the cases to CASE1 at the same maximum percentage we have for 100%, a reduction of 0.63% in the fuel consumption of CASE2 in comparison to CASE1, the reductions for CASE3, CASE4 and CASE5 are about 0.2%, 0.6% and 0.6%, respectively. For 90%, these reductions are a bit higher around 0.9% for CASE3 and CASE4, and around 1.0% for CASE2 and CASE5. For 80% the numbers reach around 1.6% for CASE2 and CASE5, around 1.4 for CASE3 and around 1.1 for CASE4.

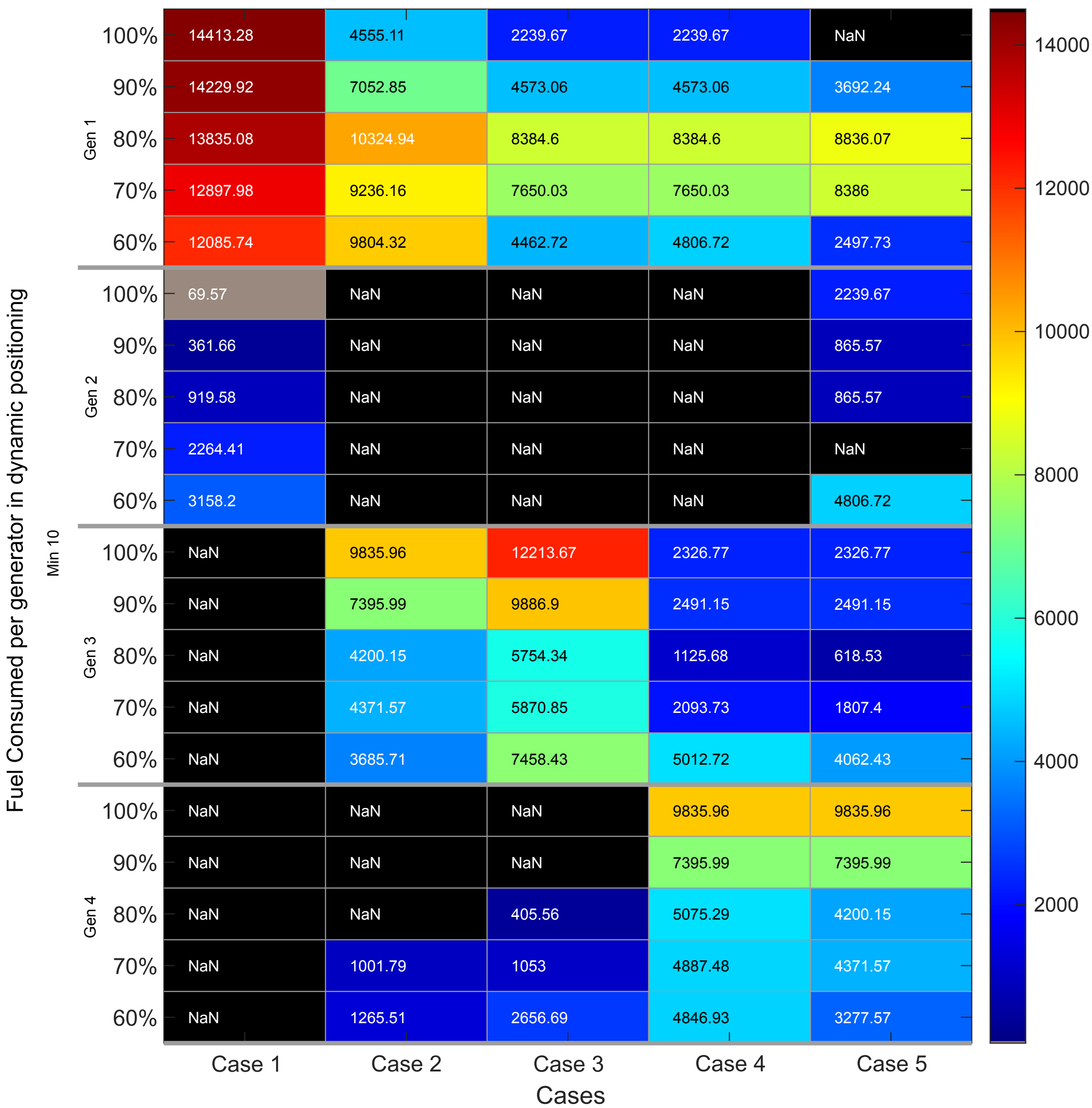

Figure A.3 – Fuel Consumed during DP operation in liters for each generator in each case for different maximum percentage of generator rated power. The minimum load of generators was set to 10% and 50% for DP operation.

Source: Author.

Analyzing the cases with a maximum percentage of 70% we have that all cases provide a reduction, the reductions obtained with cases 2,3,4 and 5 are 3.65%, 3.88%, 3.5% and 3.9%. Finally, for a maximum percentage of 60%, we see a reduction higher for cases 3 and 4, they are around 4.4% and 3.8%, respectively. The number for CASE2 is slightly smaller than the value presented for a maximum percentage of 70%, it was around 3.2%.

When we compare CASE1 to CASE5, for a maximum percentage of 60% we see that the numbers are the same presented for a maximum percentage of 70%.

A.4 Standby(ST)

Moving the analysis to the results presented in Fig. A.4 we can see that CASE2 presented a reduction of 4.8% in comparison to CASE1. Moreover, the use of cases 3, 4 and 5 reached the highest fuel consumption reduction, it was around 18.5%. Although the fuel consumed using CASE1 is lower than the fuel consumed for LP, the numbers for percentage reduction are higher than those achieved for LP.

In terms of fuel consumption the use of the 1624kW generator, named as 'gen3' for cases 3, 4 and 5, allowed a reduction of 464.2 liters in only one mission. On the other hand, CASE2 reduced in 121 liters the fuel consumed.

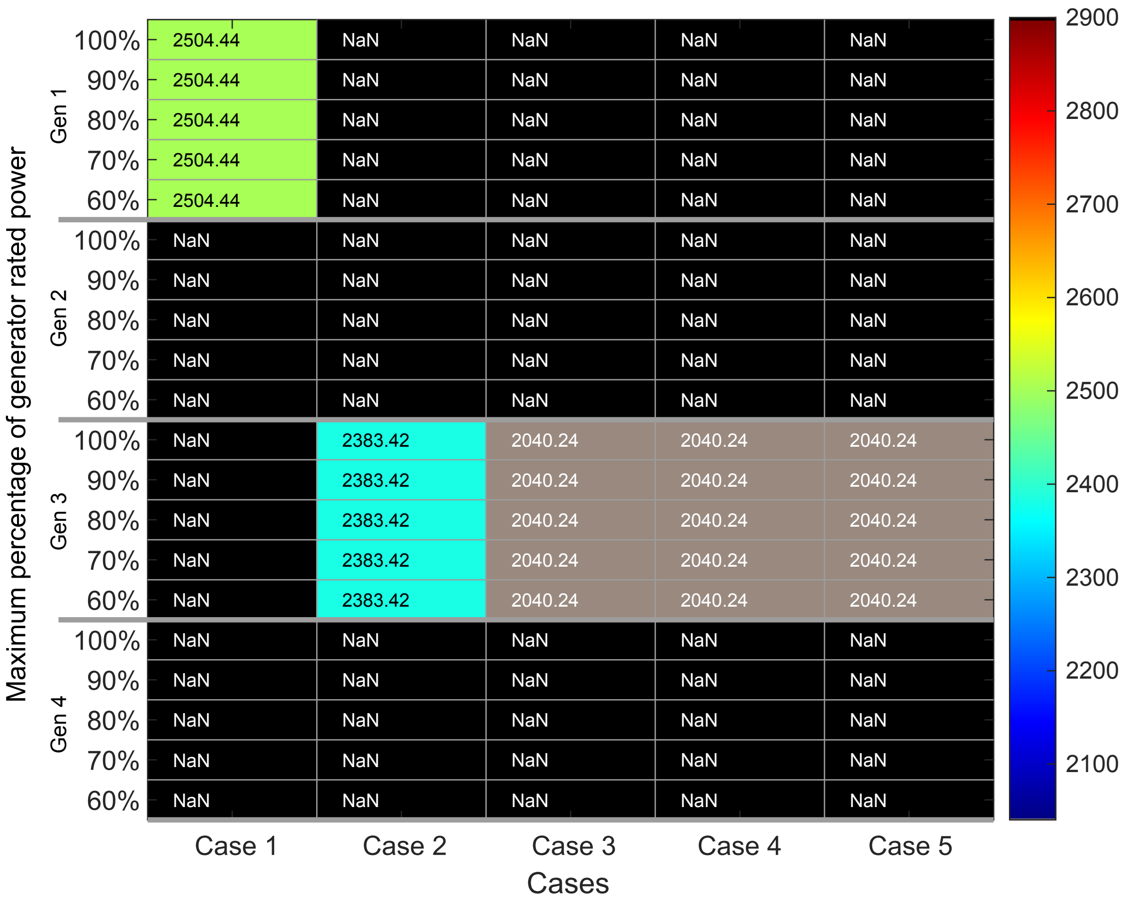

Figure A.4 – Fuel Consumed during ST operation in liters per generator in each case for different maximum percentage of generator rated power. The minimum load of generators was set to 10% for ST operation.

Source: Author.

A.5 Percentage of time in each operation zone

In Figs. A.5 and A.6 the percentage of using time that each generator of each case is operating in each range of percentage of its rated power.

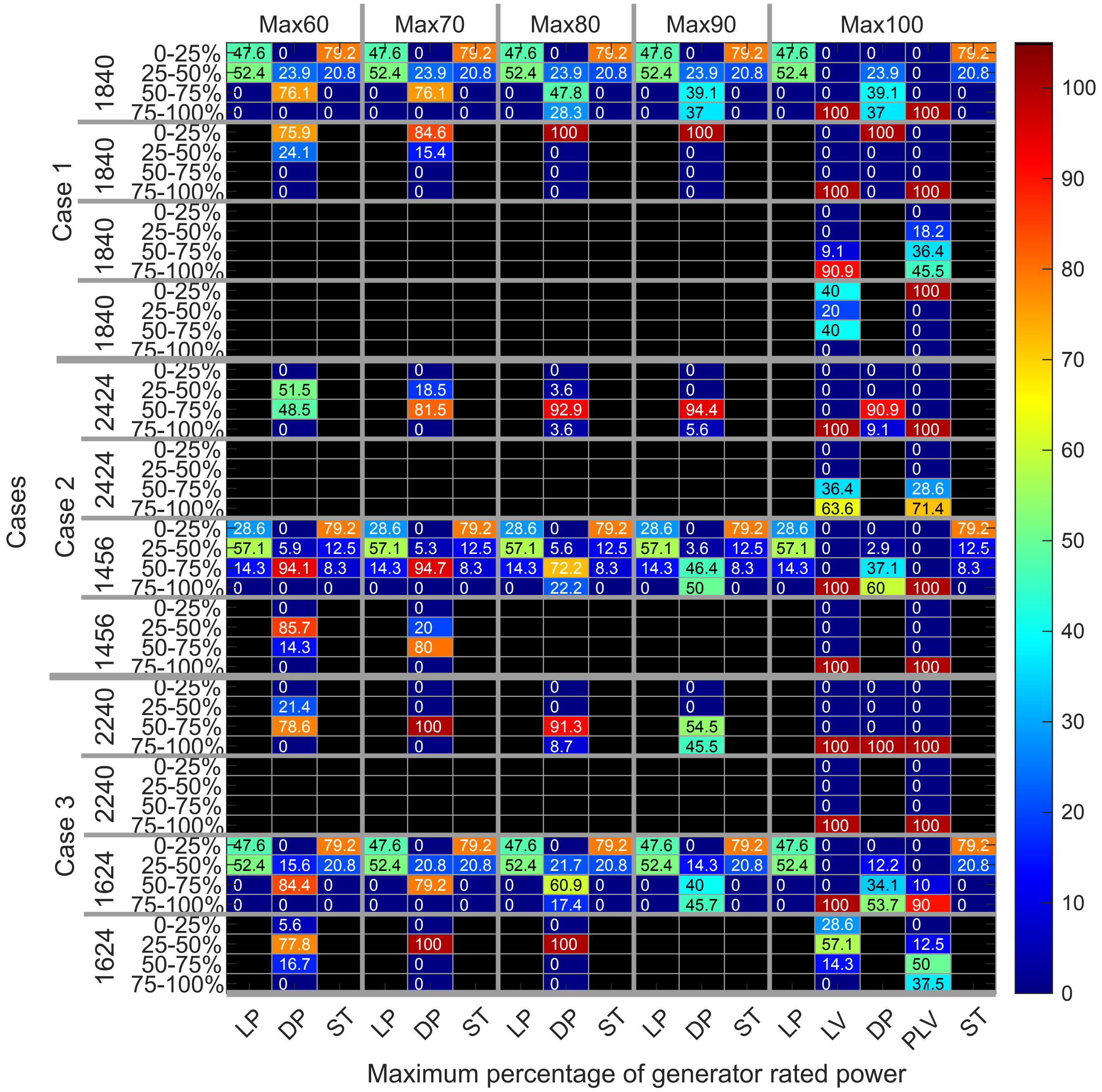

Figure A.5 – Percentage of time that each generator is operating in each zone of operation.

Source: Author.

Figure A.5 provides the results to cases 1,2 and 3. As can be seen, for LP and ST, CASE1 provides very similar results than CASE1 for CAT generators, as presented in Fig. 4.6. Considering that, the generators comprised in CASE1 of CAT and MTU generators are very similar we can say that these results were expected. For DP and the voyages the results change slightly.

When we analyze CASE2 results we can see that in comparison to CASE1, the numbers for operation under 25% for ST are the same. For LP the percentage of time that the operation occurs in this zone reduces from 47.6 to 28.6%. For DP, we can see that the three generators that operate for a maximum percentage of 60% and 70% do not operate in the range from 0% to 25%. The two generators that operate in a maximum percentage of 80%, 90% and 100% also do not operate in this range. It is a considerable advantage in relation to CASE1, in this case the second 1840kW had a higher percentage, above 75.9% in this zone under 25%. Analyzing LV and PLV, we can see that all four generators operate above 50%, this is another advantage in relation to CASE1.

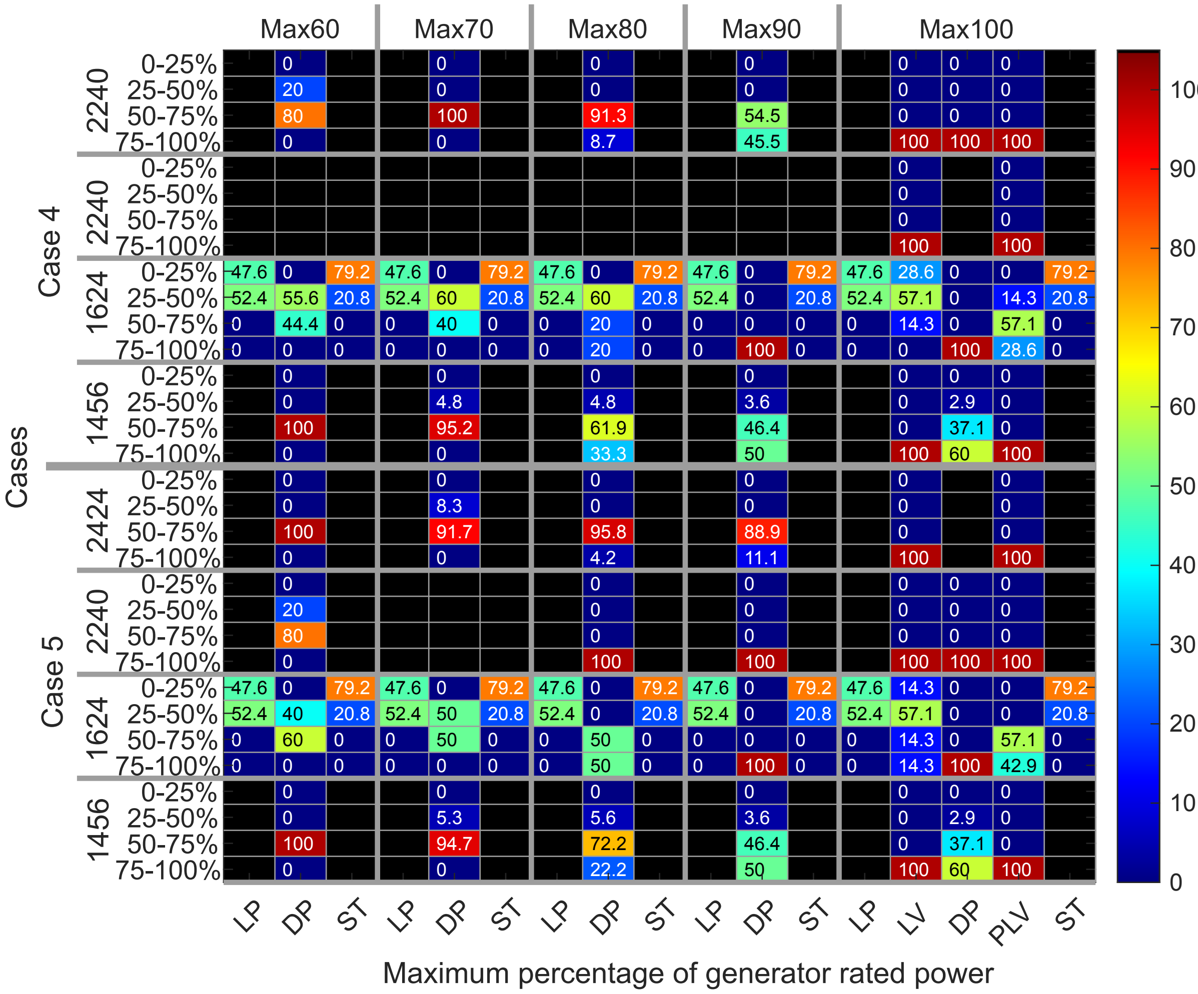

Figure A.6 – Percentage of time that each generator is operating in each zone of operation.

Source: Author.

The results for CASE3 display similar results to CASE1 for LP and ST. So, CASE2 also portrays better results than CASE3. For DP, CASE3 also presents worst numbers than CASE2. We can see that in CASE3 one 1624kW generator operates for 5.6% in an operation zone under 25%. CASE3 presented better results for PLV than CASE1 but worst than CASE2. For LV, we can see that the percentage of time under 25%, is lower for

CASE3 than CASE1, 28.6% vs 40%. Since CASE2 does not operate under 25%, CASE2 provides better results than CASE3.

In Fig. A.6, we can see the results for CASE4 and CASE5, for both cases the results for LP and ST present similar results of CASE1. For DP, we can see that these two cases do not operate under 25%. Moreover, for a maximum percentage of 100%, we can see that in cases 4 and 5, the 1456kW generator operate for 2.9% in this region from 25% to 50%. When we analyze the numbers for LV and PLV, we can see that the 1624kW of CASE5 operated around 14.3% under 25%, this generator operating in CASE4 increased this value to 28.6% in this region under 25%.

ANNEX B

Battery impact on generator sensitivity

This annex provides the results for the battery dispatch comprising maximum percentages of rated power equals to 60% and 70%.

B.1 Battery dispatch for a maximum percentage equals to 60% and 70%

Fig. B.1 presents the reductions obtained for a maximum percentage of 60% and 70%. These reductions are in relation to a base case, which is CASE1 operating at 100%. Remembering from chapter 4, we can see that comparing all cases to the base case, CASE1 has an increase on fuel consumption of 2.93%, while cases 2, 3, 4 and 5 had a reduction of 2.5%, 3.87%, 4.58% and 4.37%, respectively.

As can be seen in Fig. B.1, CASE1 had a great benefit from using the battery. Instead of increasing the fuel or emissions by 2.93%, this case presented reductions of 0.5% when a battery of 1MW with a DoD of 70% and RTE of 96% is evaluated. If we consider a 2MW battery, the reduction achieved for the same battery configuration is 0.9%.

When we consider cases 2, 4 and 5, we can see that the case using the battery only as a reserve provided better results than when the battery was dispatched. It occurs mainly due to the increase of the fuel consumption during the voyages and the DP operation.

Moving the analysis to CASE3, which is the one that achieves the highest reduction when the 2MW battery is analyzed with an RTE of 98% and a DoD of 50%, we can see that for most of the configurations analyzed the battery dispatch provides an increase in the fuel consumption reduction in comparison to the results provided considering the battery only as reserve. When we consider the 1MW battery the highest fuel consumption reduction is achieved with two configurations, RTE of 98% with DoD equals to 30% and equals to 50%.

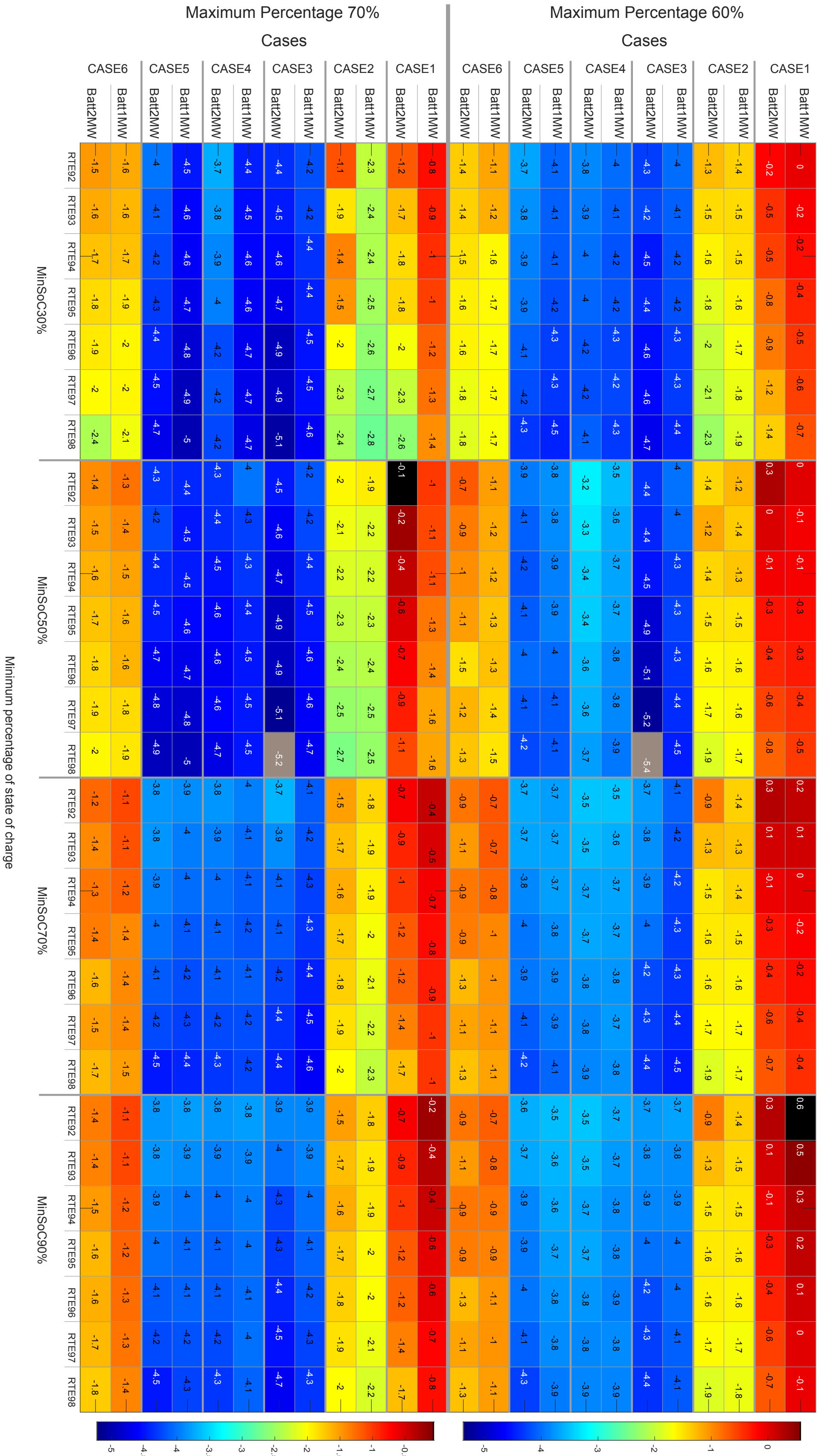

Figure B.1 – Reduction Percentage obtained by batteries.

Source: Author.

Considering a minimum SoC of 30% and an RTE of 98%, CASE5 had very similar results for the operation considering battery only as a reserve and considering the battery dispatch, it occurred when the 1MW battery was used.

The analysis of the lower part of Fig. B.1 shows a lower increase for the majority of cases in comparison to the results without battery presented in the last chapter. One interesting point is the results provided by CASE1 operating with a maximum percentage of 70% and a 2MW battery, where a reserve of 90% provided similar reductions than using a reserve of 70% but much better results than using a reserve of 50%. For 1MW battery, the opposite happens, setting a reserve of 50% provides better results than higher reserves, and also provides better results than a reserve of 30%. The best results for CASE1 is achieved when the 2MW battery dispatches to a minimum SoC of 30% and the RTE is 98%. As presented for a maximum percentage of 60% of rated power, the dispatch of batteries with CASE1 provided considerable reductions in comparison to the case in which battery is used only as reserve.

For a maximum percentage of 60%, the use of the 1MW batteries, when the minSoC is set to 30% with an RTE higher than 96%, provides a reduction in the fuel consumption in comparison to the numbers presented in the analysis using battery only as a reserve when CASE5 is analyzed.

For CASE3 the use of battery may, in the majority of the configurations analyzed, provide a higher reduction than the results of chapter 4. As can be seen the maximum reduction for the maximum percentage equals to 70% is obtained when the 2MW battery is dispatched with a reserve of 50% and the RTE equals to 98%. It was around 5.2%.

some cases, present an increase in the reduction. It is obtained in scenarios in which the battery was dispatched in relation to the use of battery only as a reserve. Even though the difference is minimal, once again, using a reserve of 50% presented better results than using a reserve of 30% for both battery sizes. The highest reduction of all cases for this maximum percentage is portrayed in gray, a reduction of 5.2% is around 1% higher than the reduction obtained when we evaluate only the optimal dispatch using battery as a reserve, which was around 4.19%. It is interesting to note that the increase in the maximum percentage did not provide an increase on the reduction. Actually, the opposite happens when the minimum SoC is under 50%.

The increase of the maximum percentage to 70% achieved higher reductions for almost all scenarios evaluated in CASE5 when the minSoC was set to 30% and the RTE higher than 96%. For CASE6, we also have higher reductions for both batteries in comparison to the results presented in chapter 4. These reductions are higher when the minSoC equals to 30% and 50% for all RTEs, and when the reserve is 70% with RTEs higher than 95%.

B.2 Battery cycles for a maximum percentage equals to 60% and 70%

The mainly difference presented in Fig. B.2 is that the highest number of years is achieved with CASE4 for a maximum percentage of 60%. This highest value is obtained with the 2MW battery.

Another point in comparison to the results for max80 and max 90 is that the difference between the 1MW and 2MW battery is much higher.

The highest number of years is obtained with the minSoC equals to 70% for the majority of cases, the exceptions are CASE3 and CASE4. CASE1 has the lowest amounts of years compared to the other cases.

The lowest number of years for the 2MW battery is achieved with the minSoC equals to 90%, whereas for the 1MW battery it happens with the minSoC of 30%, the exception for the 1MW battery is CASE3 that has the lowest "life" when the reserve is equals to 90%.

When we increase the maximum percentage from 60% to 70%, we can see that the number of years has a slight reduction for the majority of cases.

When we analyze the lower part of Fig. B.2, we can see that the maximum number of years is achieved with CASE6 operating with a 2MW battery, DoD of 70% and RTE equals to 97%. As happened for 60%, the lowest number of years is obtained with CASE1 with the 1MW battery, DoD of 90% and RTE equals to 95%.

For the two levels of maximum percentage, we cannot assume a clear relation between the RTE and the number of years. In various cases, we can see that the highest number of cycles is achieved with the lowest RTE.

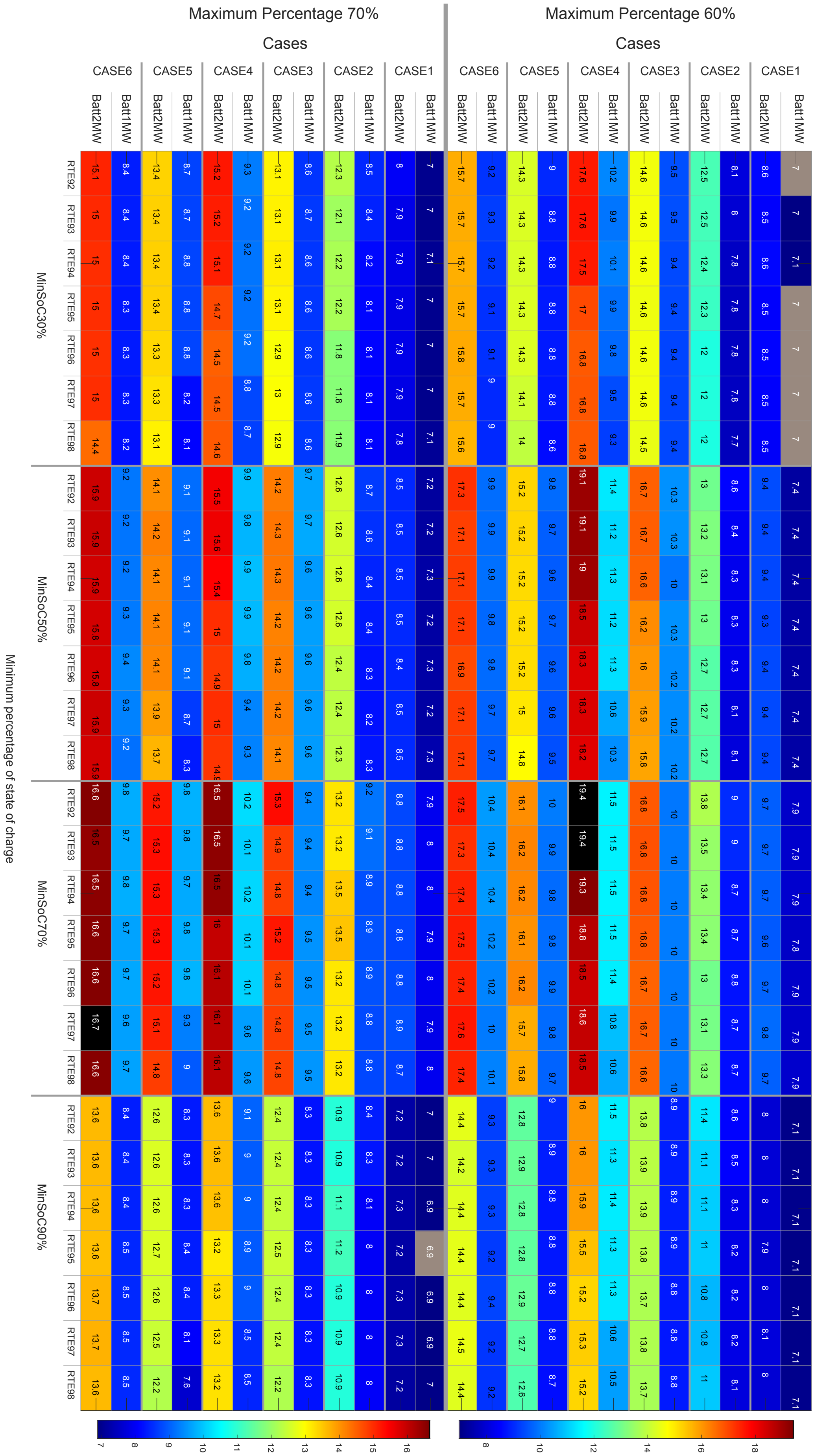

Figure B.2 – Number of years that the battery will last for a maximum percentage of the rated power of the generators of 60% and 70%.

Source: Author.

ANNEX C

Annex

This annex presents the tables comprising the speed and the power for normal and zero curves. Moreover, the percentage reduction of fuel consumed for normal and zero curves, for each speed reduction, is shown for CAT generators.

For MTU generators, the results for calculated, normal and zero curves are shown.

C.1 Relation between speed and power

In the following pages, Tables C.1, C.2,C.3 and C.4 present the data of power demand used for the analysis and the related speed of each power demand. As can be seen, the analysis performed in this paper will consider a reduction that varies from 5% to 15%. These Tables show that a reduction above 9% requires two extra hours to travel the same distance.

Table C.1 – Comparison between the original demand and speed of the laden voyage and the speed and demand obtained for reductions from 0.15 to 0.05% using the the reference curve with no parameters set to zero to correlate speed and power.

% reduction	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13
Original	Original Speed	14.69	15.84	16.19	15.54	16.19	16.27	16.24	15.95	15.50	15.64	15.65	0	0
	Original Demand	4730	6150	6625	5750	6625	6740	6700	6300	5700	5875	5900	0	0
15%	Reduced Speed	12.49	13.47	13.76	13.21	13.76	13.83	13.81	13.56	13.17	13.29	13.31	13.03	13.03
	New Demand	2666.01	3481.12	3757.32	3249.76	3757.32	3824.42	3801.08	3568.18	3220.92	3321.93	3336.37	3096.26	3096.26
14%	Reduced Speed	12.63	13.63	13.92	13.36	13.92	13.99	13.97	13.72	13.33	13.45	13.46	12.16	12.16
	New Demand	2778.28	3628.07	3915.68	3387.03	3915.68	3985.52	3961.23	3718.74	3356.98	3462.23	3477.28	2427.73	2427.73
13%	Reduced Speed	12.78	13.78	14.09	13.52	14.09	14.16	14.13	13.88	13.48	13.60	13.62	11.29	11.29
	New Demand	2894.05	3779.30	4078.58	3528.37	4078.58	4151.22	4125.95	3873.66	3497.08	3606.66	3622.33	1878.70	1878.70
12%	Reduced Speed	12.93	13.94	14.25	13.67	14.25	14.32	14.29	14.04	13.64	13.76	13.78	10.42	10.42
	New Demand	3013.36	3934.84	4246.04	3673.81	4246.04	4321.56	4295.29	4032.97	3641.25	3755.27	3771.57	1443.72	1443.72
11%	Reduced Speed	13.08	14.10	14.41	13.83	14.41	14.48	14.46	14.20	13.79	13.92	13.93	9.55	9.55
	New Demand	3136.22	4094.73	4418.11	3823.38	4418.11	4496.56	4469.27	4196.72	3789.52	3908.07	3925.02	1117.34	1117.34
10%	Reduced Speed	13.22	14.26	14.57	13.98	14.57	14.64	14.62	14.36	13.95	14.07	14.09	8.69	8.69
	New Demand	3262.66	4259.01	4594.82	3977.10	4594.82	4676.27	4647.94	4364.94	3941.93	4065.10	4082.72	894.11	894.11
9%	Reduced Speed	13.37	14.42	14.73	14.14	14.73	14.81	14.78	14.52	14.10	14.23	14.25	7.82	7.82
	New Demand	3392.72	4427.70	4776.21	4135.01	4776.21	4860.73	4831.32	4537.65	4098.49	4226.40	4244.68	768.59	768.59
8%	Reduced Speed	13.52	14.58	14.89	14.30	14.89	14.97	14.94	14.68	14.26	14.38	14.40	13.90	
	New Demand	3526.41	4600.84	4962.31	4297.16	4962.31	5049.95	5019.46	4714.89	4259.24	4391.98	4410.95	3889.72	
7%	Reduced Speed	13.66	14.73	15.06	14.45	15.06	15.13	15.11	14.84	14.41	14.54	14.56	12.16	
	New Demand	3663.76	4778.45	5153.16	4463.55	5153.16	5243.99	5212.40	4896.69	4424.23	4561.88	4581.56	2427.73	
6%	Reduced Speed	13.81	14.89	15.22	14.61	15.22	15.29	15.27	15.00	14.57	14.70	14.72	10.42	
	New Demand	3804.81	4960.59	5348.79	4634.23	5348.79	5442.87	5410.15	5083.10	4593.47	4736.15	4756.54	1443.72	
5%	Reduced Speed	13.96	15.05	15.38	14.76	15.38	15.46	15.43	15.16	14.72	14.85	14.87	8.69	
	New Demand	3949.56	5147.26	5549.23	4809.21	5549.23	5646.64	5612.77	5274.14	4767.00	4914.81	4935.93	894.11	

Table C.2 – Comparison between the original demand and speed of the partial load voyage and the speed and demand obtained for reductions from 0.15 to 0.05% using the reference curve with no parameters set to zero to correlate speed and power.

% reduction	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13
Original	Original Speed	14.48	14.84	14.75	14.80	14.79	15.46	15.26	15.14	15.54	15.14	14.30	0.00	0.00
	Original Demand	4500	4900	4800	4850	4840	5650	5400	5250	5750	5250	4300	0	0
15%	Reduced Speed	12.31	12.61	12.54	12.58	12.57	13.14	12.97	12.87	13.21	12.87	12.15	12.34	12.34
	New Demand	2535.90	2762.59	2705.73	2734.15	2728.46	3192.10	3048.36	2962.37	3249.76	2962.37	2423.29	2554.37	2554.37
14%	Reduced Speed	12.46	12.76	12.69	12.73	12.72	13.30	13.12	13.02	13.36	13.02	12.30	11.51	11.51
	New Demand	2642.44	2879.06	2819.74	2849.39	2843.45	3326.95	3177.11	3087.45	3387.03	3087.45	2524.84	2008.84	2008.84
13%	Reduced Speed	12.60	12.91	12.84	12.87	12.87	13.45	13.28	13.17	13.52	13.17	12.44	10.69	10.69
	New Demand	2752.36	2999.14	2937.29	2968.20	2962.02	3465.81	3309.74	3216.33	3528.37	3216.33	2629.64	1566.83	1566.83
12%	Reduced Speed	12.75	13.06	12.98	13.02	13.01	13.60	13.43	13.32	13.67	13.32	12.58	9.87	9.87
	New Demand	2865.69	3122.83	3058.40	3090.61	3084.17	3608.71	3446.27	3349.02	3673.81	3349.02	2737.74	1223.72	1223.72
11%	Reduced Speed	12.89	13.21	13.13	13.17	13.16	13.76	13.58	13.47	13.83	13.47	12.73	9.05	9.05
	New Demand	2982.44	3250.20	3183.12	3216.65	3209.93	3755.68	3586.74	3485.58	3823.38	3485.58	2849.14	974.89	974.89
10%	Reduced Speed	13.04	13.36	13.28	13.32	13.31	13.91	13.73	13.62	13.98	13.62	12.87	8.22	8.22
	New Demand	3102.64	3381.23	3311.45	3346.33	3339.36	3906.76	3731.17	3626.00	3977.10	3626.00	2963.88	815.70	815.70
9%	Reduced Speed	13.18	13.51	13.43	13.47	13.46	14.07	13.89	13.77	14.14	13.77	13.01	7.40	7.40
	New Demand	3226.32	3515.97	3443.45	3479.70	3472.44	4061.98	3879.60	3770.34	4135.01	3770.34	3081.98	741.54	741.54
8%	Reduced Speed	13.33	13.65	13.57	13.61	13.61	14.22	14.04	13.93	14.30	13.93	13.15	13.16	
	New Demand	3353.50	3654.45	3579.11	3616.77	3609.24	4221.35	4032.04	3918.62	4297.16	3918.62	3203.46	3208.05	
7%	Reduced Speed	13.47	13.80	13.72	13.76	13.75	14.38	14.19	14.08	14.45	14.08	13.30	11.51	
	New Demand	3484.21	3796.69	3718.47	3757.57	3749.76	4384.92	4188.55	4070.85	4463.55	4070.85	3328.34	2008.84	
6%	Reduced Speed	13.62	13.95	13.87	13.91	13.90	14.53	14.34	14.23	14.61	14.23	13.44	9.87	
	New Demand	3618.46	3942.73	3861.58	3902.15	3894.02	4552.73	4349.13	4227.09	4634.23	4227.09	3456.66	1223.72	
5%	Reduced Speed	13.76	14.10	14.02	14.06	14.05	14.69	14.50	14.38	14.76	14.38	13.58	8.22	
	New Demand	3756.29	4092.57	4008.43	4050.49	4042.08	4724.78	4513.82	4387.34	4809.21	4387.34	3588.44	815.70	

Table C.3 – Comparison between the original demand and speed of the laden voyage and the speed and demand obtained for reductions from 0.15 to 0.05% using the reference curve with some parameters set to zero to correlate speed and power.

% reduction	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13
Original	Original Speed	14.63	15.97	16.37	15.61	16.37	16.46	16.43	16.09	15.57	15.72	15.75	0	0
	Original Demand	4730	6150	6625	5750	6625	6740	6700	6300	5700	5875	5900	0	0
15%	Reduced Speed	12.43	13.57	13.91	13.27	13.91	13.99	13.96	13.68	13.23	13.37	13.38	13.12	13.12
	New Demand	2904.81	3776.87	4068.58	3531.22	4068.58	4139.21	4114.64	3868.98	3500.51	3607.99	3623.34	3414.30	3414.30
14%	Reduced Speed	12.58	13.73	14.08	13.43	14.08	14.16	14.13	13.84	13.39	13.52	13.54	12.25	12.25
	New Demand	3008.54	3911.75	4213.87	3657.32	4213.87	4287.02	4261.58	4007.15	3625.52	3736.83	3752.73	2775.96	2775.96
13%	Reduced Speed	12.73	13.89	14.24	13.58	14.24	14.32	14.29	14.00	13.54	13.68	13.70	11.37	11.37
	New Demand	3114.72	4049.80	4362.58	3786.39	4362.58	4438.31	4411.97	4148.57	3753.47	3868.70	3885.16	2222.59	2222.59
12%	Reduced Speed	12.87	14.05	14.40	13.74	14.40	14.49	14.46	14.16	13.70	13.84	13.86	10.50	10.50
	New Demand	3223.36	4191.06	4514.75	3918.46	4514.75	4593.13	4565.86	4293.27	3884.39	4003.65	4020.68	1748.12	1748.12
11%	Reduced Speed	13.02	14.21	14.57	13.89	14.57	14.65	14.62	14.32	13.85	13.99	14.01	9.62	9.62
	New Demand	3334.50	4335.56	4670.42	4053.57	4670.42	4751.50	4723.29	4441.30	4018.32	4141.69	4159.32	1346.50	1346.50
10%	Reduced Speed	13.17	14.37	14.73	14.05	14.73	14.81	14.79	14.49	14.01	14.15	14.17	8.75	8.75
	New Demand	3448.17	4483.35	4829.63	4191.75	4829.63	4913.46	4884.30	4592.70	4155.30	4282.88	4301.10	1011.65	1011.65
9%	Reduced Speed	13.31	14.53	14.89	14.21	14.89	14.98	14.95	14.65	14.17	14.31	14.33	7.87	7.87
	New Demand	3564.39	4634.46	4992.41	4333.03	4992.41	5079.07	5048.93	4747.50	4295.36	4427.23	4446.07	737.49	737.49
8%	Reduced Speed	13.46	14.69	15.06	14.36	15.06	15.14	15.11	14.81	14.32	14.47	14.49	14.00	
	New Demand	3683.19	4788.93	5158.81	4477.45	5158.81	5248.36	5217.21	4905.74	4438.52	4574.79	4594.26	4143.70	
7%	Reduced Speed	13.60	14.85	15.22	14.52	15.22	15.31	15.28	14.97	14.48	14.62	14.64	12.25	
	New Demand	3804.61	4946.80	5328.86	4625.05	5328.86	5421.37	5389.19	5067.45	4584.83	4725.60	4745.71	2775.96	
6%	Reduced Speed	13.75	15.01	15.38	14.68	15.38	15.47	15.44	15.13	14.63	14.78	14.80	10.50	
	New Demand	3928.66	5108.09	5502.62	4775.86	5502.62	5598.14	5564.91	5232.68	4734.33	4879.68	4900.44	1748.12	
5%	Reduced Speed	13.90	15.17	15.55	14.83	15.55	15.64	15.61	15.29	14.79	14.94	14.96	8.75	
	New Demand	4055.38	5272.86	5680.11	4929.91	5680.11	5778.71	5744.41	5401.46	4887.04	5037.08	5058.51	1011.65	

Table C.4 – Comparison between the original demand and speed of the partial load voyage and the speed and demand obtained for reductions from 0.15 to 0.05% using the reference curve with some parameters set to zero to correlate speed and power.

% reduction	Hour	1	2	3	4	5	6	7	8	9	10	11	12	13
Original	Original Speed	14.39	14.80	14.70	14.75	14.74	15.52	15.29	15.15	15.61	15.15	14.17	0	0.00
	Original Demand	4500	4900	4800	4850	4840	5650	5400	5250	5750	5250	4300	0	0
15%	Reduced Speed	12.23	12.58	12.49	12.54	12.53	13.19	13.00	12.87	13.27	12.87	12.04	12.32	12.32
	New Demand	2763.56	3009.21	2947.80	2978.50	2972.37	3469.81	3316.28	3224.16	3531.22	3224.16	2640.74	2825.53	2825.53
14%	Reduced Speed	12.37	12.73	12.64	12.69	12.68	13.35	13.15	13.03	13.43	13.03	12.19	11.50	11.50
	New Demand	2862.25	3116.68	3053.07	3084.87	3078.51	3593.72	3434.70	3339.30	3657.32	3339.30	2735.04	2297.26	2297.26
13%	Reduced Speed	12.52	12.88	12.79	12.83	12.82	13.50	13.30	13.18	13.58	13.18	12.33	10.68	10.68
	New Demand	2963.26	3226.67	3160.82	3193.74	3187.16	3720.54	3555.91	3457.14	3786.39	3457.14	2831.56	1839.32	1839.32
12%	Reduced Speed	12.66	13.03	12.94	12.98	12.97	13.66	13.45	13.33	13.74	13.33	12.47	9.86	9.86
	New Demand	3066.62	3339.22	3271.07	3305.14	3298.33	3850.32	3679.95	3577.73	3918.46	3577.73	2930.33	1446.67	1446.67
11%	Reduced Speed	12.80	13.17	13.08	13.13	13.12	13.81	13.61	13.48	13.89	13.48	12.61	9.03	9.03
	New Demand	3172.36	3454.35	3383.85	3419.10	3412.05	3983.08	3806.83	3701.08	4053.57	3701.08	3031.37	1114.31	1114.31
10%	Reduced Speed	12.95	13.32	13.23	13.28	13.27	13.97	13.76	13.63	14.05	13.63	12.75	8.21	8.21
	New Demand	3280.50	3572.10	3499.21	3535.65	3528.36	4118.86	3936.60	3827.25	4191.75	3827.25	3134.70	837.20	837.20
9%	Reduced Speed	13.09	13.47	13.38	13.42	13.41	14.12	13.91	13.78	14.21	13.78	12.90	7.39	7.39
	New Demand	3391.07	3692.50	3617.14	3654.82	3647.29	4257.68	4069.28	3956.25	4333.03	3956.25	3240.35	610.32	610.32
8%	Reduced Speed	13.24	13.62	13.52	13.57	13.56	14.28	14.07	13.93	14.36	13.93	13.04	13.14	
	New Demand	3504.10	3815.57	3737.71	3776.64	3768.85	4399.59	4204.91	4088.11	4477.45	4088.11	3348.36	3429.15	
7%	Reduced Speed	13.38	13.77	13.67	13.72	13.71	14.43	14.22	14.09	14.52	14.09	13.18	11.50	
	New Demand	3619.60	3941.35	3860.92	3901.13	3893.09	4544.62	4343.52	4222.87	4625.05	4222.87	3458.73	2297.26	
6%	Reduced Speed	13.52	13.91	13.82	13.87	13.86	14.59	14.37	14.24	14.68	14.24	13.32	9.86	
	New Demand	3737.63	4069.87	3986.81	4028.33	4020.03	4692.81	4485.15	4360.56	4775.86	4360.56	3571.51	1446.67	
5%	Reduced Speed	13.67	14.06	13.96	14.01	14.00	14.74	14.52	14.39	14.83	14.39	13.46	8.21	
	New Demand	3858.19	4201.14	4115.40	4158.27	4149.70	4844.17	4629.82	4501.22	4929.91	4501.22	3686.71	837.20	

C.2 Results for CAT generators using normal and zero curves

The results shown in this section comprise the percentage reduction obtained with speed reductions varying from 5% to 15%. These results are presented for laden and partial load voyage.

C.2.1 Laden Voyage - Normal Curve

Fig. C.1 portrays the results for laden voyage using the normal curve. As can be seen, a 5% reduction in speed led to a reduction of 15% of fuel consumption for CASE1. When CASE3 was analyzed, a reduction about 18.2% was obtained. Cases 4 and 5 provided a reduction of at least 17%, whereas cases 2 and 6 had a reduction of at least 15.7%.

For the normal curve, the speed reduction above 9% provided one extra hour of increase on the demand curve. When we analyze the fuel consumption reduction for this level of speed reduction, we see that there is a considerable increase from 8% to 9%. It was also presented when the calculated curve was analyzed.

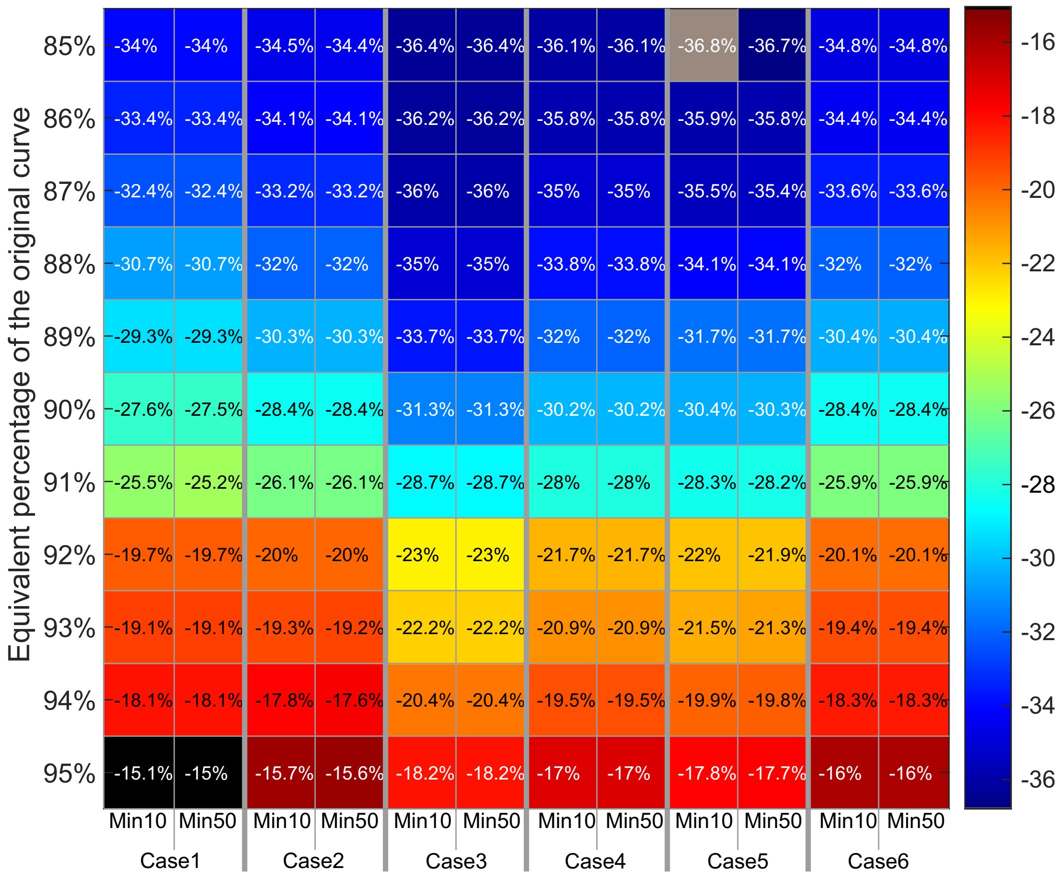

Figure C.1 – Percentage reduction of fuel consumed by varying the speed reduction during laden voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the Normal curve.

Although CASE5 presents the highest fuel consumption reduction for the complete curve, it does not present the highest numbers for speed reduction during laden voyage. For a speed reduction from 5% to 14%, CASE3 obtained the highest fuel reduction. The highest fuel reduction obtained with CASE5 was around 36.8%. This number is 3% higher than the value presented for the calculated curve when the laden voyage was analyzed.

Regarding the saturation presented in the results for calculated curve, the results for the normal curve do not show it. We can see that the 1% reduction of speed step above 13% present smaller increases in fuel consumption reduction when CASE3 is analyzed, but this smaller increase may not be considered a saturation.

Considering the speed reduction of 10%, which was proposed by IMO, we can see that the fuel consumption reduction was at least 27.6%. Cases 4 and 5 have reductions of around 30.3%, whereas cases 2 and 6 provided equal reductions, about 28.4%. It is important to note that the reduction obtained with CASE3 for this level of speed reduction is only achieved with CASE1 for a speed reduction 3% higher.

Comparing CASE1 to CASE6, we can see that, as presented in the calculated curve results for the laden voyage, the use of auxiliary generators is beneficial in terms of fuel reduction. The smaller contribution happened for a fuel reduction of 9%, whereas the biggest happened with a speed reduction of 8%, which was about 1.4%.

C.2.2 Partial Load Voyage - Normal Curve

Fig. C.2 presents the results for the partial load voyage, considering the normal curve to associate speed and power. As we can see, comparing the numbers for the laden voyage and the partial load voyage, the values for fuel consumption reduction are smaller for the voyage with the lowest demand peaks. It also occurred when the calculated curve was analyzed.

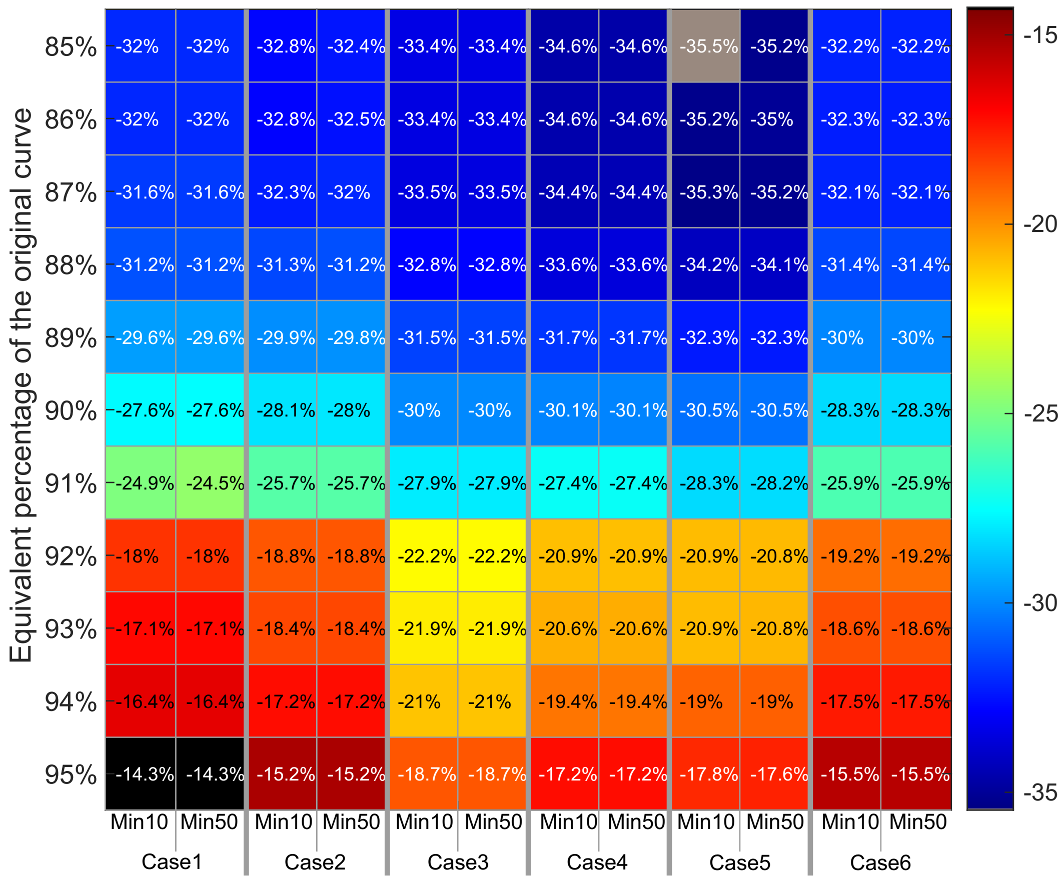

Figure C.2 – Percentage reduction of fuel consumed by varying the speed reduction during partial load voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the Normal curve.

For a speed reduction of 5%, the six cases analyzed obtained a fuel reduction of at least 14.3%; this number was obtained using CASE1. Using auxiliary generators increased the fuel reductions by 1.2%, reaching 15.5%. The use of generators presented in CASE2 achieved a fuel reduction of 15.2%. Cases 4 and 5 had a reduction of 17.2% and 17.8%, respectively. Finally, CASE3, which reached the highest fuel reduction at this level of speed reduction, obtained a fuel reduction of about 18.7%.

As occurred in the last three results presented, CASE5 achieved the highest results. Different from what happened in Fig. C.1, CASE5 had the highest fuel consumption reduction for all speed reductions above 9%. One interesting point is that CASE4 presented the second highest reduction for speed reductions, from 10% to 15%. For speed reductions from 5% to 8%, CASE3 achieved the highest fuel reductions.

Again, analyzing the numbers for the speed reduction proposed by IMO, we can see that for CASE1, this reduction would save 27.6% of the fuel originally consumed. Cases 2 and 6 resulted in fuel reductions of around 28.1% and 28.3%, respectively. Cases 3 and 4 displayed similar reductions of around 30%. CASE5 achieved the highest reduction of around 30.5%. Another interesting analysis is that, for this normal curve, this level of speed reduction presented similar savings for cases 1, 4, 5 and 6. CASE2 and CASE3 have a difference of 0.3% and 1.3%. It shows that for both voyages, the fuel savings expected from IMO can be around 28%. Further, the use of batteries in curves considering speed reduction will be considered, but as presented in the last chapter, the use of batteries during voyages provides much lower benefits than reducing speed.

C.2.3 Laden Voyage - Zero Curve

Fig. C.3 shows the results for laden voyage using the zero curve to associate power and speed. As can be seen, a reduction of 5% in the speed reduction achieves a reduction of 13.1% for CASE1. This reduction is the lowest among all cases at this level of speed reduction. When we increase the speed reduction to 7%, the reduction for CASE1 is higher than the reduction for CASE2.

The highest reduction for all levels of speed reduction is achieved with CASE3. For a 5% of speed reduction, this case presents a reduction of 16.1%. Then, the second highest fuel reduction is achieved with CASE5.

We can see that cases 2, 3 and 4 present saturation after a given speed reduction. For cases 2 and 4, the given percentage of speed reduction is around 14%, whereas for CASE3, it is 13%. CASE2 maximum reduction was around 28.8%; cases 3 and 4 presented maximum values of around 31.5% and 30.5%, respectively.

Considering the 10% speed reduction indicated by IMO, the reductions achieved in cases 1, 2 and 6 present similar reductions of around 24.4%. Cases 3, 4 and 5 present a reduction from 36.5% and 27.3%.

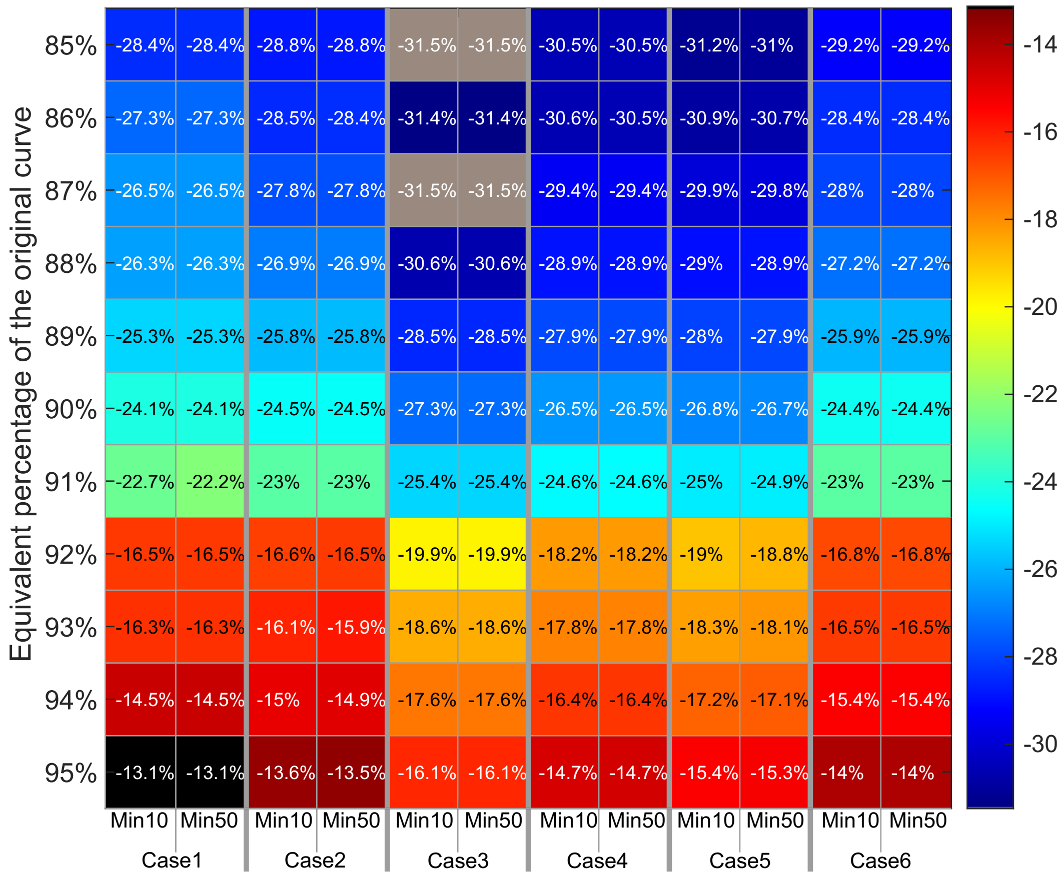

Figure C.3 – Percentage reduction of fuel consumed varying the speed reduction during laden voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the Zero curve.

C.2.4 Partial Load Voyage - Zero Curve

Fig. C.4 presents the reductions achieved for partial load voyage. As can be seen, the numbers presented here are lower than those presented in Fig.C.3.

A 5% speed reduction already results in a consumption reduction of 11.9% for CASE1. Cases 2 and 6 portray reductions of 12.9% and 12.7%, respectively. Cases 3, 4 and 5 achieve reductions of 16.4%, 15% and 15.3%, respectively.

On the contrary of the results presented in Fig.C.3, the highest reductions are achieved with CASE5 for speed reductions above 10%. For speed reductions under or equal to 10%, the highest reductions are achieved with CASE3.

All cases may present a saturation on fuel reduction for speed reduction above 14%. Cases 1, 2 and 6 have reductions of around 26.6%, cases 3, 4 and 5 have reductions of 27.8%, 28.9% and 30%, which is the maximum reduction among all cases.

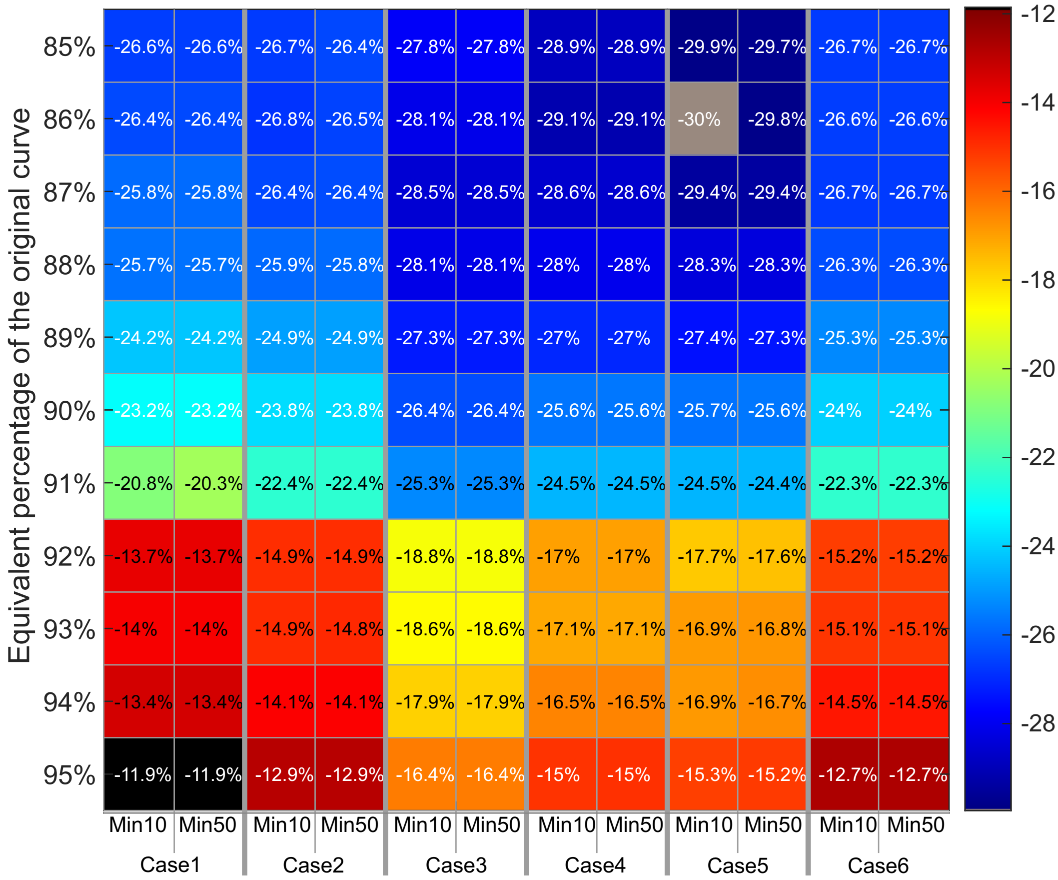

Figure C.4 – Percentage reduction of fuel consumed by varying the speed reduction during partial load voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the Zero curve.

When we consider the 10% of speed reduction proposed by IMO, the reductions achieved are 23.2%, 23.8% and 24% for cases 1, 2 and 6, respectively. Cases 4 and 5 achieve a reduction close to 25.7%, Finally, the CASE3 reduction for this level of speed reduction is similar to the reduction achieved by cases 1,2 and 6 when a speed reduction of around 14% is analyzed.

C.3 Results for MTU generators using calculated, normal and zero curves

Now, we can analyze the reductions obtained with MTU engines. In Fig. C.5 the results for the laden voyage are presented.

C.3.1 Laden Voyage - Calculated Curve

As can be seen, the results for MTU have a similar pattern as the results for CAT generators, there is a considerable increase in the fuel reduction when the speed reduction increases from 8% to 9%. On the other hand, as presented in the results of Chapter 4, the differences among the cases evaluated are minimal. It is shown in all levels of speed reduction.

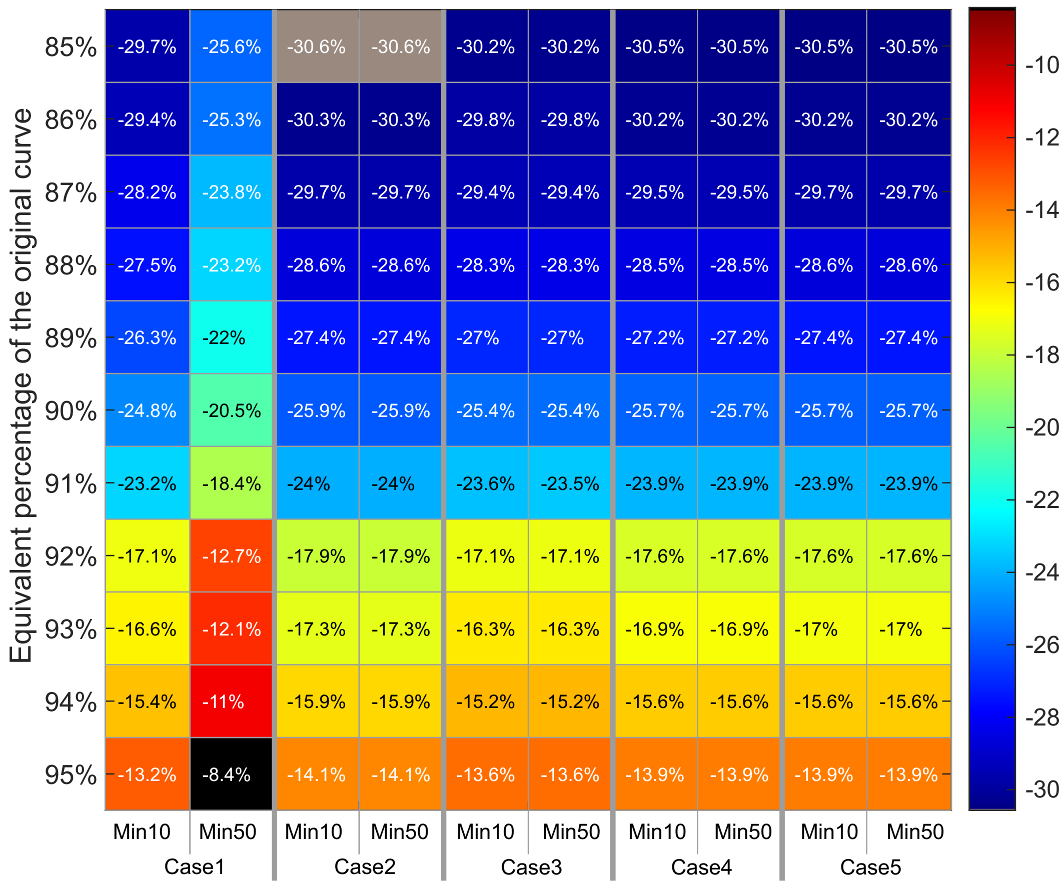

Figure C.5 – Percentage reduction of fuel consumed varying the speed reduction during laden voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the calculated curve.

For a speed reduction of 5%, the fuel consumed during laden voyage by a generator set like CASE1 is reduced in 13.2%. For CASE1 the reduction, for a minimal percentage of rated power equals to 50%, is probably connected to an excess of electricity generated. It happens when the generator cannot operate in a given power, which would be ideal to meet the demand. Then, HOMER dispatches the generator at the minimal power allowed by the restriction, causing an excess of electricity generated. In a real case, it would imply an increase of frequency, leading to a possible total ship power system impairment. In the results presented in Chapter 4, the minimum of 50% was omitted due to this excess of generation in some cases, as this operation should not occur.

As can be seen, when we compare these reductions to those presented in Fig. 6.6, which also comprises results for laden voyage using the calculated curve, we can see that the numbers here are close to those presented by cases 1, 2 and 6.

CASE2 portrayed the highest fuel reduction for most levels of speed reduction, in some of them, such as 11%, 12% and 13%, CASE5 displayed the same numbers.

When we consider the reductions for the value indicated by IMO, we can see that the reductions are around 25.7% for cases 4 and 5, slightly lower, around 25.4% for CASE3, and around 25.9% for CASE2. CASE1 achieved a reduction of 24.8%.

C.3.2 Partial Load Voyage - Calculated Curve

Then moving the analysis for partial load voyage, we can see in Fig. C.6 that CASE1 achieved the highest reduction of all cases when the speed reduction was set to 14%. The same reduction was achieved by CASE2 for the same speed reduction.

It is interesting to note that CASE1 had the highest reduction only above 14% of speed reduction; for all lower levels, other cases presented higher numbers. CASE3 had the worst numbers for all levels of speed reduction above 8%.

As happened with CAT generators, the reductions in partial load voyages for MTU generators present a saturation for speed reductions above 13%. For a speed reduction of 10%, the reductions are 24.4% for CASE3, which is the lowest reduction for this level, 24.5% for CASE1, 24.7% for CASE4 and for cases 2 and 5 a reduction of 24.9%, which is the highest reduction for this level.

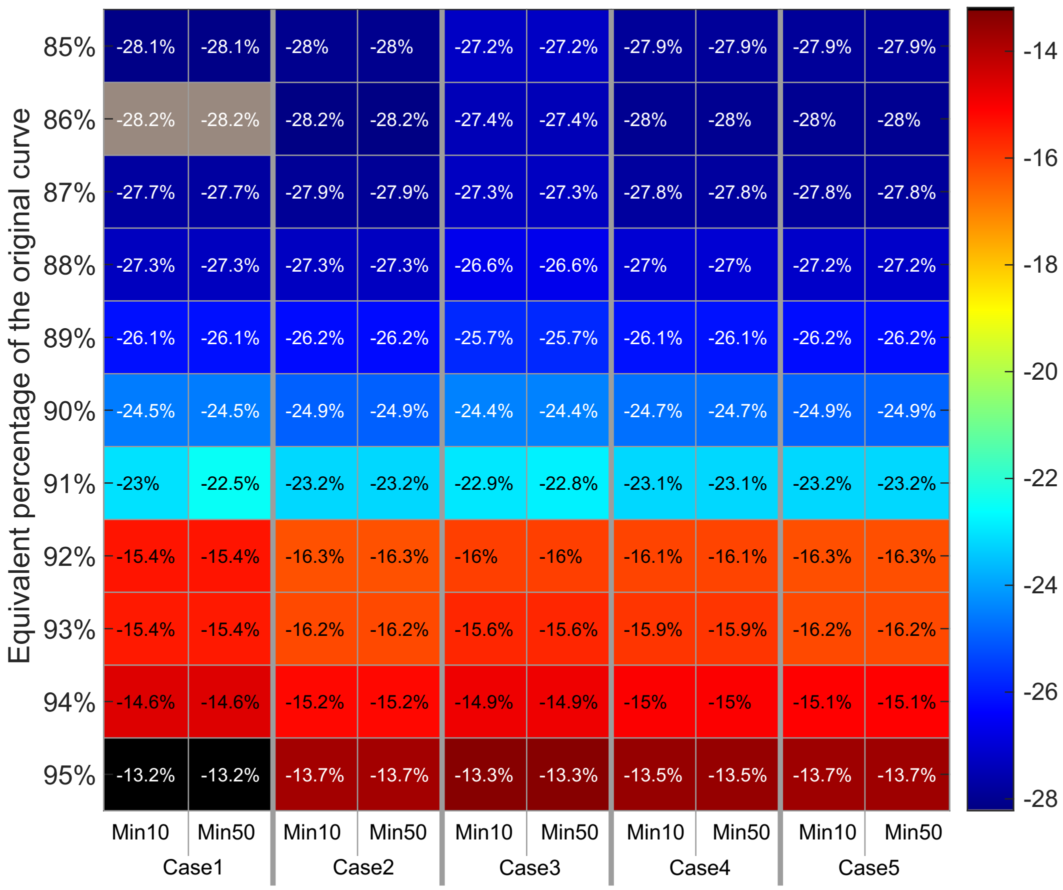

Figure C.6 – Percentage reduction of fuel consumed by varying the speed reduction during partial load voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the calculated curve.

C.3.3 Laden Voyage - Normal Curve

The results comprising the Normal curve are presented in Figs. C.7 and C.8. In Fig. C.7 the results for laden voyage are presented. As happened for Fig. C.5 the use of a generator set like CASE1 with a minimum percentage of 50% do not provide a result that can be considered.

Cases 2 and 5 achieve the highest reduction, with a speed reduction of 15%. For speed reductions under 14%, CASE2 presented the highest reductions for most of the speed levels; for the speed level of 11%, 12%, and 14%, cases 2 and 5 also presented the same reduction. Once again, CASE3 displayed the lowest decreases of consumption for speed reductions under 7%.

For a speed reduction of 10%, the reductions are around 28%. The highest reduction is achieved with CASE2, which is 28.5%, and then the following reductions from the highest to the lowest are 28.4%, 28.3%, 28.2%, and 27.4% for cases 5, 4, 3, and 1, respectively.

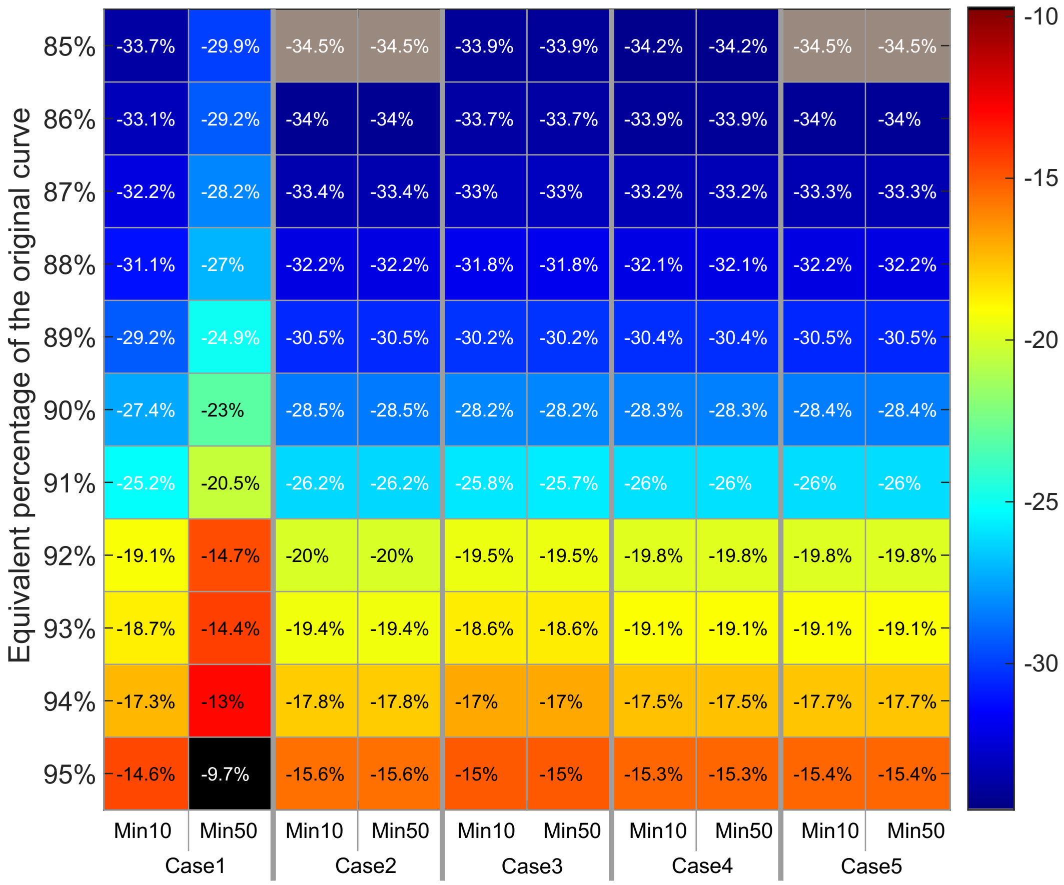

Figure C.7 – Percentage reduction of fuel consumed by varying the speed reduction during laden voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the Normal curve.

The Normal curve provides the highest amplitude among the reductions from 5% and 15%. For example, CASE2 has a reduction of 15.6% when the speed reduction is the lowest and 34.5% when it is the highest; the difference is 18.9%. For CASE5, this difference reaches 19.1%.

C.3.4 Partial Load Voyage - Normal Curve

Fig. C.8 presents the fuel reductions achieved for partial load voyage using the Normal curve to relate demand and speed. It is interesting to note that the reductions for partial load voyage for a speed reduction around 5% and 6% are close to the reductions presented for laden voyage in Fig. C.7, considering the same speed reduction.

CASE3 also presented the lowest reductions for this evaluation when the speed reduction was above 9%. For the speed reduction of 9% and under this level, CASE1 had the lowest reductions. On the other hand, for speed reductions different than 6% and 7%, CASE2 present the highest reductions in comparison to other cases at the same speed reduction level. For these two-speed reduction levels, CASE5 displayed the highest reductions. The highest reduction is achieved with a speed reduction of 14%; it is around 32.7%.

As portrayed in other partial load voyages, saturation occurs for speed reduction above 14%. Considering a speed reduction of 10%, the reductions are 27.6% for CASE3, 27.9% for cases 1, 4, and 5, and 28% for CASE2.

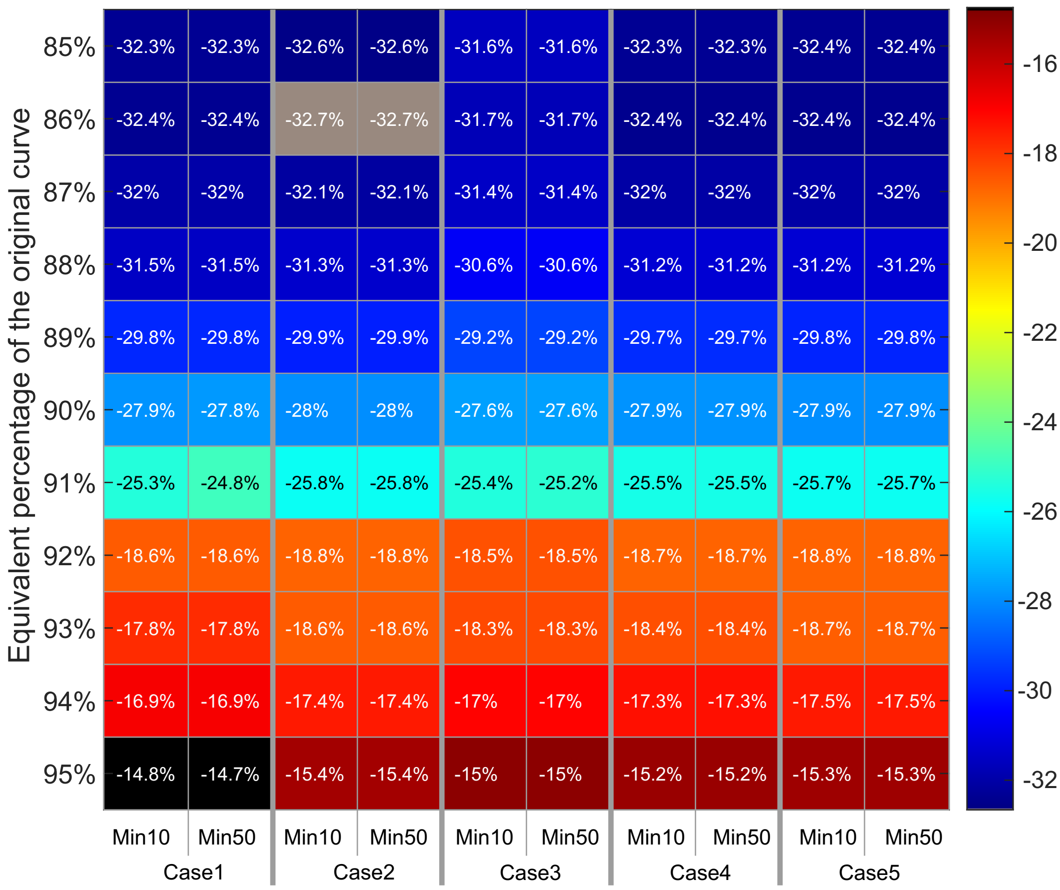

Figure C.8 – Percentage reduction of fuel consumed by varying the speed reduction during partial load voyage from 5% to 15%.Numbers for each case for two minimum percentages of rated power. Results for the Normal curve.

C.3.5 Laden Voyage - Zero Curve

Finally, Figs. C.9 and C.10 present the fuel reductions for laden and partial load voyage when the Zero curve is used to relate power and speed.

As can be seen in Fig.C.9, the highest reductions are achieved with a speed reduction of 15%; it is around 28.9% and is achieved with CASE2. Compared to the other curves, the highest values for reductions are the lowest. For a reduction of 5%, the values are close to those presented for the calculated curve.

When we analyze the speed reduction of 10% for the reductions of laden voyage achieved with the Zero curve, we can see that these are the lowest values among all three curves. The highest reduction for this level of speed reduction is achieved with CASE2, around 24.6%.

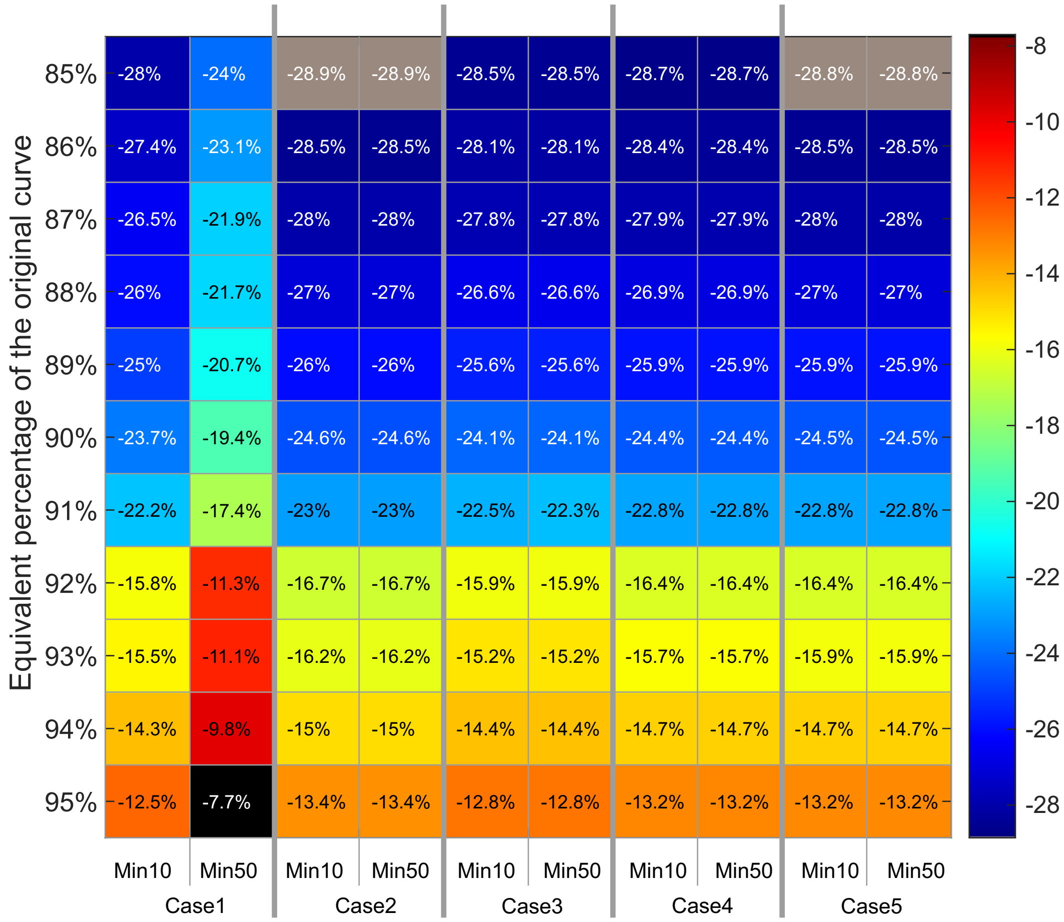

Figure C.9 – Percentage reduction of fuel consumed by varying the speed reduction during laden voyage from 5% to 15%. Results for the Zero curve.

C.3.6 Partial Load Voyage - Zero Curve

Moving to the analysis of the results of the partial load voyage, we can see that the highest reductions are also smaller than the values portrayed for the other curves. Even though, except for CASE3, all other cases have a reduction that is close to each other, CASE1 achieved the highest fuel consumption reduction when the speed reduction is 14%. CASE1 also presents the lowest reduction for speed reduction coming from 5% to 10%.

Once again, the results for the partial load voyage present a saturation. For cases 2, 3, 4, and 5, it occurs for speed reduction above 13%. For CASE1, above 14%.

The small difference among the results is also present for a speed reduction of 10%. Here, cases 1 and 3 present the lowest reduction, around 23.5%; CASE4 achieves a reduction of 23.7%; and cases 2 and 5 achieve a reduction of 23.8%.

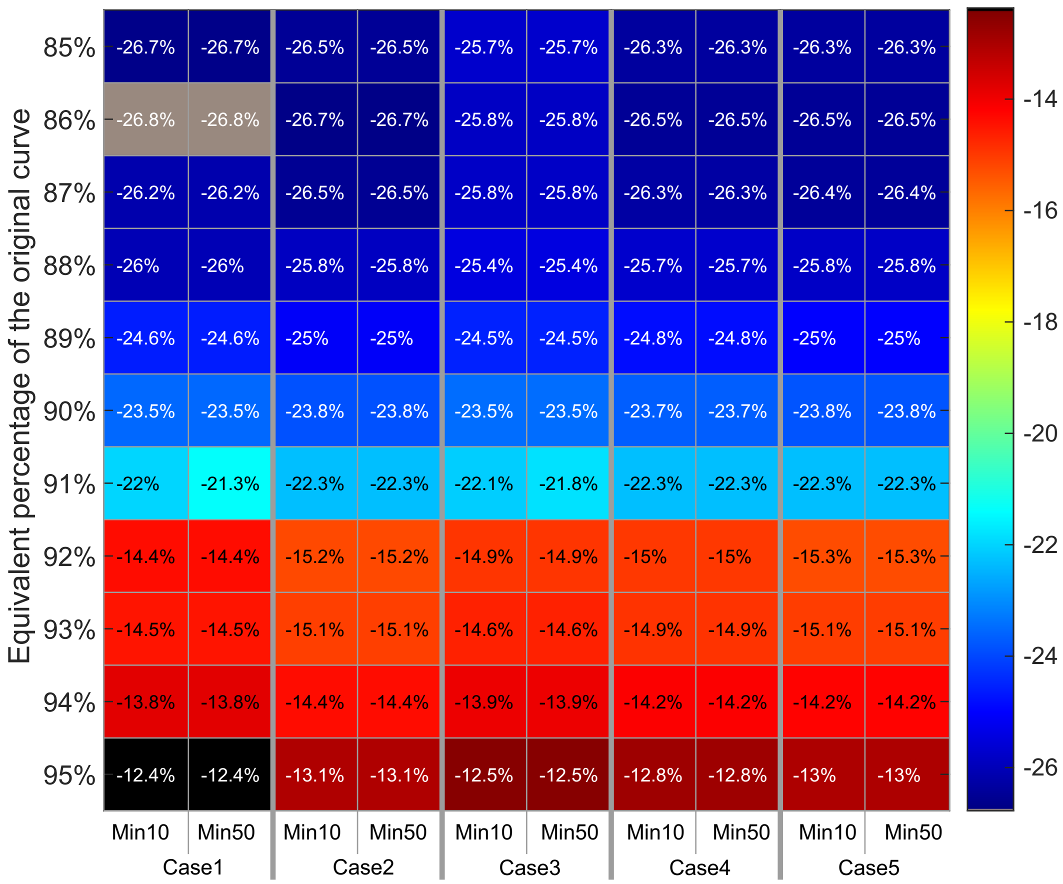

Figure C.10 – Percentage reduction of fuel consumed by varying the speed reduction during partial load voyage from 5% to 15%. Numbers for each case for two minimum percentages of rated power. Results for the Zero curve.