POSSIBILITIES FOR HYBRID CRUISE VESSEL PERFORMANCE OPTIMIZATION THROUGH DATA-DRIVEN BATTERY USAGE

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Industrial Engineering and Management, Master's thesis

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Teemu Kuusisto

Examiners: Professor Marko Torkkeli

Associate professor Kalle Elfvengren

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Engineering Science
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Teemu Kuusisto

Possibilities for hybrid cruise vessel performance optimization through data-driven battery usage

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Keywords: Hybrid cruise vessel, Energy storage system, Battery, Performance optimization, Digital twin, Wärtsilä

The burning topics of climate change and emission efficiency are shaping the trends of global energy production, also requiring fundamental changes in the maritime industry. Battery energy storage system is the leading alternative power source technology transforming the means of vessel power supply. As smaller hybrid vessels are rapidly popularizing, interest towards hybridization has also been shown in the cruise segment. However, the research on battery suitability and feasibility on a cruise vessel has been lacking, hindering the technological diffusion. This thesis aims to fill the research gap by examining the concept and feasibility of battery hybrid power supply on a cruise ship.

Diverse sources of information are studied with four different research methods, literature review, interviews, simulation, and data analysis, to carry out this qualitative research. Battery and power supply concepts are studied from the academic literature to understand the hybrid system’s potential benefits, challenges and applicability in the cruise context. Vessel register data is analysed and experts across the cruise industry are interviewed to investigate the hybrid vessel market situation and drivers for future development. Finally, a digital twin of the hybrid cruise power supply is modelled and simulated to estimate the monetary and emission savings potential and to assess the battery investment feasibility.

The results of the thesis show that batteries offer multiple valuable benefits on cruise vessels, mainly deriving from the disconnection of the direct link between power production and consumption. Enabling optimal engine operation lowers fuel consumption, creating direct cost and emission benefits, also generating various indirect advantages such as enhanced brand and compatibility with regulation. Batteries can also complement other sustainable power sources, main ones being fuel cells and combustion engines running on renewable fuels such as methanol and hydrogen. The popularization of these technologies, together with the operational and business drivers, is expected to boost the adoption of batteries as a secondary power source already in the near future. The main challenges of cruise vessel batteries are balancing the weight and space constraints with the high power and energy demand, and high investment cost considering the low OPEX savings potential, based on the simulation. With the expectations of increasing fuel prices and decreasing battery CAPEX, the financially unjustifiable investment can in the coming years become feasible.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUT Teknis-luonnontieteellinen
Tuotantotalous

Teemu Kuusisto

Hybridiristeilijän suorituskyvyn optimointimahdollisuudet akuston datavetoisella hyödyntämisellä

Tuotantotalouden diplomityö
2023
165 sivua, 56 kuvaa, 6 taulukkoa ja 4 liitettä
Tarkastajat: Professori Marko Torkkeli ja Tutkijaopettaja Kalle Elfvengren

Avainsanat: Hybridiristeilijä, Energianvarastointijärjestelmä, Akku, Suorituskyvyn optimointi, Digitaalinen kaksonen, Wärtsilä

Ilmastonmuutos ja päästötehokkuus ohjaavat globaaleja energiantuotannon trendejä, vaatien perustavanlaatuisia muutoksia myös meriteollisuudessa. Energianvarastointijärjestelmät, erityisesti akkuteknologia, ovat vaihtoehtoisia tehonlähteitä, jotka vaikuttavat merkittävästi laivojen tehontuotantoon. Akkujen yleistyessä pienemmän kokoluokan aluksilla, hybridiratkaisut ovat alkaneet herättää kiinnostusta myös risteilysegmentissä. Akkuteknologian soveltuvuutta risteilyaluksilla on kuitenkin tutkittu hyvin vähän, mikä on hidastanut teknologista diffuusiota. Tämän diplomityön tavoitteena on täydentää puuttuvaa ymmärrystä tutkimalla akkuhybridin tehontuotannon konseptia ja kannattavuutta risteilijällä.

Työ toteutettiin kvalitatiivisena tutkimuksena käyttäen kirjallisuuskatsausta, haastatteluja, simulaatiota sekä data-analytiikkaa tutkimusmenetelminä. Akuston ja tehontuotannon konsepteja tutkittiin akateemisen kirjallisuuden pohjalta, kasvattaen ymmärrystä hybridijärjestelmän mahdollisuuksista ja haasteista risteilijällä. Hybridialusten markkinatilannetta ja sen kehityksen ajureita tutkittiin analysoimalla laivarekisteridataa ja haastattelemalla risteilytoimialan asiantuntijoita. Hybriditehontuotannon päästö- ja kustannussäästöpotentiaalia sekä akkuinvestoinnin kannattavuutta arvioitiin simuloimalla todellista risteilijädataa case-laivoista mallinnettujen digitaalisten kaksosten avulla.

Työn tuloksista havaitaan akkuteknologian tarjoavan useita hyötyjä risteilijöille, pääasiassa poistamalla tehontuotannon ja -kulutuksen välisen suoran yhteyden. Moottorien optimaalisen toiminnan mahdollistaminen vähentää polttoaineenkulutusta luoden päästö- ja kustannussäästöjä. Tällä luodaan myös kestävämpää brändiä ja valmistaudutaan mahdollisiin lainsäädännöllisiin vaatimuksiin. Akuilla voidaan myös tukea muita vaihtoehtoisia tehonlähteitä, tärkeimpinä polttokennoja ja uusiutuvilla polttoaineilla, kuten metanolilla ja vedyllä, toimivia polttomoottoreita. Näiden teknologioiden yleistymisen yhdessä muiden ajureiden kanssa odotetaan kiihdyttävän akkujen käyttöönottoa toissijaisena tehonlähteenä jo lähitulevaisuudessa. Akkuteknologian suurimmat haasteet liittyvät risteilijöiden korkean tehon- ja energiantarpeen ja tila- ja painorajoitteiden yhteensovittamiseen, sekä korkeaan hankintahintaan kustannussäästöpotentiaalin ollessa matala. Koska polttoaineiden odotetaan kallistuvan ja akkujen hintojen laskevan, voi vielä toistaiseksi taloudellisesti kannattamattomasta investoinnista tulla lähivuosina perusteltu.

ACKNOWLEDGEMENTS

Finishing this master's thesis marks the completion of my University studies in Lappeenranta. Five years of studies have required a lot of hard work and self-transcendence, and wouldn't have been possible without the support of such amazing study peers. Big thanks to everyone who has shared this University journey with me.

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Espoo, 30.6.2023

Teemu Kuusisto

ABBREVIATIONS

AC	Alternating Current
AI	Artificial Intelligence
API	Application Programming Interface
AIS	Automatic Identification System
BESS	Battery Energy Storage System
BMS	Battery Management System
BOP	Balance Of Plant
CAPEX	Capital Expenditure
CII	Carbon Intensity Indicator
CO2	Carbon Dioxide
CO2eq	Carbon Dioxide Equivalent
COVID19	Coronavirus Disease 2019
DC	Direct Current
DNV	Det Norske Veritas
DoD	Depth of Discharge
DSoC	Delta State of Charge
EASE	European Association for Storage of Energy
ECA	Emission Control Area
ECDIS	Electronic Chart Display and Information System
ECMS	Equivalent Consumption Minimization Strategy
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EMS	Energy Management System
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gas
GT	Gross Tonnage
HESS	Hybrid Energy Storage System
HFO	Heavy Fuel Oil
IAS	Integrated Automation System

IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
IoT	Internet of Things
LFO	Light Fuel Oil
Li-ion	Lithium-ion
LNG	Liquified Natural Gas
MCR	Maximum Continuous Rate
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NMC	Nickel Manganese Cobalt
NOx	Nitrogen Oxide
NPV	Net Present Value
OPEX	Operational Expense
PCS	Power Conversion System
PESTEL	Political, Economic, Social, Technological, Environmental, Legal
PM	Particulate Matter
PMS	Power Management System
RES	Renewable Energy Source
ROI	Return On Investment
RRR	Required Rate of Return
RTE	Round-Trip Efficiency
SFOC	Specific Fuel Oil Consumption
SoC	State of Charge
SoH	State of Health
SOx	Sulphur Oxide
SusAF	Sustainability Awareness Framework
SWOT	Strengths, Weaknesses, Opportunities, Threats
UPS	Uninterruptible Power Supply
WACC	Weighted Average Cost of Capital
WHR	Waste Heat Recovery

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1 Introduction

In the 2020s, under the forces of digitalization, increasing environmental awareness and tightening emission regulations, the traditional maritime industry faces the imperative to transform itself. Tens of thousands of vessels are sailing the seas of the world every day and hundreds of new vessels are ordered and built yearly (Statista, 2022). Maritime transport is responsible for almost 90 % of global trade and freight movements thus having a major impact on the world economy, and more importantly, on the environment (Alnes et al., 2017; Baldi et al., 2022). Shipping alone was estimated to produce around 1076 million tonnes of Greenhouse Gases (GHG) in 2018, accounting for 2.5 – 3 % of global emissions. These numbers represent an increase of almost 10 % since 2014. (International Maritime Organization, 2020) Even though shipping is the major polluting part of maritime business, critical decisions and actions can and must be taken throughout the whole industry, from ship design to end-of-life recycling, to contribute to the battle against climate change.

Environmental concerns have continuously raised interest during the first decades of the 21st century and gained ground also in the maritime business where the vast majority of vessels are sailing with non-environmentally friendly fossil fuels. Maritime business is regulated and controlled by the International Maritime Organization (IMO) working under the United Nations (International Maritime Organization, 2019). IMO has set global short and long-term emission reduction targets, as well as energy efficiency regulations for both newbuild and existing vessels. To be able to answer these goals and challenges, maritime industry needs to come up with efficient and environmentally sustainable innovations and solutions to reduce the carbon footprint. (International Maritime Organization, 2018) One solution to address this problem is the introduction of onboard batteries. Operating a fully electric battery-powered vessel produces zero emissions during the voyage, meaning 100 % emission savings potential compared to traditional vessels (Ritari et al., 2020). The weight, capacity and cost of current battery systems make it unfeasible for certain types of vessels to become fully electric. However, implementing a battery system as a secondary power source supporting the fuel burning engines has been proven to reduce fuel consumption, emissions and operating costs up to 30 %, depending on the vessel type and operating profile.

To be able to fully utilize the benefits of hybrid power supply, operational vessel data must be collected and analysed to provide insights on the optimal propulsion configuration, battery characteristics, energy control strategy and many other aspects adding up to the function. (European Maritime Safety Agency, 2020)

Energy Storage Systems (ESS) and the hybrid vessel concept are already highly studied fields with much research done on multiple pilot vessels and different energy storage technologies. Battery systems in particular have become common in the automotive industry and in the field of stationary energy storage. Vessel batteries, however, have not been studied as intensively as they have so far been relatively small in terms of capacity, thus the usage and benefit potential have been lower. (Skjong et al., 2016) The maritime industry has already seen multiple hybrid and fully electric short-distance ferries, and a few merchant vessels with small capacity batteries used only for a specific purpose. Still missing from the market, and from deeper assessment of feasibility, are battery installations onboard cruise vessels. There are some smaller cruise vessels that have implemented battery systems, but the vast majority are still fully relying on fuel burning combustion engines. Previous studies have estimated that the savings potential of an ESS on a cruise vessel is significantly lower than on many other vessel types, such as ferries and bulk vessels, but the analysis has remained on a high level and lacks evidence data to support the estimation as there are only few cruise vessels utilizing batteries. (European Maritime Safety Agency, 2020) This thesis study aims to fill the gap in the feasibility estimations of batteries onboard cruise vessels.

1.1 Scope and limitations

This thesis examines battery systems on hybrid cruise vessels. The focus is on finding ways to utilize the battery system to optimize vessel performance and reduce fuel consumption. The study is conducted with an analytical approach as data is the enabling element of battery and performance monitoring, controlling and optimization. Cruise vessel, propulsion and ESS concepts and characteristics are introduced and discussed as they greatly inform the battery usage and possible advantages, but the technical solutions won’t be studied in detail. Even though this thesis studies data-driven battery control and optimization possibilities, the target is not to build an optimization model or algorithm, but rather to investigate the feasibility, requirements and limitations of creating one.

The current hybrid vessel market situation is explored without regard to vessel type, but the battery usage and optimisation research, as well as the savings potential analysis, is limited to cruise vessels. This limitation is set because cruise vessels are one of the least studied segments for onboard batteries, and their operating profile and characteristics differ greatly for example from merchant vessels and ferries. Different propulsion systems are shortly introduced, however the research and analysis focus on electric propulsion due to its prevalence in the cruise segment and compatibility for harnessing the full potential of batteries. ESS and battery types and technologies are listed but the scope is limited to the currently most used and feasible Lithium-ion (li-ion) battery technology. Also, as fully electric power supply is not feasible for cruise vessels in near future considering their operating profile, the study is limited to hybrid power supply. In the context of this thesis, the term hybrid vessel means a vessel utilizing hybrid power supply, not to be confused with hybrid propulsion. Charging the battery by connecting to the shore electricity grid is taken into account in the analysis, but deeper research of the availability of shore power infrastructure, together with the shore electricity origin, cost, emissions and other varying aspects, are out of scope. Onboard ESS safety and certification aspects, having a major effect on the whole hybrid vessel concept, are discussed but not studied in detail within this thesis.

1.2 Goals, objectives and research questions

The goal of this thesis is to gather, combine and create knowledge on the feasibility of utilizing a battery system on a cruise vessel. To create a big picture of the topic, hybrid vessels are studied with different approaches, from physical battery implementation to future market potential. The research is divided into four main elements: battery usage and optimisation review, market situation study, savings potential analysis, and investment feasibility assessment. The thesis aims to suggest ways to utilize the onboard battery system and estimate its potential savings from both monetary and environmental aspects. Therefore, this thesis contains valuable information about the market situation and usage of batteries, together with a future outlook. It also characterizes the range of monetary and environmental benefits and how they correspond to the investment cost and emission reduction targets. This information can be further used as an insight to support battery investment decision making and designing optimal ESS characteristics for selected cruise vessels. This study can also work as a basis of creating a data-driven battery optimization model or algorithm.

The main research question this thesis aims to answer is:

How can a hybrid vessel's operational performance be optimized with battery usage?

The supporting sub-questions are:

- How can batteries be used to improve cruise vessel's performance?
- What are the limitations and challenges of onboard battery systems?
- What does the hybrid vessel market look like, and how is it expected to develop in the future?
- How much operational savings can batteries generate and are they a profitable investment?

1.3 Research methods, material and process

This thesis aims to combine the benefits of quantitative (Clarksons Research, 2023; Det Norske Veritas, 2022a) and qualitative research (Baldi et al., 2022; European Maritime Safety Agency, 2020; Geertsma et al., 2017), however emphasizing the latter. The study features four different research methods to address the supporting research questions and generate the answer to the main question. These methods are literature review, qualitative interviews, data simulation and data analysis.

Vessel and ESS concepts are studied from academic literature, creating the theoretical framework and basis for the thesis. The battery usage and optimisation study is done as a literature review. Peer-reviewed publications are examined to gather knowledge on onboard battery possibilities and challenges related to cruise vessels. These publications, mainly books and journal articles, are obtained from multiple academic sources using different search engines. As battery and hybrid vessel topic is vibrant and rapidly evolving, timeliness of the publications must be emphasized to ensure the reliability and validity of the results.

Research of the current and future hybrid vessel market situation is done with statistical data analysis and interviews. Public vessel data from the ship register of Det Norske Veritas (DNV) and Clarksons database is used for the current and near future data analysis. Secondly, selected cruise lines and other key stakeholders from the cruise industry are interviewed regarding their interest in and predictions of hybrid cruise vessel market development and future power sources of the maritime industry.

Finally, the battery savings potential estimation is done by comparing the literature baseline to the results of the data simulations on selected case vessels. Digital twin models of the case vessels' power systems are configured and inputted with real cruise data to analyse the operating cost reduction potential of specified onboard battery systems. This potential is then compared with the estimated investment cost to calculate the profitability of different battery investment options, supported by sensitivity and scenario analyses of the most critical variables.

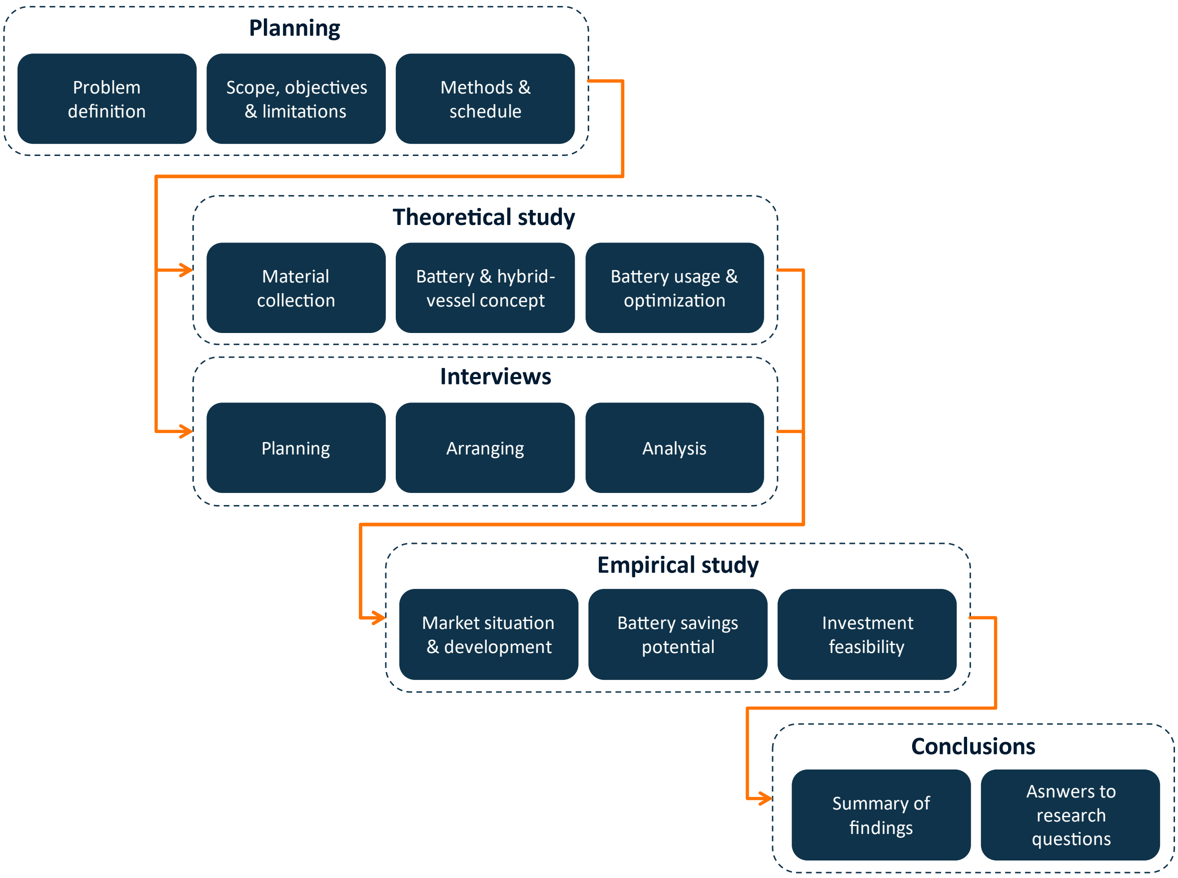

Figure 1. Thesis study process flow

The process flow of this thesis study is visualized in Figure 1 above. The planning phase starts with defining the problem, clarifying the objectives and limiting the scope. Then research methods and project schedule are defined. After the planning phase, theoretical study begins with material collection and literature review to understand and build the framework of a hybrid cruise vessel and a battery energy storage system. Then a deeper investigation is conducted on battery use cases and optimisation possibilities, including the benefits, challenges and sustainability aspects. Simultaneously interviews are planned and arranged for gathering knowledge on the maritime battery market and future development. The empirical study starts with the market situation analysis to summarize the current hybrid vessel market and to predict the future development. After finding the optimal ways to utilize onboard batteries, data simulation and analysis are performed to estimate the savings potential. Based on the simulation results, the profitability of different battery investment scenarios can be estimated and analysed. Finally, the main findings of the study are concluded to answer the research questions.

1.4 Thesis structure

The structure of this thesis follows the study process described in Figure 1. Chapter one introduces the topic, background and motivation for the study, as well as scope, objectives, limitations, methods and research questions. Chapter two discusses battery and hybrid vessel concepts based on the literature review and explains relevant terminology. Chapter three focuses on the core question of optimal battery usage on a cruise vessel and summarizes the related benefits, challenges and sustainability impacts. Chapter four introduces interviews as a qualitative research method and gives the background and summary of the interviews done for this thesis. Chapter five summarizes the hybrid vessel market situation analysis and examines the main drivers for hybrid power supply and impacts of the global operating environment. Chapter six introduces the results of the savings potential analysis based on the battery system simulations employing actual vessel data. Chapter seven evaluates the indicated battery investment profitability together with sensitivity and scenario analyses. Finally, chapter eight concludes the findings of this thesis study to provide answers for the research questions, discusses the reliability and validity of the research and discloses the areas of future investigation.

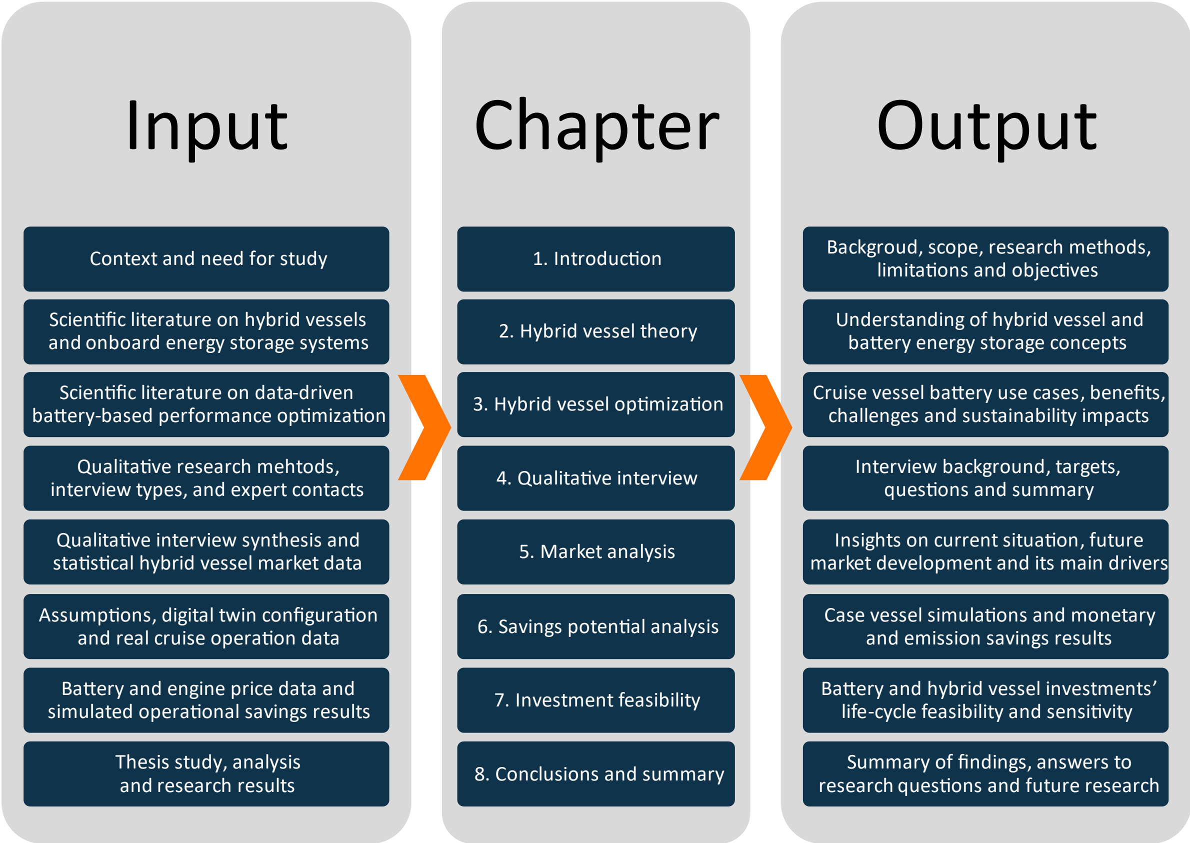

Figure 2. Thesis input and output structure

Figure 2 above describes the thesis structure with inputs and outputs of each chapter. Outputs symbolize the results and value each chapter brings to the thesis. Inputs are taken from the four research methods (literature review, interviews, simulation and data analysis) and from the outputs of previous chapters.

2 Battery powered maritime

Onboard electrical systems have been introduced already in the 19th century in the form of light bulbs powered by diesel engine combined with an induction motor on cargo and passenger steamship SS Columbia. Since then, the development and interest toward electrical possibilities onboard vessels started to rise quickly. First diesel-electric vessel was launched in early 20th century and the first fully electric propulsion system shortly after that. (Skjong et al., 2016, 2015) However, the emergence of battery systems on vessels took almost hundred years more. First onboard batteries were introduced at the turn of the millennium, using lead-acid or nickel-cadmium technologies and having the capacity of less than 100 kWh. Since late 2000s, lithium-ion battery technology has gained ground and become the most common choice for vessel battery systems. Feasibility of hybrid power supply depends on the vessel's characteristics and operating profile, which is the main reason why small passenger vessels and ferries of short distance started the hybrid vessel trend. In today's world, due to the development and advances in battery technology, besides hybrid ferries we can see large merchant and cruise vessels sailing with up to ten-megawatt hour battery systems. Large battery capacity, versatile operating profile, real-time data collection and centralized Energy Management Systems (EMS) create possibilities for vessel performance optimization resulting in various benefits. (Bordin and Mo, 2019; Hoedemaker, 2022)

This chapter introduces the basic concepts of vessel propulsion and power supply together with the vessel data systems enabling energy management, performance monitoring and optimization. Battery system types, characteristics and limitations will also be discussed in the context of hybrid vessel, along with battery lifetime and cost development.

2.1 Hybrid cruise vessel concept

At a high level, vessels can be categorized into merchant and passenger vessels. Merchant vessels are designed for material transportation, such as container ships, bulk carriers or tanker vessels, or performing other types of offshore business, like oil exploration and construction work. Apart from special offshore vessels, merchant vessels typically sail long distances with little crew and huge cargo. The sailing speed is very constant and relatively low as they can travel several days between ports all over the world. Merchant vessels spend majority of the time sailing in the sea, and relatively little at the port or manoeuvring, which means sailing in reduced speed typically when entering or exiting coastal waters to arrive at or departure from port. Passenger vessels on the other hand are focused on carrying and entertaining passengers. Passenger vessels can be further divided into ferries and cruise ships, former operating on shorter distances typically on a fixed route, also transporting vehicles. (European Maritime Safety Agency, 2020)

Cruise vessels represent a whole other world in terms of size, purpose and operating profile. Their main purpose is to entertain passengers as a luxurious floating hotel with all services and activities you can imagine of, from restaurants and swimming pools to roller coasters and skydiving simulators (Carnival Cruise Lines, 2023; Royal Caribbean International, 2023). Cruise vessels operate on different routes with varying speeds, typically staying several hours in ports to let passengers explore exotic destinations. Compared to merchant vessels, cruise ships spend a lot more time at the port and manoeuvring. Another significant difference between the vessel categories is the power demand. For merchant vessels the propulsion power, turning the propellers to make the vessel move, makes around 80 – 90 % of the total power demand. This means that other functions like vessel control, lighting, heating and air conditioning, all together referred to as service power, are responsible only for around 10 – 20 %. For cruise vessels that essentially seem like small floating cities, the ratio can be as high as 50/50, however typically around 70 % for propulsion and 30 % for service power (Wärtsilä, 2023a). On cruise vessels the power demand varies greatly depending on the time of the day and weather conditions. It is also worth mentioning that the service power demand on a cruise vessel remains rather constant during port stays even when propulsion power is zero. High power demand variations and more time spent in manoeuvring creates battery-based performance optimization possibilities for hybrid cruise vessels. (European Maritime Safety Agency, 2020)

2.1.1 Propulsion configurations

Vessel’s power supply and transfer systems are typically decided based on the chosen propulsion type, which is the main power consumer. Three main propulsion types are mechanical, electrical and hybrid propulsion, which are shown in Figure 3 below.

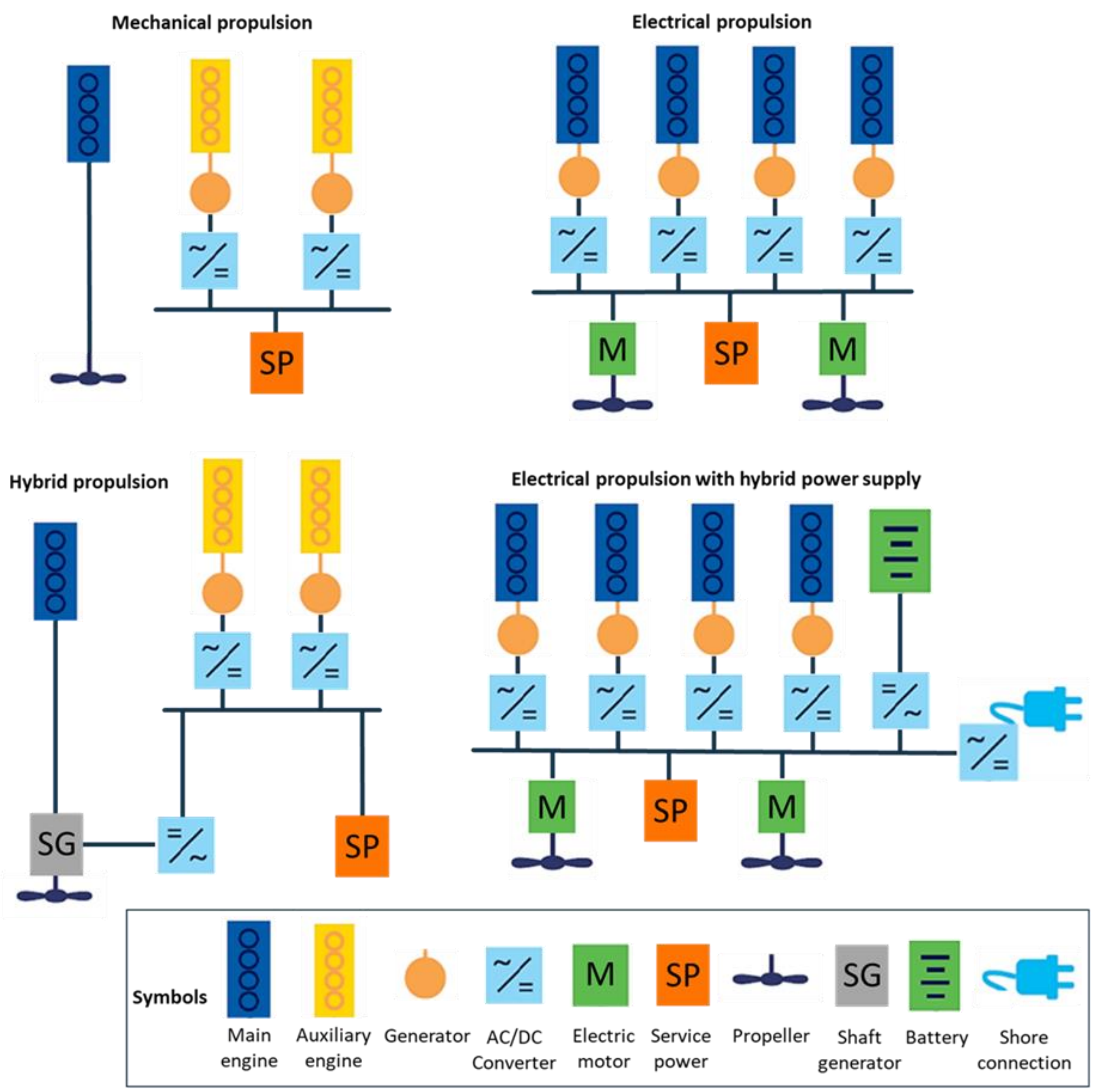

Figure 3. Vessel propulsion configurations (adapted Det Norske Veritas, 2016; European Maritime Safety Agency, 2020; Geertsma et al., 2017)

In the traditional mechanical propulsion system typically one bigger main engine is directly connected to the propeller being solely responsible for moving the ship. Besides main engine, one or more smaller auxiliary engines with electricity generators, both together known as gensets, are required to supply the service power demand through an electrical network. Mechanical propulsion might be suitable for some merchant vessels that operate on stable speeds of around 80 – 100 % of the top design speed. (Geertsma et al., 2017) It has been proven that the most fuel and emission efficient load for vessel engines is around 75 – 85 % of the Maximum Continuous Rating (MCR), optimal being closer to 85 % (Baldi et al., 2022; Reusser et al., 2018). This optimal load range comes from the parabola shape of the engine's Specific Fuel Oil Consumption (SFOC) curve which represents the amount of fuel required to produce a kilo-watt hour of power (Al-Falahi et al., 2018). Figure 4 below visualizes the shape of a typical maritime diesel engine's SFOC-curve, showing that the best power to fuel ratio is achieved around 85 % of MCR.

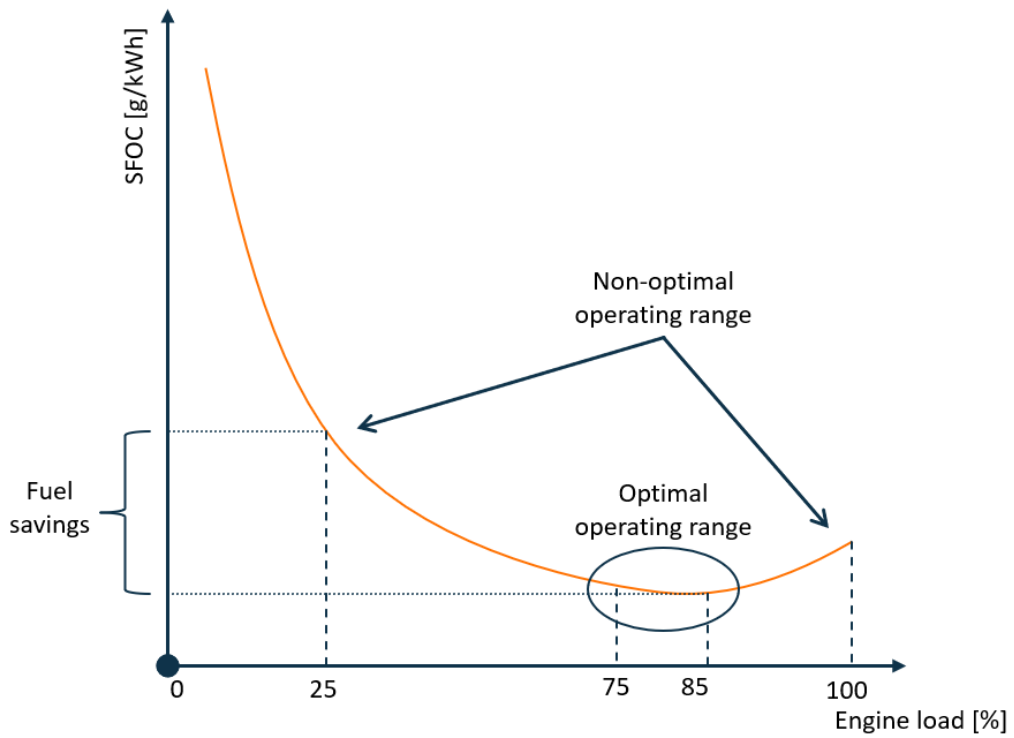

Figure 4. Typical maritime diesel engine SFOC-curve (adapted Reusser et al., 2018)

As shown in the figure, running the engine on optimal load (85 %) creates significant fuel savings compared to non-optimal loading (25 %). As the propulsion and service power demands are handled separately in the mechanical propulsion system, the main engine can be designed to run on the optimal load most of the sailing time, minimizing fuel consumption and emissions. Other benefits of mechanical propulsion are low purchase cost and minimal power losses due to system simplicity. On the other hand, simplicity of the configuration creates challenges such as limited operative control and lower manoeuvrability, low fuel efficiency on lower sailing speeds, increased need for maintenance also affecting the availability, and finally increased noise. (Geertsma et al., 2017; Skjong et al., 2017) Batteries could be implemented to the auxiliary power production, but as mechanical propulsion is not common among cruise vessels and its optimization possibilities are limited to service power, mechanical propulsion will not be focused on in this thesis.

The most common propulsion system for cruise vessels is electrical propulsion (Kanerva and Hansen, 2009). In this configuration all engines are combined with electricity generators (Figure 3) providing energy for the electrical network covering the whole ship as an isolated microgrid (Skjong et al., 2016). Engines can have different power load capacities, but typically cruise vessels only have 4 – 6 same size main engines and no auxiliary engines. The power flow in the electricity network is controlled by a Power Management System (PMS) which is responsible for balancing the power production with the consumption. With transformers and power converters electricity is directed to supply the auxiliary service power loads and propulsion motors that turn the propellers. (Geertsma et al., 2017) Unlike mechanical propulsion, electrical propulsion enables utilizing the full potential of an onboard battery system, as all generated power is transformed to electricity before consumption, and on the other hand, all consumers are connected to the same microgrid. Therefore, electrical propulsion will be the main focus in the scope of this thesis. An example of electrical propulsion with hybrid power supply consisting of a battery and shore power connection is shown in Figure 3.

Electrical propulsion provides many advantages compared to the traditional mechanical propulsion, but its profitability depends on the vessel's operating profile. As there typically are no smaller capacity auxiliary engines, all energy is taken from the main engines. The efficiency hereby depends on the load that main engines are running on. In case the operating profile is stable and service power demand is low, electrical propulsion might not be the best option as the full benefit of stable propulsion can't be utilized, like it could with having one purpose-designed main engine. On the other hand, if the operating profile is diverse and auxiliary loads are high, the shared energy production can be better controlled and optimized than having separate power production for both loads. (Geertsma et al., 2017) PMS coordinates the electrical power production by having minimum required number of engines running on as optimal loads as possible, resulting in high fuel efficiency. Electrical propulsion enables running the engines evenly and optimally leading to reduced need for maintenance and higher availability and reliability. In case one engine breaks down, electrical propulsion is not affected, whereas mechanical propulsion would be left either without propulsion or service power, depending on which engine failed. Other benefits of electrical propulsion are reduced noise and vibration, increased manoeuvrability and control, and high fuel efficiency also in lower speeds. (Kanerva and Hansen, 2009) The main trade-off in electrical propulsion is the power losses caused by more complex system consisting of multiple power conversion phases between the power generation and consumption. The losses have been estimated to be around 2 % per converter leading to increased fuel consumption. Other challenges are voltage and frequency swings in the electrical network and non-optimal engine loads when reserve power is required or power demand varies quickly. (European Maritime Safety Agency, 2020)

Third propulsion option, visualized in Figure 3, is hybrid, combining the two previous approaches. Hybrid propulsion typically consists of one main engine responsible for propulsion and few gensets responsible for service power. The differentiating element in hybrid propulsion is a shaft generator producing electricity from the mechanical energy generated by the main engine, or the other way around producing mechanical energy from the electricity generated by auxiliary engines (Farnsworth, 2019). This configuration enables addressing the benefits of both mechanical and electrical propulsion systems, being able to run the main engine on an optimal load also maintaining control over load demand fluctuations and manoeuvrability with the reserve power available from the gensets. With good planning and vessel design hybrid propulsion can reduce vessel's fuel consumption and environmental footprint. However, trade-offs are also linked to hybrid propulsion, for example on system requirements, increased complexity, higher purchase and installation costs and power losses on conversions between mechanical and electrical power. Different battery system configurations can be implemented to hybrid propulsion, either centrally to the electrical network or directly connected to each propulsion unit to minimize power losses. (Det Norske Veritas, 2016; Geertsma et al., 2017)

2.1.2 Power demand and supply

While sailing, cruise vessels can be considered as small isolated and independent cities that need to balance their power consumption and production. The level and difficulty of power management depends greatly on the vessel's characteristics and power system configuration. (Baldi et al., 2022) Figure 5 below summarizes the distribution of possible power consumers and producers on a cruise vessel.

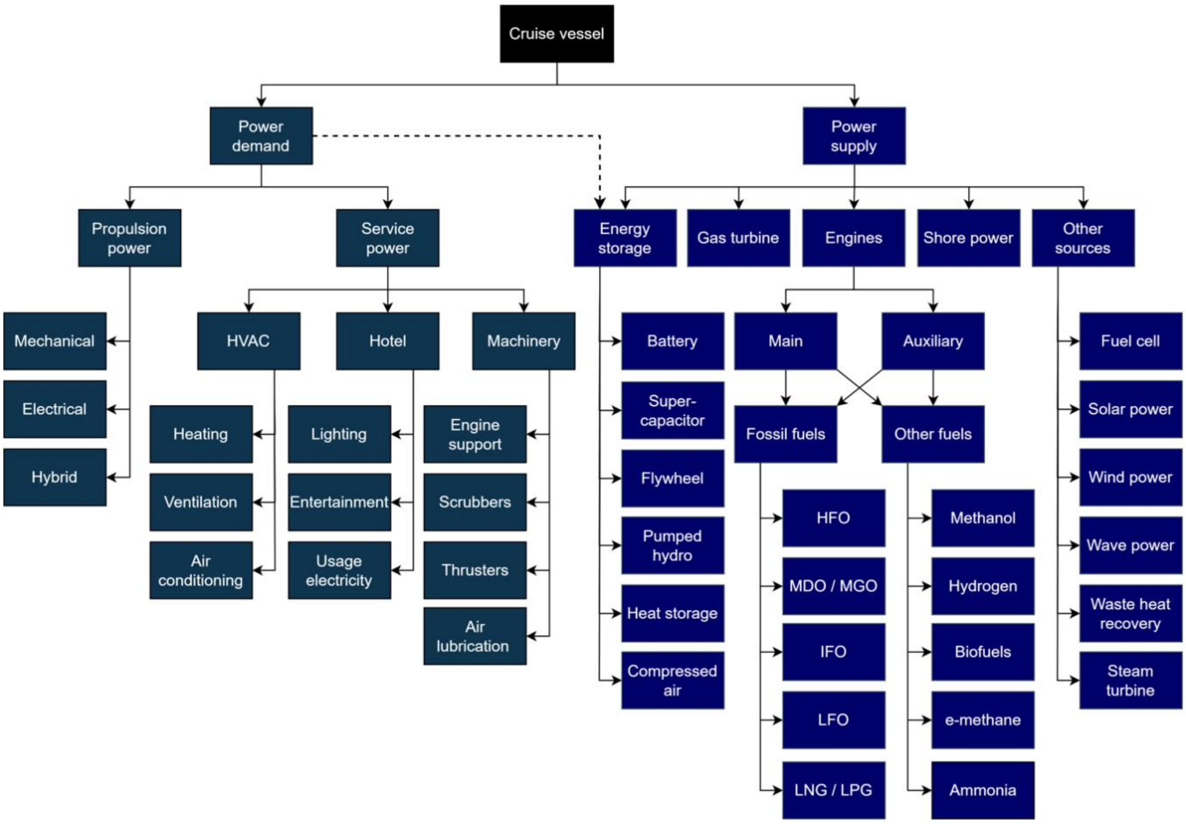

Figure 5. Cruise vessel power demand and supply (adapted Baldi et al., 2022)

Vessel's power demand is divided into propulsion power and service power. Service power plays an important role in the power and fuel efficiency management since in the case of cruise vessel it is a relatively big and varying element. As mentioned, for cruise vessel the ratio between propulsion power and service power can sometimes be even 50/50 but typically propulsion power is higher during sailing and service power during port stays. (Wärtsilä, 2023a) Service power accounts basically for all power consumed onboard that is not directly related to the propulsion. Service power consumers are vessel specific and there is no standard categorization. Some divide service power based on the energy type to electric, thermal and mechanical power, and others by the system where the power is consumed (Baldi et al., 2018). Figure 5 gives a three-part system-based example of service power division to HVAC (Heating, Ventilation, Air Conditioning), hotel and machinery power, which is used on many vessels and shipyards. HVAC systems are responsible for the basic heating, ventilation and air conditioning of the vessel. Hotel power is related to the onboard passenger facilitation and entertainment, consisting for example of lighting, cabin and galley electricity and the entertainment systems such as rollercoaster and movie theatre. Rest of the power consumers are addressed to the machinery category, which is responsible for technical systems “under the hood”, for example pumps supporting the engines, scrubbers cleaning the exhaust gases, thrusters used for manoeuvring the ship sideways, and air lubrication that is used to reduce the frictional resistance between the vessel’s hull and water. The borders of this service power categorization are not clear, as for example some vessels or shipyards categorize the thrusters into propulsion power instead of machinery power, but it gives an idea of the big picture of vessel’s power consumption. (Wärtsilä, 2023a) Even though energy storage systems, such as batteries and supercapacitors, are essentially seen as power suppliers, they don’t actually produce energy and need to be “charged”, thereby also being considered in the power demand side of Figure 5.

Diesel engines are still the main source of power in today’s cruise vessels. As mentioned, cruise vessels typically don’t have smaller auxiliary engines as they rely on electrical propulsion. Vast majority of vessels run with fossil fuels, mainly with diesel oils of different sulphur levels: Light Fuel Oil (LFO), Intermediate Fuel Oil (IFO), Marine Diesel or Gas Oil (MDO/MGO), or Heavy Fuel Oil (HFO). New, more and more environmentally friendly, fuels are continuously introduced and being used in the maritime industry, for example Liquified Natural or Petroleum Gas (LNG/LPG), methanol, hydrogen, methane, ammonia and biofuels. However, their power efficiency is typically lower than diesel’s and the purchase price can be higher. (Det Norske Veritas, 2022b). Other traditional power sources are gas turbines that are mainly used for suddenly increasing power demand as they have greatly faster start-up times than diesel engines (General Electric, 2023). Gas turbines can be used as a main or support power source as they are capable of producing high amounts of power by burning fuels, similarly to combustion engines. The main reasons why engines are nowadays preferred over gas turbines, even though gas turbines are much lighter and smaller, are the fuel flexibility and higher fuel efficiency, especially on lower loads. (Wärtsilä, 2023b) New innovative power sources are also raising interest in the maritime field. Current market leader in energy storage systems is advanced battery technology, which has been proven beneficial in many vessel segments and its feasibility in the cruise segment is under investigation or piloting phase on several cruise lines. Besides batteries, for example supercapacitors and heat storage are investigated as possible power sources for cruise vessels. Each of the technologies have their advantages and disadvantages, which is why they fit for slightly different purposes and can also be used together complementing each other (Melancon, 2022). Along with energy storage systems, the possibility of shore power connection has emerged and already been implemented on several ports worldwide. Shore connection is like a vessel plug-in, as it means connecting the vessel's microgrid to the local onshore electricity grid to supply the service power demand and charge batteries if they are available. (Prevljak, 2022; Rantio, 2015; Shippax, 2021) Final element in Figure 5 is the other power sources that are at least so far less common or unsuitable for cruise vessel's or only able to provide small amounts of power for auxiliary purposes. Fuel cell technology is still under development and piloting but has shown a lot of potential for maritime applications, especially when combined with a battery. Examples of other power sources are Renewable Energy Sources (RES) like solar, wind and wave power (Eco Marine Power, 2023; Wello, 2023). These can be used for minor energy production, but they have a lot of limitations in the context of a cruise vessel. Waste Heat Recovery (WHR) is the process of harvesting or reusing heat energy produced by the combustion process of diesel engines. This waste heat can be used for example to boil water and use the steam to produce electricity via steam turbine. (Jouhara et al., 2018) When the vessel's onboard power supply consists of two or more alternate power elements it is called hybrid power supply. This means utilizing both fuel, typically in engines or turbines, and electricity, typically from an ESS, to power the vessel. The most common hybrid power supply combination in maritime industry is diesel engines supported by a battery energy storage. (Ghosh, 2022)

Geertsma et al. (2017) have listed performance criteria for power generation on today's vessels with diverse operating profiles and operational requirements:

1. Fuel consumption
2. Emissions
3. Radiated noise

4. Propulsion availability
5. Manoeuvrability
6. Comfort (noise, vibration and smell)
7. Maintenance cost
8. Purchase cost

The priority is given to fuel consumption and emissions, which have the most effect on the operating costs and environmental impact. Noise and comfort aspects are especially important in the cruise segment as passenger entertainment and satisfaction are in the core of the business. Availability and manoeuvrability are also placed on the list as precise control of the vessel affects passenger experience and safety. The relationship between maintenance and purchase costs must also be considered from the life-cycle point of view when making big long-term investments on vessel's power supply and propulsion configurations. (Geertsma et al., 2017)

2.1.3 Vessel data systems

The continuous development and increase in the need and use of data in maritime industry has led to vessel datification, referring to the process of transforming operation related events and phenomena into usable data with the help of sensors and information management systems. Internet of Things (IoT) is one of the main enablers of vessel data monitoring and utilization. IoT means the dynamic communication between physical and digital things. This is typically made possible by IoT sensors measuring physical events and sharing the collected data wirelessly to a digital endpoint where it can be further analysed and used. (Xu et al., 2019) Modern cruise vessels are packed with IoT sensors, data sharing and information systems for safety, monitoring and controlling purposes. These systems generate different types and levels of data that can be used in performance optimization from various aspects. Figure 6 below visualizes the four main levels of vessel data, divided into internal and external information. The two inner circles represent endogenous information about systems, events and current state within the vessel. The two outer circles in turn describe exogenous information providing insights of the external operating environment and global vessel fleet. (Baldi et al., 2022)

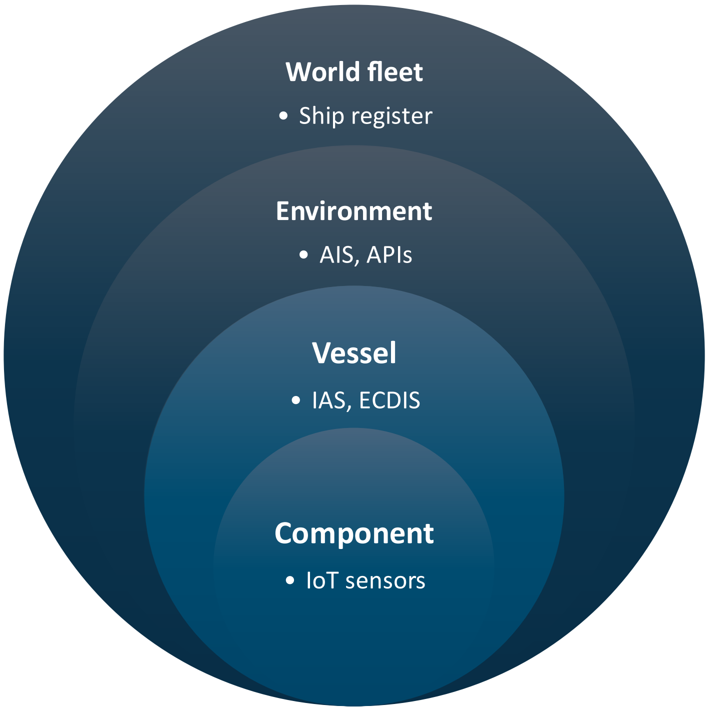

Figure 6. Vessel data levels (adapted Baldi et al., 2022)

Starting from the lowest component level in Figure 6, IoT sensors are connected to different parts and elements of the vessel sharing measurement data for example from engines, propulsion, and electricity consumers. Today's vessels can generate tens of thousands of data points in high frequency of less than a second. From the energy efficiency point of view, real-time power consumption data monitoring is highly important to be able to provide sufficient amount of power from the engines, batteries or other sources as efficiently as possible. Besides efficiency, sensor data is used for ensuring high reliability and availability of propulsion and service power. The power demand of a cruise vessel is harder to predict than of a merchant vessel, as cruise vessels spend a lot of time manoeuvring and the service power fluctuations can be sudden and significant. (Baldi et al., 2022) Matching power supply with the demand requires an overview of the whole vessel's power consumption. This is achieved with an Integrated Automation System (IAS) that collects and monitors the onboard IoT sensor data. IAS enables the use of data-driven technologies, such as Power Management System (PMS), alarm and safety management systems and ship performance monitor, which are often integrated in the IAS. (Norwegian Electric Systems, 2023; Pepliński, 2019) Another possibility enabled by IAS data is creating a digital twin, meaning an exact digital copy of the vessel, or its subsystem like propulsion, consisting of real-time automation data. Digital twin can be used for multiple valuable purposes such as system or scenario simulation, operational performance improvement and predictive maintenance. (Baldi et al., 2022; VanDerHorn and Mahadevan, 2021) Besides IAS, vessels also have other information systems for safety and navigation purposes. Since 2018, vessels with the Gross Tonnage (GT) of over 3000 sailing on international waters are required to have Electronic Chart Display and Information System (ECDIS) implemented onboard. The main purpose of ECDIS is to replace traditional navigation relying on paper charts. ECDIS gathers and displays navigation related data from several sources, such as location data from Global Positioning System (GPS), heading from gyrocompass, vessel's speed log, weather data and radar view of nearby vessels. (Brčić et al., 2019; Brčić and Žuškin, 2019)

ECDIS is an example of a system working in between internal and external information as it combines vessel's endogenous measurement and automation data with exogenous data. Examples of external data from vessel's surrounding operating environment are weather data and Automatic Identification System (AIS) data. Weather and forecast data are received through an Application Programming Interface (API) and can be used for navigation and route planning on ECDIS. (Brčić and Žuškin, 2019) AIS data sharing has been statutory in maritime industry since the beginning of the 21st century. It was originally developed to increase maritime safety by sharing data from vessel to its surroundings by high frequency radio signals from a transceiver. Near-by vessels received the signal either directly or through a coast transceiver spreading the signal to a wider area. AIS enabled monitoring near-by vessels' movements on the ECDIS radar to avoid collisions. Today, AIS data is shared mainly through a satellite connection in high frequency, typically with the span of seconds to couple minutes, containing static, dynamic and voyage specific information. Static information consists of vessel characteristics, like identity and size, dynamic of ship's position, speed, navigation direction and status, and finally destination, draught and estimated time of arrival are voyage specific information. The use of AIS data has evolved from pure safety purposes to many advanced applications such as ship behaviour analysis, environmental impact and emission evaluation, and ship and port performance analysis. Besides vessel specific analyses, today's AIS works as a publicly available near to real-time world fleet monitoring tool and as a global database of all over 300 GT vessels sailing on international waters. (Yang et al., 2019) In addition to AIS, there are other global vessel databases like the ship register maintained by Det Norske Veritas, which contains a lot of vessel specific information like characteristics, configurations and onboard systems, including battery systems. This external data can be used for fleet wide performance monitoring, control and optimization as well as for market situation analysis and predictions. (Det Norske Veritas, 2022a, 2022b)

2.2 Battery as an energy storage

Energy Storage Systems (ESS) have been said to be the biggest “game changer” in vessel power systems since the invention of electrical propulsion. ESS consists of three elements: energy storage, power conversion and power control. (Mutarraf et al., 2018) This chapter focuses on batteries as energy storage devices also discussing the power control systems and strategies, but not diving deeper in the power conversion aspects. The selection of energy storage technology depends on the form of energy and its intended use. Four main forms of storable energy are electrical, chemical, thermal and mechanical. Electrical energy can be stored for example into superconducting magnetic energy storage systems or supercapacitors that typically have relatively high power density (kW/kg) but lower energy density (kWh/kg). This means that they can output high power loads quickly but only for a short duration. Despite the low investment costs, electrical energy storages are not optimal for cruise vessels as they can’t supply power for longer periods of time. Thermal energy storing means capturing heat or cold to be either used directly, like from hot water storage, or transformed into electricity, like from compressed air storage. Flywheel and pumped hydro are options for mechanical energy storing. Flywheel is a heavy metal wheel that holds kinetic spinning energy, which can be stored by accelerating and released by decelerating the spinning motion. Pumped hydro on the other hand stores potential energy by pumping water to a higher location and then releasing it through a generator unit to transform it back to electricity. Both of these options are rather limited in the context of a cruise vessel and they face similar challenges as electrical energy storages such as low energy density. (Palizban, 2016; Skjong et al., 2017) Due to the nature and operating profile of cruise vessels, following requirements have been emphasized for selecting an appropriate ESS:

1. Long lifetime
2. High energy capacity
3. Low cost
4. High energy and power density
5. Safety

Based on the requirement list, chemical energy storage technologies have been found the most suitable for cruise business, batteries being the predicted market leader. (European Maritime Safety Agency, 2020) Besides batteries, electrochemical energy producing fuel cells have shown great potential as a high energy and power density solution, but the technology still faces challenges that need to be overcome before wider implementation in maritime business. When looking at the operation principle of fuel cells, instead of storing energy, they actually generate electricity from hydrogen-rich fuel with electrochemical redox reactions. This is why they have extremely high energy density, but the main challenge is low energy efficiency of only 40 – 60 %, mainly caused by the redox reactions generating a lot of heat as a by-product. With waste heat recovery, fuel cells could potentially achieve the efficiency of over 80 %, but this is still quite low compared to batteries. Besides hydrogen, similar fuel cell solutions are being developed that could utilize other fuels such as LNG or methanol, but these technologies are far less mature. (Melancon, 2022) Some cruise lines, such as Viking Ocean Cruises and Royal Caribbean International, are already piloting hydrogen fuel cell technology, pushing their vessels' sustainability to new levels (Bahtić, 2022; Cullinan, 2022). Different energy storage technologies can also be used together to create a Hybrid Energy Storage System (HESS). HESS enables utilizing the varying benefits of energy storage devices with different characteristics. For example battery-supercapacitor combines the high energy density of a battery with the high power density of supercapacitor becoming a feasible solution for wider range of applications than either of the technologies alone. (Mutarraf et al., 2018; Tang and Khaligh, 2010)

2.2.1 Battery concept

Rechargeable battery technology was invented already in the 19th century, first battery utilizing lead-acid cells. Research on today's most common lithium-ion (li-ion) battery technology started in the 1960s and was commercialized in early 1990s. (Boddula et al., 2020) Battery consists of an electrolyte connecting negative and positive poles, anode and cathode. Typical li-ion battery uses lithium salt as the electrolyte, graphite as anode and metal oxide as cathode. Ions, carrying an electric charge, are transferred from pole to another via electrolyte to store or release energy to the connected electrical circuit. Transferring ions from cathode to anode will charge the battery, and vice versa from anode to cathode will discharge it. Batteries can be placed on different parts of the electrical or hybrid propulsion configuration of a vessel, for example own battery for each propulsion unit or for each genset. In electrical propulsion the most feasible approach is to connect the battery directly to the vessel's microgrid with a power converter, like shown previously in Figure 3. This enables the use of one bigger battery for supporting the whole powertrain, not limited to specific power producer or consumer. However, the energy taken from one centralized battery has to go through several power conversions to serve all consumers, each conversion step creating losses and affecting the system's energy efficiency. (Det Norske Veritas, 2016; European Maritime Safety Agency, 2020)

When battery is used as the energy storage device in an ESS, it can be called Battery Energy Storage System (BESS) (He et al., 2022). Battery generates electricity at Direct Current (DC) and with varying voltage levels. Some vessels' electrical network can also use DC, thus DC-DC power converter between the battery and microgrid is needed to balance the voltage. However, in most cases, especially in electrical propulsion where the service and propulsion power loads are supplied by the same microgrid, Alternating Current (AC) is used. These systems require a bi-directional AC-DC power converter for battery charging and discharging. When a battery is integrated in the power generation system, it can be called hybrid power supply. As mentioned, in the context of this thesis, hybrid power supply is meant when talking about hybrid vessels. Hereby, the term hybrid vessel is not linked to hybrid propulsion vessel, which can but doesn't necessarily have hybrid power supply system. (European Maritime Safety Agency, 2020; Geertsma et al., 2017)

2.2.2 Battery characteristics and limitations

Many characteristics and limitations affect the feasibility and possibilities of batteries for industrial applications. Battery's State of Charge (SoC) refers to the remaining percentual capacity level in the battery. The complement of SoC is Depth of Discharge (DoD) which means the percentage of total capacity discharged from the battery. For example, if a 100 kWh battery has 80 kWh capacity available, the SoC is 80 % and DoD 20 %, and if then 60 kWh is discharged from the battery, the SoC becomes 20 % and DoD 80 %. As demonstrated, the DoD describes the overall capacity discharged compared to full battery capacity, not specific to the charge or discharge cycles. A better variable to describe the battery discharge of a cycle is Delta State of Charge (DSoC), meaning the change of available capacity in one cycle. As in the previous example of a 100 kWh design capacity battery, discharging 60 kWh from the starting point of 80 % SoC will result in 80 % DoD even though the cycle specific DSoC was only 60 %. Only in the starting point of 100 % SoC, the DoD and DSoC of a cycle are equal, but in other cases the DoD can be misleading. (European Maritime Safety Agency, 2020; Zhang et al., 2017) The speed of charging and discharging the battery is described with a C-rate. It’s defined as the charge or discharge current compared to the theoretical current that would charge or discharge the battery in one hour from 0 % to 100 % or from 100 % to 0 % respectively. Hereby, discharging the entire battery capacity in one hour is referred to with 1 C, charging in 2 hours with 0.5 C and discharging in 10 minutes with 6 C. The charge and discharge C-rates can be different for the given battery, but unless separately specified, they can be assumed equal. (Bordin and Mo, 2019) Batteries with C-rate over one are referred to as power-designed as they are capable of providing high power rates in short time. On the other hand, batteries with C-rate less than one are called energy-designed as they are designed to provide continuous energy flow for over an hour. The design choice between power and energy greatly affects the battery’s suitability for different applications. (Tsiropoulos et al., 2018) All these characteristics affect the battery’s lifetime. Advanced battery systems can estimate the battery degradation, meaning the decrease in the maximum achievable capacity. Degradation and battery condition are measured with State of Health (SoH), which is a percentage of the battery’s max design capacity. In case the maximum capacity a 100 kWh battery can reach after time is 95 kWh, the SoH is 95 %. SoC and DoD are relative to the battery’s maximum capacity at the current SoH, so if the SoH is 95 % and available capacity is 95 kWh the SoC is 100 % and DoD is 0 %. (Alnes et al., 2017)

Different metals have been experimented as the anodes and cathodes of batteries creating multiple competing technologies with varying results. European Association for Storage of Energy (2023) lists ten electrochemical energy storage technologies together with their characteristics and suitability for commercial applications. Table 1 below summarizes the key performance measures of these technologies. Maritime suitability has been categorized as good, medium or bad depending on the presented characteristics. Power and energy ranges describe the battery capacity sizes available. Best available discharge rate is presented in the C-rate scale, and the selected C-rate affects the other variables like cycle-life and lifetime.

Battery's response time depends on the operating temperature, but in normal conditions it is some milliseconds for all of the listed battery types. Battery efficiency, also called Round-Trip Efficiency (RTE), means the net energy ratio between discharging and charging the battery. Energy losses happen during the cycle due to power conversions, air and temperature conditioning, internal resistance and heating. However, the efficiency described in the Table 1 below doesn't include the auxiliary power losses of air and temperature conditioning, so it only describes the efficiency after internal resistance and power conversions. Energy density means the battery capacity relative to weight or volume, which is critical in hybrid vessels as the space is limited and weight increases propulsion power demand. Capital Expenditures (CAPEX) estimate the investment cost of a battery relative to energy capacity. CAPEX is affected by the chosen battery capacity and C-rate which is why the cost ranges given here are wide and only guiding.

Table 1. Battery technology summary (adapted European Association for Storage of Energy, 2023; European Maritime Safety Agency, 2020)

Technology / Measure	**Lithium-ion**	**Lead-acid**	**Nickel-metal**	**Sodium-nickel-chloride**	**Sodium-sulphur**	**Flow battery**	**Nickel-cadmium**	***Metal-air***	**Lithium-metal-polymer**	**Sodium-ion**
Maritime suitability	Good	Medium	Medium	Bad	Bad	Bad	Bad	*Medium*	*Medium*	*Bad*
Power range	1 kW to 50 MW	Some MW	Some kW to some MW	Several MW	200 kWh to 50 MW	Some kW to some MW	Some kW to some MW	*Some MW*	*Some MW*	-
Energy range	< 10 MWh	< 10 MWh	< 10 MWh	4 kWh to several MWh	1 MWh to 400 MWh	100 kWh to some MWh	< 10 MWh	*Some MWh*	*Some MWh*	-
Best discharge rate	6C	10C	7C	0.5C	0.1C	< 1C	7C	-	-	-
Cycle life	< 10000 cycles	< 3000 cycles	< 5000 cycles	< 5000 cycles	> 4500 cycles	> 12000 cycles	< 5000 cycles	-	-	-
Lifetime	15 – 20 years	5 – 15 years	10 – 15 years	< 15 years	15 – 20 years	10 – 20 years	10 – 20 years	-	-	-
Response time	Some ms	Some ms	Some ms	Some ms	Some ms	Some ms	Some ms	-	-	-
Efficiency	90 – 98 %	75 – 85 %	60 – 70 %	85 – 95 %	70 – 80 %	70 – 75 %	60 – 70 %	*75 %*	-	-
Energy density	120 – 180 Wh/kg	25 – 35 Wh/kg	75 – 80 Wh/kg	100 – 120 Wh/kg	200 Wh/kg	10 – 25 Wh/L	30 – 70 Wh/kg	-	*100 Wh/kg*	-
CAPEX (energy)	700 – 1300 €/kWh	100 – 200 €/kWh	400 – 700 €/kWh	550 – 750 €/kWh	300 – 450 €/kWh	100 – 400 €/kWh	400 – 700 €/kWh	*150 €/kWh*	-	-

Table 1 can be used to compare the characteristics of different battery types. Some types like lead-acid and flow battery have low energy and power density whereas sodium-ion and lithium-ion provide higher energy and power rates in relation to weight or volume. Sodium-based battery technologies tend to have very low C-rates, meaning that their full charging/discharging will take several hours, which is not optimal for the use cases on a cruise vessel. Metal-air, lithium-metal-polymer and sodium-ion batteries are separated from others as these technologies are not yet commercially available or ready for maritime utilization. Li-ion understandably holds the market leader position, especially in maritime applications, as its characteristics are sufficient on every dimension. Li-ion provides high power and energy ranges, high C-rate, long lifetime, very high efficiency and relatively high energy density. The main challenge of li-ion is the high CAPEX cost and material sustainability and availability. (European Association for Storage of Energy, 2023; European Maritime Safety Agency, 2020)

2.2.3 Battery lifetime

Battery lifetime is an extremely important aspect to consider when planning on integrating a BESS onboard a vessel. Lifetime of a battery can differ greatly depending on the system characteristics and operation profile, and therefore have huge impact on the life-cycle profitability and Return On Investment (ROI). As described in Table 1, typical battery lifetime is between 10 – 20 years in normal use. However, battery technology, capacity, C-rate, cycles, DSoC, DoD, SoC range and operating conditions such as temperature and humidity are factors affecting the lifetime and pace of battery degradation. In most cases, battery is considered to have reached end-of-life at 80 % SoH, but in some applications the suitability for original purpose might be lost even before that. (Mongird et al., 2020) In maritime industry, the BESS design choice is relative to the estimated lifetime of the vessel. Cruise vessel’s typical lifetime is 25 – 30 years, meaning that the battery system will likely need to be updated at least once during its life (Bijwaard and Knapp, 2009). Besides newbuilds, batteries can be retrofitted to existing vessels, which is when the ship’s expected remaining lifetime affects the battery technology selection.

Battery degradation can be divided into operational and calendar degradation, both of which can be controlled by design and usage choices. Operational degradation is typically measured in the number of charge/discharge cycles the battery is capable of, referred to as cycle-life. Three main elements affecting cycle-life are temperature, C-rate and DoD or DSoC. Mongird et al. (2020) suggest that the battery cycle-life can be presented as the function of DoD, where the number of cycles decreases as DoD gets bigger. This relationship is visualized for a li-ion battery as the blue line in Figure 7 below. We can see that discharging the whole battery capacity from 100 % to 0 % is possible only couple hundred times before the battery dies, whereas 10 % discharges can be made 15 000 times. On the grey bars we can also see the total power output, as a multiplier of the full capacity, of the battery during its lifetime depending on the DoD, and it’s clear that the battery is capable of providing more power by decreasing the cycle size. Most lifetime power is enabled with 20 % DoD cycles, but being able to only use 20 % of the capacity in industrial applications would require huge battery capacities to fulfil the energy and power demand. These trade-offs of capacity, cost, cycle size and lifetime must be considered in the BESS integration planning (Battery University, 2021a)

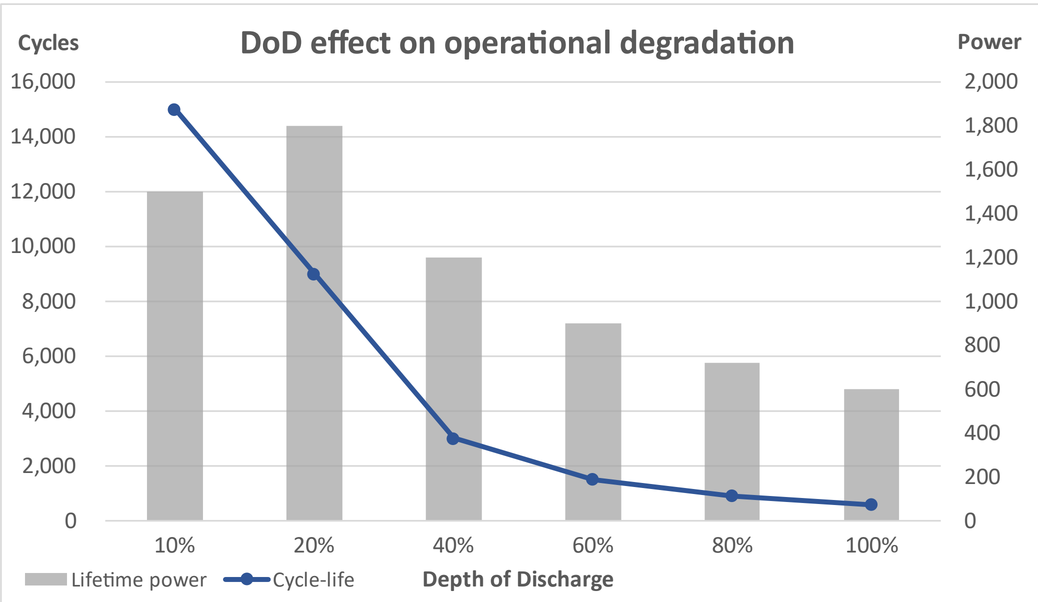

Figure 7. Battery operational degradation (adapted Battery University, 2021a)

Even though DSoC is the most critical factor of operational degradation, the range of SoC also affects the function. Battery voltage differs during charging and discharging, being most stable, efficient and controllable between 20 – 80 % SoC (Ovrum and Bergh, 2015). Fully charging or discharging the battery exposes it to higher voltages and elevated temperatures that make the battery cells wear out faster. This is why batteries are suggested to be operated between 20 – 80 % SoC whenever possible to increase their cycle-life (Al-Falahi et al., 2018). Figure 8 below visualizes this SoC range effect for two example DSoC levels as the function of cycles. The blue and red lines represent same DSoC level of 60 % but the red one is operated from 100 to 40 % and blue from 85 to 25 %. The difference in SoH degradation is clearly visible already after 1000 cycles, being over 2 %. Same trend continues and after 5000 cycles the difference is ~5 %. Orange and green lines follow the same pattern but with a lower DSoC of 50 %. In smaller DSoC levels the range difference is emphasized as the difference in SoH degradation after 5000 cycles is around 7 %. (Battery University, 2021a)

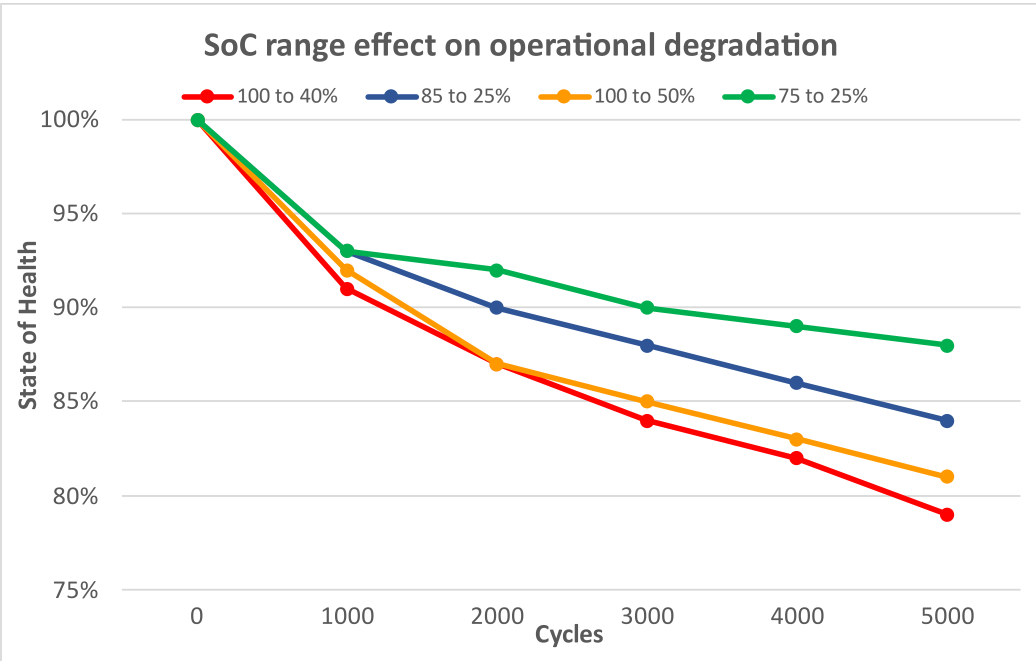

Figure 8. SoC range effect on operational degradation (adapted Battery University, 2021a)

C-rate must also be added to the operational degradation function of a li-ion battery as it greatly impacts the cycle-life due to lithium plating. It means the formation of lithium metal around the anode during fast charging, increasing the internal resistance, decreasing voltage and energy efficiency and lowering the maximum available capacity. For example, the degradation of a 3 C battery can be over four times faster than on a 1 C battery already after 300 to 400 cycles. Even though lithium plating only applies to lithium-based batteries, similar challenges related to high C-rates have been reported on most other battery technologies as well. (Battery University, 2021b)

Final element of operational degradation is temperature. Battery operations are enhanced in higher temperatures as the chemical reactions happen faster. This increases the battery performance and available capacity in short-term, but in the long run it will make the battery cells degrade faster. On the other hand, battery operating on low temperatures has lower efficiency and available capacity, higher resistance and increased safety risks due to thermal instability. (European Maritime Safety Agency, 2020) Zhang et al. (2017) studied lead-acid battery SoH in three different operational temperatures, 15, 25 and 35 ˚C. The degradation to 80 % SoH took 35, 20 and 11 months, respectively. However, in 15 ˚C the battery was only able to provide about 95 % capacity even in the first place, but the lifetime was significantly, over three times, longer than in the higher temperature of 35 ˚C. Optimal operating temperature for most battery types has been defined between 20 to 30 ˚C, but these guidelines mainly focus on the capacity performance instead of emphasizing the lifetime and life-cycle profitability. From the perspective of ROI, enabling longer lifetime by using the battery on lower temperatures and between 20 – 80 % SoC could be beneficial. (Zhang et al., 2017)

Temperature is an element also causing calendar degradation. This means the decrease of SoH over time not related to usage as unwanted chemical reactions happen continuously in the battery. Besides temperature, humidity and storage SoC are factors affecting calendar degradation. Figure 9 below visualizes the calendar degradation of a li-ion battery in one year on different storage temperatures. Blue bars indicate the SoH degradation at 40 % storage SoC and orange bars at 100 % SoC. The orange bar with a pattern on 60 ˚C is an extrapolated estimate, as the measurement was halted in 60 % SoH after 3 months. Graph clearly shows that both higher temperature and higher SoC accelerate the degradation greatly. It’s also notable that the change in SoH of storing a battery at 40 % SoC on 0 ˚C and 25 ˚C is only 2 % and the faster degradation starts in higher temperatures of over 25 ˚C. DNV (2016) has also evaluated the calendar degradation of a li-ion battery as the function of temperature and SoC. Their study shows similar results that on storage temperatures above 30 ˚C the degradation becomes much faster than below that, for example storing the battery in the temperature of 50 ˚C for 5 years wears out the usable capacity completely, similarly 10 years in 40 ˚C. On the other hand, storing the battery with over 80 % SoC lowers the SoH a lot compared to SoC of 60 % and less. It is worth mentioning that storing the battery, especially li-ion, in a very cold temperature or very low SoC is also not suggested, and the optimal storage conditions lie somewhere between 0 – 20 ˚C and 20 – 60 % SoC. (Det Norske Veritas, 2016) Mongird et al. (2020) also studied the degradation on battery efficiency (RTE) over time. Research shows that during 10 years of calendar life the RTE of a li-ion battery dropped to ~96 % of the starting point, referring to almost 0.5 % annual loss in RTE.

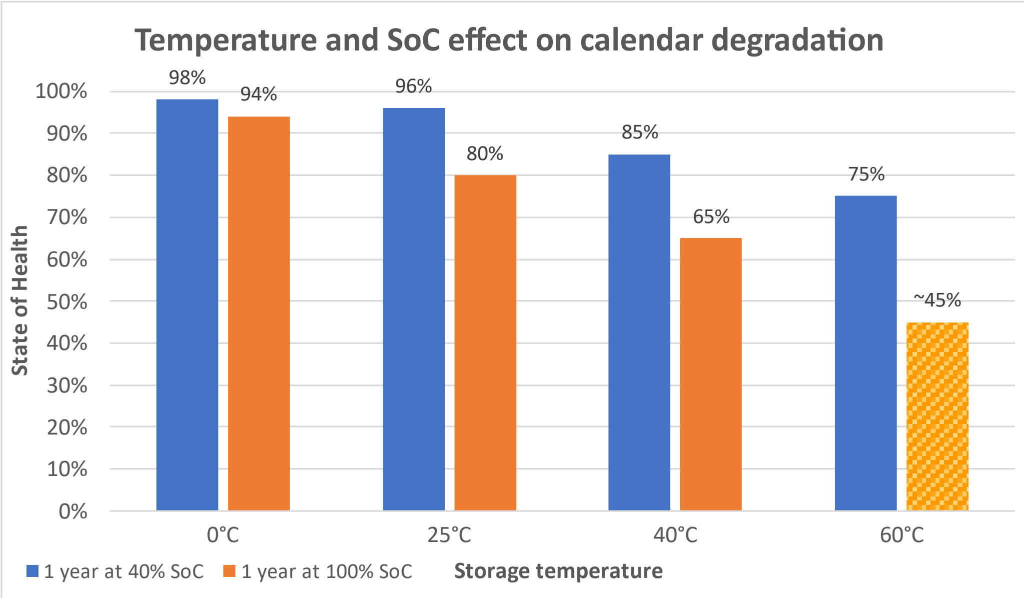

Figure 9. Temperature and SoC effect on calendar degradation (adapted Battery University, 2021a)

Total battery lifetime estimation is difficult as there are so many operational factors affecting it on top of the dependencies on battery technology and characteristics. DNV (2023a) has developed an Artificial Intelligence (AI) based battery degradation analysis tool, that estimates the battery lifetime and capacity degradation based on battery characteristics and operating profile. Some of the inputs given to the tool are battery chemistry, capacity, manufacturer, model year, operating temperature, C-rate, storage SoC and limit values for the cycle usage. The estimation isn't of course 100 % accurate, but it gives an educated guess on the lifetime which can then be used when planning the optimal battery system for the specific vessel's purpose. (Det Norske Veritas, 2023a) To increase the battery lifetime it might be beneficial to implement a BESS with ~40 % more capacity than actually needed, to enable operating on more optimal SoC range between 20 – 80 % (Al-Falahi et al., 2018). Other things to consider in the life-cycle oriented BESS planning are the battery space conditions, such as cooling and ventilation, where it’s possible to improve the battery ROI significantly with proper design choices.

2.2.4 Battery pricing and market development

The costs of a battery energy system can be divided into investment and operating costs. These are commonly referred to as Capital Expenditures (CAPEX) and Operational Expenses (OPEX). In the case of BESS, CAPEX plays a key role in decision making as OPEX is relatively low for the system. Mongird et al. (2020) has broken down the CAPEX into four elements: battery packs, Power Conversion System (PCS), Balance Of Plant (BOP), and construction and commissioning. As the costs are relative to system size, they are measured in $/kW or $/kWh. Most studies only focus on the price of the battery packs, which understandably is the main component when thinking of BESS. However, the cost of the PCS can be as high or even higher than the battery packs’, depending on the capacity and power rate the PCS must be able to handle. According to Baldi et al. (2022) the cost of battery packs in a typical Electric Vehicle (EV), most often a car, represent about 80 % of the total BESS cost, whereas for large capacity maritime applications the share can be as low as 40 %. BOP refers to the supporting auxiliary systems required to keep the BESS stable and operational. The fourth component, construction and commissioning, includes all the system integrating costs such as planning and design, procurement, logistics and installation. These costs together give an idea of the total investment costs of an onboard BESS. (Mongird et al., 2020)

Table 2 below summarizes the CAPEX costs for two common battery technologies with the C-rate of 0.5 C based on three different sources from years 2015, 2017 and 2018. Even though PCS and BOP costs are typically measured in $/kW, they have now been transformed to $/kWh to enable easier comparison between CAPEX components. The construction and commissioning costs are included in the battery pack costs in the table. European Association for Storage of Energy (EASE) has only separated the battery pack cost, but still gives the total CAPEX. The average CAPEX is calculated as the average CAPEX of all three sources. Based on the averages on Table 2, the total investment cost of an example maritime BESS with 6 MWh capacity and C-rate of 0.5 C can be estimated. The cost of such battery with the li-ion technology would be around 5.2 million dollars, of which the estimated price of battery packs would be around 2.8 million. The example CAPEX of a lead-acid battery with same characteristics would be ~3.1 million dollars, battery pack being responsible for ~2 million.

Table 2. CAPEX of two different battery technologies (adapted European Association for Storage of Energy and European Energy Research Alliance, 2017; Mongird et al., 2020; Zakeri and Syri, 2015)

C-rate: 0.5C	Lithium-ion				Lead-acid			
Component	**Mongird 2018**	**EASE 2017**	**Zakeri 2015**	**Avg**	**Mongird 2018**	**EASE 2017**	**Zakeri 2015**	**Avg**
Battery packs	372	250	795	472	436	100	463	333
Power conversion system	144	-	192	168	175	-	189	182
Balance of plant	50	-	40	45	50	-	44	47
CAPEX $/kWh	566	1000	1027	**864**	661	200	695	**519**
CAPEX of 6MWh	**$5,185,000**				**$3,112,000**			

When it comes to life-cycle profitability, the OPEX must be taken into account. As battery system’s lifetime can be as high as 10 – 20 years, even the relatively small operational costs add up. The share of OPEX is estimated to be around 3 % of the total life-cycle costs of an ESS. (Resendiz, 2022) OPEX can be divided into fixed and variable costs, former measured in $/kW-year relative to the battery capacity and latter in cents/kWh-year relative to the battery usage. Fixed OPEX includes costs, such as yearly maintenance, that are necessary to keep the BESS safe and operational through its lifetime. Fixed costs are estimated to be fairly similar for all battery technologies, around 2 – 4 $/kWh/year. Variable OPEX includes all costs relative to the battery usage. This can include usage-based maintenance costs, but also the cost of electricity if the battery is charged from the shore. Variable maintenance costs are typically around 0.3 cents/kWh-year, but the shore electricity price varies a lot, from couple of cents to half a dollar, depending on the location. If the battery is only charged from the engines and the fuel costs are not calculated in the battery OPEX, the yearly cost of a 6 MWh battery is estimated to be around 20 000 $. This seems small in comparison to the multimillion investment cost, but during the, for example 15-year, battery lifetime the OPEX costs can rise to over 300 000 $, excluding the shore electricity costs, and of course depending on the discounting interest rate. (Mongird et al., 2020; Zakeri and Syri, 2015)

The price of li-ion battery packs has been decreasing steadily since the turn of the millennium. Simultaneously, the demand and therefore production has increased greatly, with the annual growth of 26 % since 2010. Small electronic batteries haven't seen any major movements, but the growth in EV batteries has been enormous, jumping from less than 1 GWh production in 2010 to almost 80 GWh in 2017. Even though the biggest mass comes from electric cars, battery powered vessels contribute to the total with smaller quantity but bigger capacity per battery. The average price of an EV li-ion battery pack was around 850 €/kWh in 2010, with a lot of deviation. After steady decrease, the price in 2017 was around 200 €/kWh. This refers to an almost 20 % annual decrease. It is worth noticing that these prices only include the battery pack and do not represent the whole CAPEX. Also, the cost of an electric car's battery is much lower than the cost of larger and more use-case specific vessel battery. That being said, the price and production trends are still applicable for vessel battery packs. Battery market is continuously evolving with new technologies, suppliers and innovations. Multiple potential drivers for price reduction can be identified. Main drivers relate to the increased production volume that has developed the manufacturing process and economies of scale. Besides that, the market has seen production overcapacity and long-term supply contracts that might have also affected the battery pricing. (Tsiropoulos et al., 2018)

The decrease of battery prices is expected to continue in the future. Manufacturing capacity of li-ion battery cells is increasing greatly in near future, main players being China and USA on global level, and Sweden and Germany on Europe level. Energy storage production follows the predictions on increasing trend of EVs, mainly driven by the automotive industry. (Tsiropoulos et al., 2018) Increasing production output has been proven to lower the unit costs due to learning and gaining experience in the manufacturing process. This "experience curve effect" was introduced already in 1936 by Theodore Paul Wright who studied the factors affecting the decreasing cost of airplane production. (Wright, 1936) The learning effect on unit price, also known as Wright's law, is a constant percentual decrease every time the production doubles, regardless of the starting production amount. The percentage depends on the industry, varying from couple of percent up to 30 %, average being around 20 %. This learning effect is one of the main reasons behind the economies of scale which is a key competitive advantage in several companies. Previously the learning effect was driven by labour efficiency improvements due to increasing experience, but the emphasis has shifted significantly to the technological development of the product and manufacturing process. Li-ion batteries have shown a learning rate of 14 %, while for example fuel cells have been found to have even higher learning curve effect of 22 %. In a two-factor study the effect of research and development can be evaluated separately from the general experience effect, and it is shown to be responsible for a much greater portion of the total learning effect for both batteries and fuel cells. (Mayer et al., 2012) Due to the economies of scale and improvements in supply chain, a li-ion battery price drop of 67 % has been forecasted from 2018 to 2025. However, the increasing demand for raw materials, such as nickel, cobalt and lithium required for the production of batteries with current li-ion technology, has been estimated to narrow the price drop to about 30 %. Similar numbers have been predicted also for other battery technologies. (Alnes et al., 2017; Mongird et al., 2020) Tsiropoulos et al. (2018) have brought together multiple studies with battery price forecasts up until 2040. The average estimation is that the price settles into ~100 $/kWh for typical EV li-ion batteries around 2030 and stays in that range. However, Alnes et al. (2017) suggest that the maritime battery costs would vary between 250 – 700 $/kWh in 2030. This is a much higher but also more probable price range for large and complex vessel battery systems with high energy and power requirements.

3 Hybrid vessel performance optimization

Installing a battery to the onboard power system makes it a hybrid vessel, but without proper usage and control the battery doesn't create any benefits. The use of battery has to be planned and optimized to create both monetary and environmental savings. Vessel's internal power demand and supply data plays a key role in the energy optimization, but also external data such as weather forecasts or route plan can be utilized in the equation for example in predicting and optimizing the speed profile and power demand of an upcoming voyage. The main benefit of a battery is being able to run the minimum required number of engines, all in the optimal load that shows the highest fuel efficiency in the engine specific SFOC-curve. Batteries provide multiple use cases aiming for engine efficiency optimization, resulting in reduced fuel consumption and emissions as well as in many other direct and indirect benefits. (Baldi et al., 2022). This chapter discusses the energy management concept and systems on a hybrid vessel and presents different use cases for onboard batteries together with their advantages, limitations and challenges. Also, the life-cycle sustainability impacts of vessel batteries are introduced briefly.

3.1 Data-driven energy management

In the context of BESS, besides battery and converter, the system includes power control (He et al., 2022). The lowest level control is achieved with a Battery Management System (BMS) which is responsible for the safety and performance of the battery. BMS monitors the battery cell's or module's voltage, current and temperature as well as the SoC. Advanced BMSs can also estimate the battery's SoH and communicate it forward to be used in decision making and optimization. Through performance monitoring, BMS can control the battery operation and perform proactive actions to keep the variables within safe limits. If the safety limits, for example for voltage, are exceeded, the BMS will automatically disconnect the battery from the vessel's electrical microgrid. (Alnes et al., 2017; Det Norske Veritas, 2016) Bigger vessels, such as cruise ships, can have multiple battery packs with their own BMSs. These are then connected to and controlled either by a master-BMS or directly by the vessel's Power Management System (PMS) through the power converter. PMS is responsible for matching the vessel's power supply with the demand. This requires continuous IAS data awareness and monitoring of the energy consumption in all parts of the vessel, including both propulsion and service power, and controlling the teamwork between the battery and engines. Vessel's battery system should be fully automated and managed by the PMS without need for manual interaction by the crew. The importance of PMS is significant in terms of safety, reliability and availability. When talking about the whole vessel's energy flow and efficiency improvement, Energy Management System (EMS) is required. It can either be in charge of the power management or communicate with a separate PMS. Besides responsibilities, EMS is the main tool for data-driven performance and efficiency optimization utilizing batteries. (Det Norske Veritas, 2016) Hybrid vessel's microgrid management is visualized in Figure 10 below.

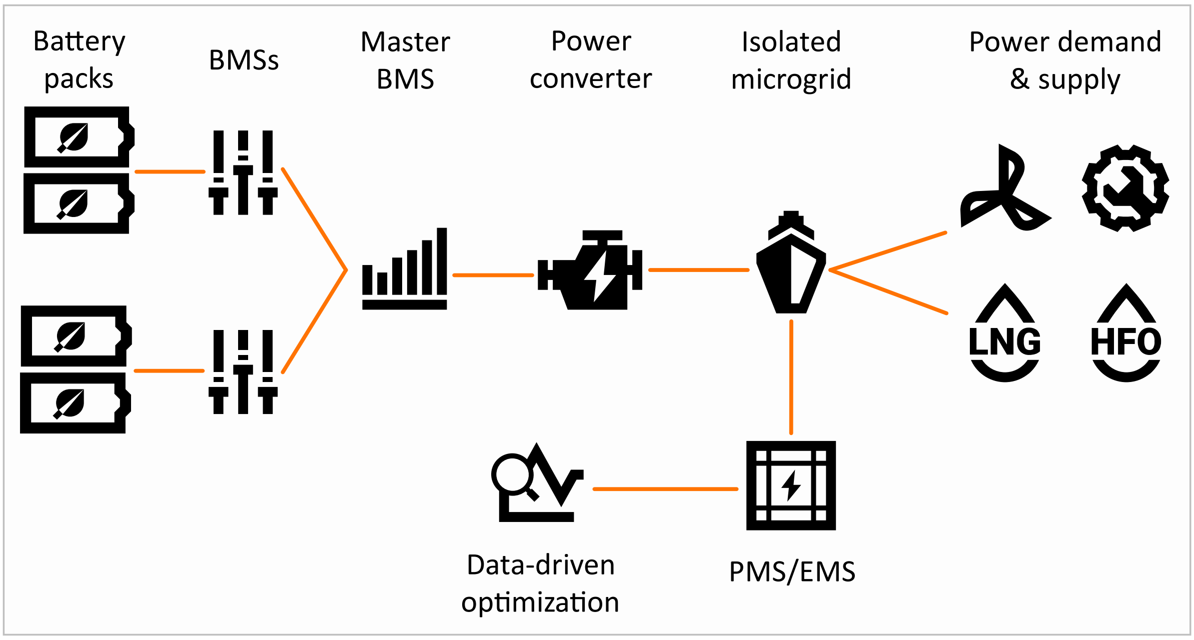

Figure 10. Battery and microgrid management (adapted Det Norske Veritas, 2016; Solovev and Petrova, 2021)

Cruise vessel's isolated microgrid can be controlled in many ways and with different approaches. Figure 11 below presents the four levels of hierarchical microgrid control. The lowest level of the hierarchy can be called level zero as there is no actual control strategy implemented. On this level the basic microgrid variables such as voltage and current are controlled and kept in safety limits by the various individual power systems and energy sources onboard such as generators and BMSs. The purpose of the lowest level is to keep the microgrid operational, and no optimization is done. (Palizban, 2016) Next on the primary control level power converters are used for balancing the grid variables making the system stable and controllable regardless of operating conditions. This increases the reliability and availability of the microgrid which is crucial for electric propulsion vessels. Even though primary control is responsible for power sharing across the vessel, no efficiency optimisation is applied. (Jin et al., 2016; Unamuno and Barrena, 2015) In the secondary control of hybrid vessels the PMS steps in taking responsibility for balancing the power demand and supply and performing grid wide voltage and frequency control ensuring sufficient power quality. Secondary control is divided into grid-connected and island modes. Island mode is the isolated approach used in cruise vessels as they are typically never connected to another microgrid of the same level. Balancing power production with the consumption reduces redundant power and losses, creating higher efficiency compared to the lower control levels. (Geertsma et al., 2017; Palizban, 2016)

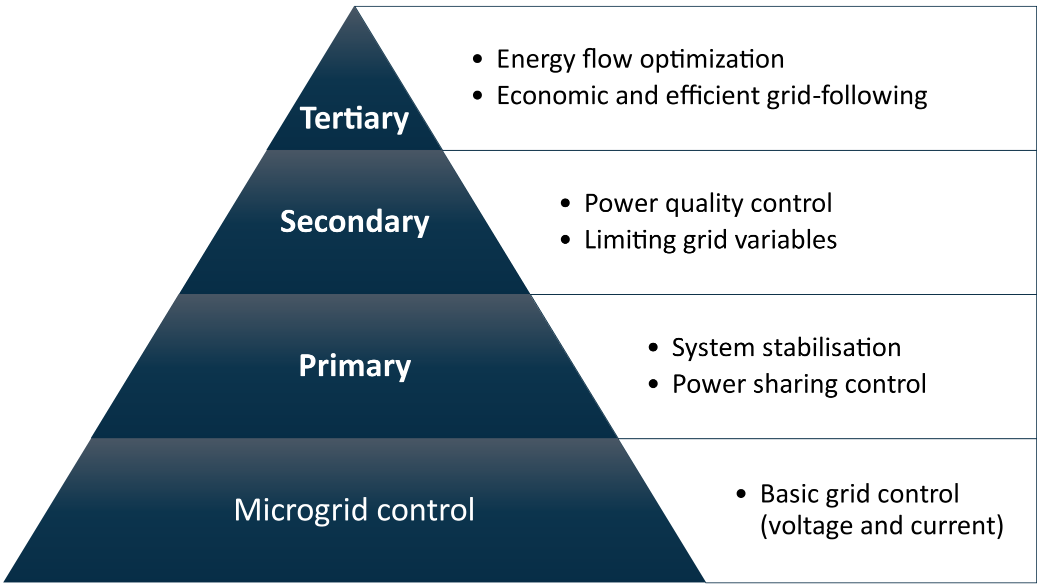

Figure 11. Hierarchical microgrid control (adapted Jin et al., 2016; Palizban, 2016)

The highest level in the hierarchical control pyramid is tertiary, where the vessel’s whole energy flow is monitored and controlled by the EMS. Just like secondary control, tertiary control can be divided into island and grid-connected modes. However, in this case the connected grid refers to an upper-level utility grid instead of another microgrid. This mode is activated when the vessel is connected to the local shore electricity grid and EMS performs grid-following. This means balancing the variables directing the power to defined consumers, for example covering the service power demand and charging batteries from the shore grid. In the island mode, EMS operates in the vessel's microgrid optimizing energy flow based on the selected grid control strategy. (Geertsma et al., 2017; Jin et al., 2016) Palizban (2016) also adds a possible fifth level to the pyramid being business planning and logistics, but the market structure and business model aspects of microgrid are not as relevant in the context of a mostly isolated hybrid cruise vessel.

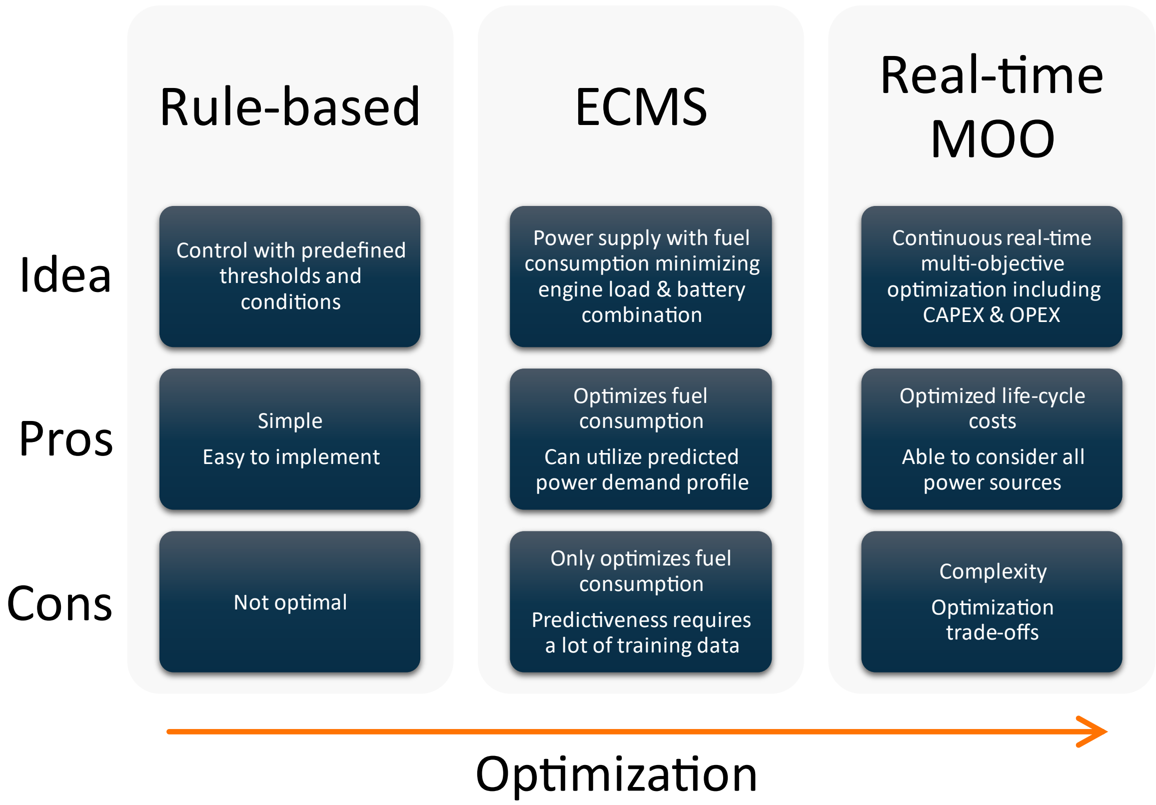

Figure 12. Smart grid control strategies

Tertiary level optimization strategies are called smart grid control strategies, focusing on performance and efficiency optimization with different approaches. The three main strategies, summarized in Figure 12 above, are rule-based control, equivalent consumption minimization and real-time data-based optimization. The simplest of the strategies is rule-based control. In this strategy EMS controls the microgrid with pre-determined configurations, like operating modes. EMS monitors the vessel's operation from grid and IAS data and performs specified actions when given conditions are fulfilled. For example, when the vessel's speed drops under a specified threshold and thrusters are activated, EMS can activate the manoeuvring mode that uses one or two gensets as main power source and any excess power demand is taken from the battery if the SoC is above some specified limit. Rule-based control is an easy and possible strategy, but considering the complex nature of cruise vessel's energy management and optimization, rule-based strategy doesn't harness the full potential of hybrid power supply. (Baldi et al., 2022) Equivalent Consumption Minimization Strategy (ECMS) is the next advanced control strategy performed by EMS. It means managing the vessel's power load with optimal setpoints calculated from a function minimizing the total fuel consumption, considering both engine's fuel consumption and the equivalent fuel consumption used to charge the battery. ECMS function finds the optimal split of power coming from the engines and batteries, aiming for engine load levelling based on optimum SFOC, also taking into account the battery SoC. ECMS can either be reactive or predictive, based on the availability of upcoming power demand profile. Model predictive ECMS optimizes the power generation mirroring the estimated power demand, enabling for example battery charging before predicted consumption peaks during port arrival. Power load estimations can be done with simplifying calculations, but due to the varying nature of cruise vessel's power demand, especially on the service power, the help of artificial neural networks or regression models might be beneficial. However, these methods need a lot of training data to find the optimum power management approach, but can be well trained during the 25-30 year lifetime of a cruise vessel. (Baldi et al., 2022; Vu et al., 2015)

Most advanced microgrid control strategies perform real-time optimization based on continuous EMS data analysis. These strategies provide maximal savings potential on any given element, but since the function complexity increases greatly, the simpler optimization solutions are currently more common in maritime applications. Typical control strategies focus on optimizing fuel consumption and cost efficiency, but they can be further developed into multi-objective optimization models also considering emissions, battery lifetime and life-cycle profitability by analysing numerous additional data variables. Even though fuel consumption is the vessel's main operational cost element, battery usage has major impacts on its lifetime, and as the investment and replacement costs for large maritime battery systems are several millions, the multi-objective optimization strategy can outperform regular ECMS in the long run. Additionally, EMS is not limited to batteries and can be developed to include all available power sources together with their characteristics and optimal use cases on a hybrid vessel. EMS can for example consider using supercapacitor for engine load levelling if batteries are not available, or charge batteries from fuel cells if hydrogen is cheaper than shore electricity in the next destination port. Each additional element and input data source increases the complexity of the system and finding the absolute optimum, so continuous EMS development is required to get the most benefit out of the new green and innovative power sources. (Dall'Armi et al., 2021; Tang et al., 2020)

3.2 Battery enabled performance optimization possibilities

Onboard BESS offers a variety of performance optimization possibilities for cruise vessels throughout the operation from port to port. The main idea behind using a battery is disconnecting the direct link between power consumption and production. This means enabling a time shift in power management, in other words generating energy at a different time than using it. In conventional power supply of an isolated microgrid the generation must always meet the consumption. Exceeding the power demand creates waste energy that is lost, and on the other hand falling short of the demand results in power shortages and system disfunctions that can have severe consequences on vessel safety and controllability. With onboard batteries a defined portion of the power can be generated and stored before consumption and then be used whenever needed. In normal shore utility grids this enables storing energy when the price or usage is low and using it when the price or demand increases. In maritime business this enables controlling the number and load of engines running at different times independently from the consumption, having major impacts on the fuel and emission efficiency. (Ritari et al., 2020; Zakeri and Syri, 2015) The main optimization possibilities enabled by an onboard battery can be divided into three categories and their sub-categories. Their relationships and key benefits are summarized in Figure 13 below.

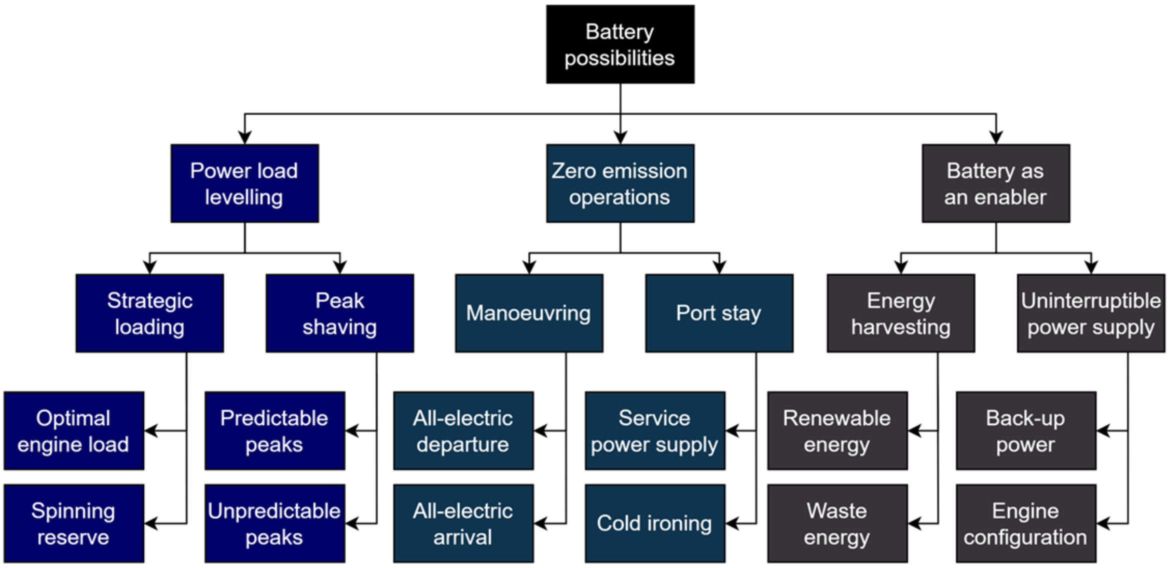

Figure 13. Onboard battery possibilities (adapted Alnes et al., 2017; European Maritime Safety Agency, 2020)

3.2.1 Power load levelling

Electricity grid power demand can vary greatly during the day and operation, depending on the consumers. Slowly or steadily increasing or decreasing power demand variations are called fluctuations. Normal shore utility grids face fluctuation hours mainly depending on the time of the day when the consumption is most active. (Zakeri and Syri, 2015) Cruise vessels also face predictable service power demand fluctuation related to the time of the day, for example high demand during the dinner time when galley devices are used, and low demand during night when entertainment services are closed and most passengers are sleeping. High and rapid demand fluctuations, occurring typically during manoeuvring, are called peaks that require fast response from the power supply system. Demand peaks can be categorized as predictable and unpredictable peaks, requiring different actions from the power supply. Quick changes in power generation cause challenges and inefficiencies that can be addressed with energy storage systems. (Geertsma et al., 2017)

Strategic loading

The main cost and emission reduction benefits on hybrid vessels are achieved by power load levelling. This means supplying the fluctuating power demand with an optimal combination of power sources in each situation, which is enabled by the previously mentioned direct link disconnection of power demand and supply. The actual monetary and environmental savings are based on the engine specific SFOC-curve, pictured earlier in Figure 4. Power load levelling can be viewed with two approaches, strategic loading and peak shaving. Strategic loading means supplying the fluctuating power demand with the combination of optimally operated engines and batteries. Based on the SFOC-curve, engine's fuel efficiency is relative to the MCR, meaning that running the engine on higher loads uses less fuel compared to the output power than running it on low MCR. (Ritari et al., 2020) According to Baldi et al. (2022) and Ritari et al. (2020) the optimal load for maritime diesel engines is around 85 %. By utilizing batteries, the engine load can be optimized regardless of power demand and its fluctuations.

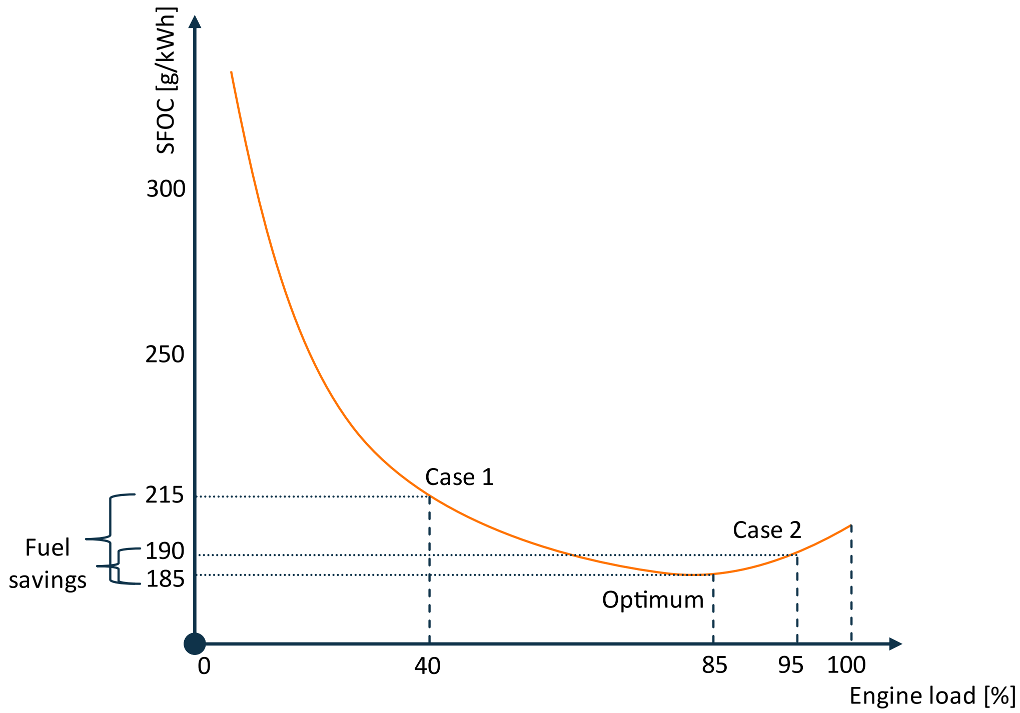

Figure 14. Fuel savings of strategic loading (Alnes et al., 2017)

Figure 14 above visualizes strategic loading and its benefit. Here in case 1, we can clearly see that when the vessel's power demand is low, in conventional power supply the engine would be ran on 40 % load with specific fuel oil consumption of 215 g/kWh. In hybrid power supply the engine could be run on optimal 85 % MCR with SFOC of 185 g/kWh and the excess energy would be stored to the battery for later use. In the second case, power demand increases, requiring 95 % of the engine's max load where the SFOC value increases above optimal range to 190 g/kWh. This time battery could be discharged to supply the extra 10 % of energy, enabling the engine to stay in the optimal operating load. (Alnes et al., 2017; Sorensen et al., 2017)

Table 3. Fuel consumption savings of optimal hybrid power supply (adapted Wärtsilä, 2019)

Engine's MCR: 14400 kW	**Case 1**		**Case 2**	
System	**Conventional**	**Hybrid**	**Conventional**	**Hybrid**
Engine load	40 %	85 %	95 %	85 %
Power demand [kW]	5760	5760	13680	13680
Engine power output [kW]	5760	12240	13680	12240
SFOC [g/kWh]	215	185	190	185
Engine fuel consumption [kg]	1238	2264	2599	2264
Battery charge power [kW]	0	6480	0	0
Battery discharge power [kW]	0	0	0	1440
Battery equivalent fuel consumption [kg]	0	-1199	0	266
Total fuel consumption [kg]	1238	1066	2599	2531
Fuel savings		**14 %**		**3 %**

Example of the strategic loading savings achieved by optimal hybrid power supply is presented in Table 3 above. The calculations are comparing the two previously described imaginary case situations (Figure 14) to the optimal power generation for one hour of operation with the Wärtsilä 12V46F four-stroke diesel engine. The engine's maximum continuous power is 14400 kW and optimal load around 85 % MCR, referring to 12240 kW power output. (Wärtsilä, 2019) In the first case, only 40 % of the engine's max load is needed to supply the power demand. In conventional power generation system, the total fuel consumption would be 1238 kg with the SFOC of 215 g/kWh. In case of hybrid vessel, the engine could have been run on optimal load, using the excess power to charge the battery. Here the engine's absolute fuel consumption is obviously larger, but after subtracting the equivalent consumption of stored power, the relative fuel consumption is 14 % less than in the conventional system, excluding battery RTE. In the second case, power demand equal to 95 % of the maximum engine load is required. By running the engine on optimal 85 % MCR and taking rest of the demanded power from the battery, which was charged with optimal engine load, the fuel savings in one hour operation are 3 % (excluding RTE). These savings are only examples of imaginary but possible battery use cases.

The other part of strategic loading is the number of engines running. In many situations, for example in manoeuvring, the vessel's power demand varies a lot and enough engines need to be running to be able to answer the possibly increasing demand. This power buffer is called spinning reserve, and it leads to having several engines running on non-optimal low loads consuming unnecessary high amounts of fuel. (Zahedi et al., 2014) DNV has set minimum spinning reserve limits for vessels in specific situations to ensure sufficient power supply for critical loads, such as propulsion and vessel control, to comply with safety standards (Alnes et al., 2017). Batteries can address this problem by acting as the spinning reserve, meaning that at least one buffer engine can be shut down and other ones can be run with higher efficiency. Battery enabled strategic loading and optimum number of engines running are dependent on the available battery capacity. If the battery SoC is low, it is beneficial to turn on a new engine earlier than required by the power demand to charge the battery while operating on optimal engine load. Similarly, if the battery SoC is high, the start-up of a new engine can be delayed until the situation when it can be run on optimal load or battery SoC has decreased to a specified lower limit. (Geertsma et al., 2017; Mo and Guidi, 2018).

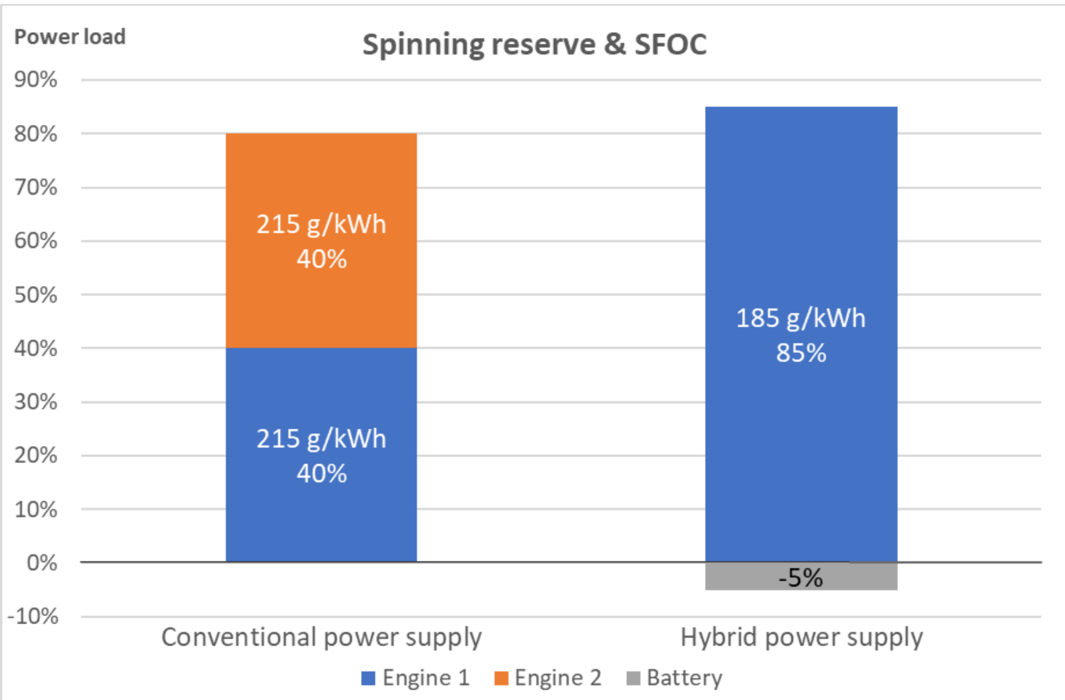

Figure 15. Spinning reserve on hybrid vessel

An example of spinning reserve is visualized above in Figure 15. Power demand in the pictured situation requires 80 % of one engine’s power load but additional spinning reserve is required for example for using thrusters. In conventional power supply system, two engines would need to be ran, both on 40 % load so that there is technically 120 % spinning reserve available from the two engines together. Here the SFOC of both engines is 215 g/kWh. In hybrid power supply, one engine could be shut down and the other one ran on optimal 85 % power load, where the SFOC is 185 g/kWh. In this situation the battery would be charged with the exceeding 5 % of engine power output, but if the power demand increases, battery can automatically by EMS be switched to discharge energy to supply the need. Here the battery capacity, together with the one engine’s reserve, must be sufficient to supply even the highest expected power demand spikes, so available battery capacity of 105 % of one engine’s max power would equal the spinning reserve of conventional power system in a short time period. For one hour spinning reserve this would mean ~15 MWh capacity, which is currently higher than any existing vessel’s BESS capacity, but for half an hour spinning reserve a battery with at least 7.5 MWh capacity and C-rate of 2 C would be sufficient and possible with the li-ion battery technology (Corvus Energy, 2023a).

Peak shaving

The other approach of power load levelling is peak shaving, which is one of the first and main functions of batteries in hybrid vessels (Corvus Energy, 2023a). The basic principle of peak shaving is similar to strategic loading, but the power demand characteristics are different. Rapid and high peak loads require much faster reaction than normal demand fluctuations. Peak loads typically occur during manoeuvring when the vessel control is crucial and thrusters are used. (Geertsma et al., 2017) Power demand can easily vary over half a mega-watt in just few seconds. To answer the fluctuation, conventional power supply system would need to rapidly change the engine load and have a lot of spinning reserve. Besides reduced fuel and emission efficiency, high load steps can harm the electricity generator and create safety risks. (Alnes et al., 2017; Sorensen et al., 2017) This is where batteries unleash their potential. Batteries with sufficient C-rates can provide high power loads rapidly, enabling the engine to stay on optimal and safe operation. Unlike fuel cells, batteries can also store the excess energy when the peak is negative, meaning a sudden drop in the power consumption. (Melancon, 2022; Skjong et al., 2017)

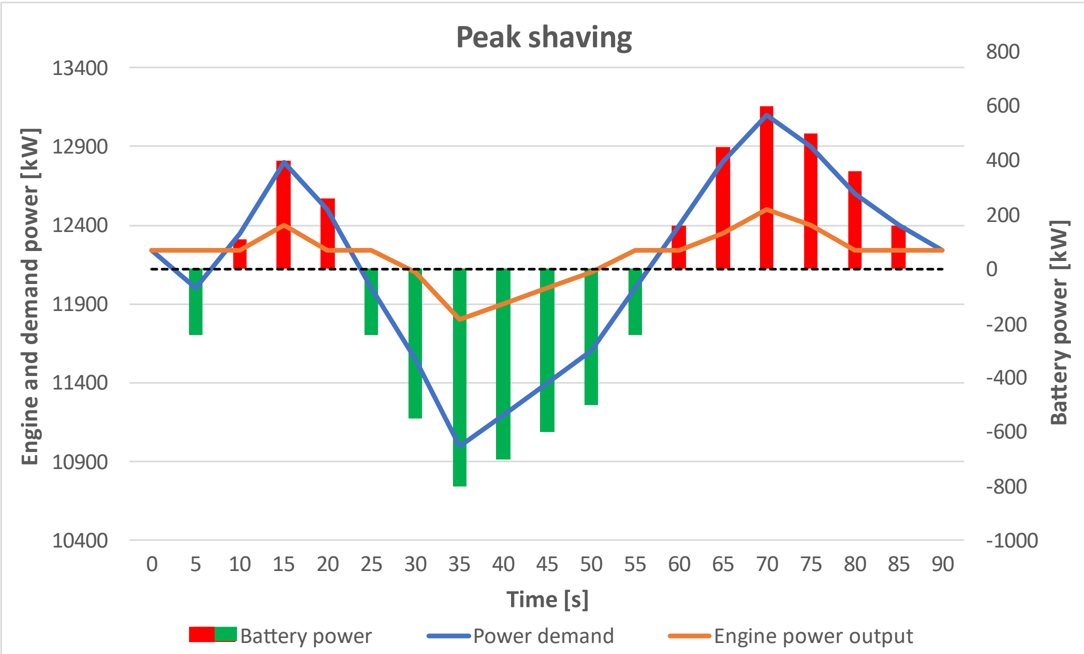

Figure 16. Peak shaving

Example of demand peaks and peak shaving is visualized above in Figure 16. Blue line represents the fluctuating power demand as the function of time. In conventional power supply the engine power output (orange) would strictly follow or exceed the demand (blue), but in this example of a hybrid vessel, battery is charged (green) and discharged (red) to shave the highest peaks to keep the engine operation as close to optimal load as possible, here 12240 kW. With optimal real-time data-driven EMS control strategy and high C-rate, battery could be used to absorb all of the power variations, but major benefits are already achieved by shaving and levelling the highest power demand peaks.

Sometimes demand peaks are hard to predict, for example when suddenly changing course or accelerating in the middle of the sea due to an emergency, so the availability of spinning reserve is not guaranteed. (Alnes et al., 2017) These unpredictable situations would require turning on a new engine which in maritime applications is a much heavier process than for example in automotive industry. Starting of a vessel engine requires warming up, connecting to the microgrid and increasing the load steadily to the required level. This process might, depending on the ship and engine, take from a minute up to ten minutes which is not sufficient to supply unpredictable demand peaks happening in seconds. (Baldi et al., 2022; Shagar et al., 2017) Batteries can prevent the need to turn on a new engine by shaving the demand peaks such that the total required power is supplied by the running engines combined with discharging the battery. Also, smaller but rapid power peaks occurring continuously on vessel's microgrid can be absorbed by batteries. These small demand spikes wouldn't require starting up a new engine or much spinning reserve, but they constantly sway the engine back and forth away from the optimum load. (Alnes et al., 2017)

3.2.2 Zero emission manoeuvring and port stay

European Maritime Safety Agency (2020) has stated that "While batteries can fully power a vessel for a short distance or duration, improving performance and energy efficiency of the overall vessel is often the key purpose." The main fuel and emission savings achieved with batteries come from optimizing engine operation. However, hybrid system's advantages are not limited to power load levelling and can be extended to all-electric operation, which is not possible with conventional power supply. This means operating the vessel fully with batteries. When talking about massive cruise vessels sailing long distances on varying routes, all-electric voyages are not possible with the current technology. Nevertheless, hybrid cruise vessels can switch to all-electric mode for short durations or distances when beneficial, for example when entering, staying or leaving port. This can create minor monetary benefits, but the main reason behind it is the totally engine- and emission-free operation. (European Maritime Safety Agency, 2020)

All-electric manoeuvring

Port arrivals and departures are done in manoeuvring mode, where the vessel operates with reduced speed, increased need of controllability and high power demand peaks. Conventional manoeuvring requires several mega-watt hours of spinning reserve, thus consuming a lot of fuel and creating high emissions in port area. This is not optimal, especially as cruise vessels typically visit ports that are on central locations close to cities or exotic areas. Since 2015, IMO has regulated the harmful sulphur and small particle emissions by setting thresholds on specified vulnerable or key locations called Emission Control Areas (ECA). On these areas vessels can't for example burn HFO without having scrubbers that reduce the otherwise high sulphur emissions. (Skjong et al., 2017) All these manoeuvring challenges can be addressed with hybrid power supply, which can with sufficient battery capacity be switched to all-electric zero emission mode by shutting down all engines and supplying the fluctuating power demand fully with batteries. Besides emission advantages, battery powered manoeuvring can also create monetary benefits depending on the shore electricity price and availability of shore power connection. Considering the differences in battery and engine efficiencies, the electricity costs might be lower than the fuel costs, meaning that discharging all extra battery capacity before arriving at port, either in all-electric or hybrid mode, could reduce the operating costs. (Al-Falahi et al., 2018; European Maritime Safety Agency, 2020) Assessing the life-cycle costs of all-electric manoeuvring compared to hybrid manoeuvring requires taking the battery investment cost and degradation into account (Baldi et al., 2022).

Zero emission port stay

The other part of port area operation is the port stay. Cruise vessels are typically docked to a pier enabling the passengers to get off the ship and explore the destination. Even though the vessel is stationary and propulsion power is zero, service power demand stays rather stable. In conventional power supply this would mean having at least one main engine running, typically with non-optimal or varying load, consuming fuel and creating emissions. Cruise vessels have two ways to avoid using engines during port stays. The best solution is cold ironing, which means using shore power by connecting the vessel's microgrid to the shore utility grid which is then used to supply the service power demand. (Alnes et al., 2017; Kanellos et al., 2015) Not all ports have shore power available, but the number is continuously increasing as shore power can create a win-win situation for both the vessel and port. Vessel can use shore electricity which depending on the location can be cheaper and cleaner than using fuel. On the other hand, besides eliminating emissions the port can sell electricity on slightly higher price than the current shore energy price to cover the infrastructure investment cost and make profit. (Baldi et al., 2022; Rantio, 2015)

Cold ironing can be implemented to a cruise vessel regardless of the power supply configuration. In case of hybrid power supply, shore power can also be used to charge the batteries. This again reduces the fuel consumption and emissions as batteries are not charged from the engines. If the port doesn't have shore power available, the other option for zero emission port stay for hybrid vessels is using batteries. The feasibility of battery-powered "cold ironing" depends a lot on the service power demand, duration of the port stay and battery capacity. If the vessel plans to use batteries during the upcoming port stay, they need to charge them from the engines before arriving at the port to have enough energy stored. This isn't optimal from cost nor emission point of view, but it enables creating the emissions in the middle of the sea instead of polluting at the port. (Baldi et al., 2022; Ovrum and Bergh, 2015) Other alternative power sources such as fuel cells could also be used for zero emission port stays (European Maritime Safety Agency, 2020).

3.2.3 Battery as an enabler

Besides the use cases aiming for direct and indirect fuel and emission reductions, batteries can be seen as an enabler for a few other functions. Energy harvesting and Uninterruptible Power Supply (UPS), listed in Figure 13, are two example BESS use cases that can support the main power sources and improve their efficiency and reliability.

Energy harvesting

Energy harvesting means collecting and storing energy from different onboard sources to be used later. Energy harvesting enables using Renewable Energy Sources (RES) such as solar, wind and wave power. (Ovrum and Bergh, 2015; Zhang et al., 2017) The use of onboard RESs is not very common on cruise vessels due to their characteristics and operating profile. Unlike merchant vessels, such as oil tankers and bulkers, cruise vessels have very limited amount of flat surfaces available for solar panels, as almost all surfaces are occupied for passenger entertainment purposes such as balconies and pools. Similar challenges are faced with wind power on cruise vessels, as they would need to have some sort of sails taking a lot of space and affecting the visual attractiveness of the vessel. (Alnes et al., 2017; Eco Marine Power, 2023) These challenges can be addressed with innovative solutions, one example being the EU-funded Envision project integrating solar power generation to all surfaces, even on windows (European Commission, 2023). By further technological development, wave power could be feasible also for cruise vessels, but the energy levels and availability are still relatively low and can only support the main power suppliers (Wello, 2023). The main challenges with RESs are low energy efficiency, insufficient power levels for maritime applications and fluctuating availability of energy.

Other part of energy harvesting is storing waste energy from other onboard systems. Vessel engines create a lot of heat as a by-product of the combustion process. Waste Heat Recovery (WHR) means re-using the heat as an energy source onboard. The heat can either be used directly for example to boil water, but it can also be transformed to electricity and stored to a BESS to be used in the propulsion. WHR and energy conversions create losses, but without energy harvesting the energy would be completely wasted. (Baldi et al., 2022) Waste energy is also created by other onboard activities such as braking. Regenerative braking energy, from the vessel or other mechanical onboard systems such as cranes, can be stored and re-used with batteries. However, regenerative braking potential is very limited in the context of cruise vessels as they don't use active braking or have heavy cranes onboard. (Baldi et al., 2022; Geertsma et al., 2017)

Uninterruptible power supply

UPS is another function enabled by onboard batteries. It means having instant back-up power continuously available. UPS is similar to batteries acting as spinning reserve, but also includes other situations than predicted power demand peaks. Where increasing the engine load takes multiple seconds, batteries are capable to react immediately, with the response time of milliseconds, to the changing power demand. This increases safety, controllability and efficiency. (European Maritime Safety Agency, 2020) Back-up power can also be used in an engine or system failure situation, eliminating power shortages and downtime (Solovev and Petrova, 2021). As batteries can function as UPS, less engines and total installed power might be needed onboard. Cruise vessels typically have 4 – 6 main engines, each of them capable of producing several mega-watts of power, maximum varying between 1 – 20 MW. The average power of a conventional cruise vessel engine is ~10 MW meaning that the average installed power, consisting of all power sources onboard, is ~50 MW. Engine number and power is of course dependent on the size of the vessel, largest cruise vessels having 6 over 15 MW engines with the total installed power closer to 100 MW. In normal conditions, cruise vessels basically never sail with all engines running at the same time.

(Wärtsilä, 2023c) By installing batteries, cruise vessels could be configured to have one engine less, as the extra power is only needed in engine malfunction or blackout situations. This way the purchase cost of one main engine could be subtracted from the investment cost of a BESS, which increases its feasibility. (Dedes et al., 2012; Skjong et al., 2016)

Battery possibility summary

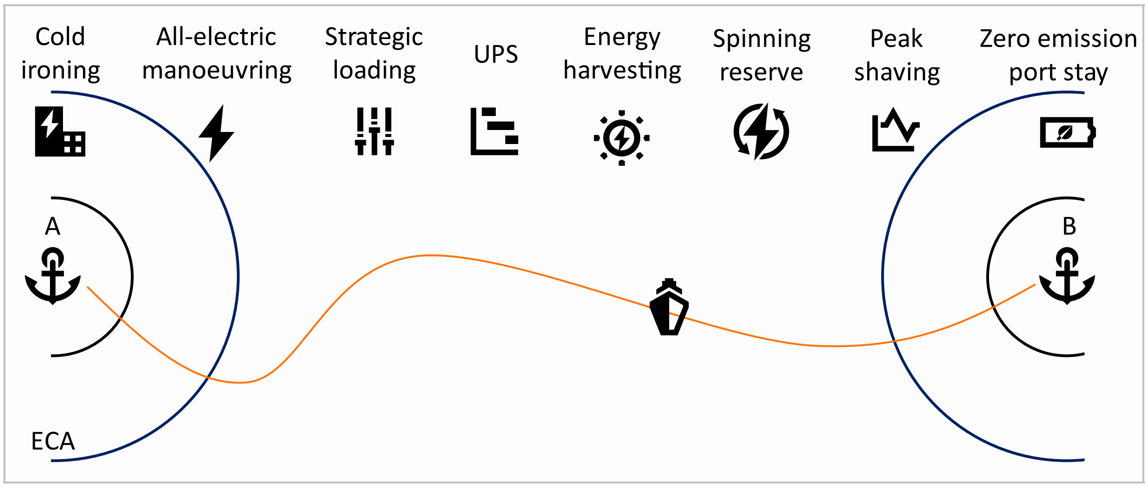

Figure 17. Battery use cases from port to port

Figure 17 above summarizes the onboard battery use cases divided to a single voyage from port A to port B. Port A, marked by the black circle around the anchor, offers shore power connection, which is used for cold ironing and charging batteries. After port departure, vessel starts all-electric manoeuvring, performed inside the blue circle, which in this case is an ECA defined by IMO. After manoeuvring, vessel starts up the main engines and begins sailing on optimal engine number and load combination, strategic loading supported by batteries. Batteries enable UPS, energy harvesting and spinning reserve for the whole voyage without consuming any extra fuel, rather saving it. When entering the coastal waters of port B, few engines are shut down and the remaining ones are supported by battery-based peak shaving. As the port B doesn’t have shore power available, but values low emissions, battery is used to supply the service power demand during the port stay.

3.3 Power generation performance improvements through BESS

Onboard battery system can be utilized in many ways and in many situations resulting in different type and scale of improvements and benefits. These advantages can be linked either directly to business value or to the overall vessel performance optimization. Thus, the benefits can be viewed from different perspectives and mirrored to the vessel's power generation performance criteria introduced in the chapter 2.1.2 . In the context of a cruise vessel, battery can't be directly compared with an engine because all-electric cruise vessels are currently not feasible. However, hybrid power supply can be compared with the conventional one and assessed within the performance criteria. The main monetary benefit of batteries comes from the reduced fuel consumption. Optimally used BESS has potential to reduce the vessel's fuel consumption by several percent, depending on the operating profile, e.g. time spent in manoeuvring. Power load levelling together with all-electric manoeuvring and charging from the shore will decrease fuel consumption notably. On top of fuel, diesel engines require other consumables, such as lube oil, the consumption of which is also reduced. Even though there aren't yet many real life examples of battery hybrid cruise vessels, energy efficiency has been proven to be improved on hybrid power system. (Geertsma et al., 2017; Sorensen et al., 2017)

The second most important performance criteria is the emissions. Besides Carbon Dioxides (CO_2), burning fossil fuels emits Sulphur Oxides (SO_x), Nitrogen Oxides (NO_x) and Particulate Matter (PM), which are hazardous both for people and for the environment (Abbasov, 2019; Sofiev et al., 2018). Multiple drivers like regulation, customer and company values, brand and image are forcing maritime business to emphasize emission efficiency and take actions to continuously improve it. Emission efficiency follows the fuel efficiency, meaning that when the engines are operated on optimal SFOC level, the emissions are also minimized. Hereby, batteries have the same emission reduction potential by power load levelling and peak shaving, compared to conventional power supply. It is worth mentioning that different fuels create different amount of emissions, and the more environmentally friendly fuels are typically more expensive, which creates the trade-off between cost and emissions (PBT International NV, 2023). Besides reducing emissions through reduced fuel consumption, batteries can replace the use of fuel completely for a short period of time in all-electric zero emission operation if batteries have been charged with shore power. In this situation the vessel doesn't create any emissions, but the overall emission efficiency depends on the origin of the shore electricity, which can be generated for example by emission-free RESs or by burning coal which produces very high emissions. The third option enabled by batteries is controlling the time and place of creating the emissions, for example charging batteries from engines during sailing and then performing all-electric manoeuvring and port stay. This option of course doesn't affect the emission efficiency, but creates other advantages such as greener brand and public health benefits for people living near the port area (Sofiev et al., 2018).

Propulsion availability and manoeuvrability criteria can be viewed together as they both affect the vessel's controllability and safety. Total power losses and engine blackouts create risks of damaging the vessel and its surroundings, risking passengers' lives and also leading to financial penalties. Sufficiently designed battery system has the capability to serve as an UPS, also covering the need for spinning reserve. (Skjong et al., 2017) Peak shaving specifically improves the performance of dual fuel engines, as they are sensitive to high and rapid load fluctuations, which might require the vessel to change from gas to liquid fuel to address the dynamically varying power demand. This is important in today's cruise business because dual fuel engines, enabling the use of new fuels like LNG, are becoming more and more popular as they have greatly reduced emissions compared to traditional diesel engines running with HFO and MGO. (Baldi et al., 2022; Bordin and Mo, 2019) By providing immediate power and shaving the demand peaks during manoeuvring, besides energy efficiency, the hybrid system has higher performance compared to the conventional one. Yet again, all-electric cruise vessel would have higher risks of reliability and propulsion availability than engine-powered, as the batteries could run out of energy or malfunction, leaving the vessel completely without power. However, in hybrid power supply system batteries provide safety and back-up power in case of engine failure, keeping the controllability high and continuously available. (Geertsma et al., 2017; Skjong et al., 2017)

Comfort is one of the key non-monetary benefits of batteries compared to conventional engine power supply. Comfort consists of elements like noise, vibration, smoke, and smell that affect the people both onboard and at port area. During sailing, engines are required and power load levelling doesn't really improve the comfort compared to conventional power supply, only keep the noise and vibration more stable if anything. (Geertsma et al., 2017)

The main comfort benefit is achieved in the all-electric manoeuvring and port stay. Some cruise lines, for example Hurtigruten, explores beautiful and exotic locations, such as the fjords of Norway and Antarctica, in manoeuvring mode. Battery-powered all-electric manoeuvring enhances the passenger experience greatly as the vessel doesn't vibrate or produce virtually any noise, smoke or smell. (Corvus Energy, 2023b) Zero emission operation mode also eliminates the noise, vibration, smoke and smell from the port stay improving brand image and port visit experience. As entertainment is the core purpose of cruise vessels, increased comfort through hybrid power supply increases business value. (Rantio, 2015; Ritari et al., 2020)

The last two elements on the Geertsma et al. (2017) power generation performance criteria list are maintenance and purchase costs. These can be evaluated in the form of OPEX and CAPEX, respectively. Cost performance is always vessel specific and can't be explicitly compared between conventional and hybrid systems, but the overall elements and trends can be assessed. As described in chapter 2.2.4 , vessel's power generation OPEX consists of fuel, electricity and maintenance costs. In addition to reducing fuel consumption and electricity being relatively cheaper energy source than fuel, battery has potential to reduce the vessel's maintenance costs related to power supply. The need and cost of battery maintenance is much lower than diesel engine maintenance, as there is really no moving parts, combustion process or mechanical movement. Battery enabled strategic loading and acting as the spinning reserve leads to running less engines, which besides fuel efficiency reduces the engine operating hours. Engine maintenance and repair costs are directly proportional to the operating hours, which means that batteries are able to directly reduce OPEX. Together with reduced engine usage, the running and maintenance costs of support systems such as fuel tanks, pumps and scrubbers are decreased. (Ovrum and Bergh, 2015; Ritari et al., 2020) Continuously fluctuating power demand and engine overloading leads to an increased need for maintenance and repair work, which can be eliminated with strategic loading and peak shaving (Geertsma et al., 2017). On top of that, as batteries can in some cases remove the need of one engine completely, having less engines onboard leads to less annual maintenance regardless of operating hours (Skjong et al., 2016).

Similarly to OPEX, CAPEX depends on the vessel's power generation system and propulsion configuration, including the number, type and size of engines, and the technology and characteristics of the BESS. Battery pricing has been discussed in chapter 2.2.4 and the example li-ion BESS with 6 MWh capacity has an estimated price tag of 5 million dollars, including planning, installation, and the whole system from energy storage to power conversion. In case the number of engines isn't affected by installing a battery, implementing hybrid power supply system will cost much more than the conventional system, and the investment cost must be justified with the reduced OPEX and non-monetary benefits. However, if the battery characteristics are sufficient to reduce the installed engine count, the removed engine's CAPEX cost, which can easily be several millions plus the cost of the electricity generator and other systems attached, can be directly reduced from the BESS investment cost, making it even more justified and shortening the relative payback time greatly. (Mutarraf et al., 2018; Skjong et al., 2016) Battery payback time, ROI and overall monetary feasibility need to be estimated case by case to evaluate the investment profitability.

3.4 Challenges of hybrid power supply

Hybrid cruise vessels face challenges related to the power supply that need to be identified and addressed to enable safe and profitable operation and to achieve the previously described benefits. Challenges are also the main reason why batteries haven't yet become more popular in the cruise segment. These challenges can be linked to the operational performance and business profitability. Four key challenges of each category are represented in Figure 18 below.

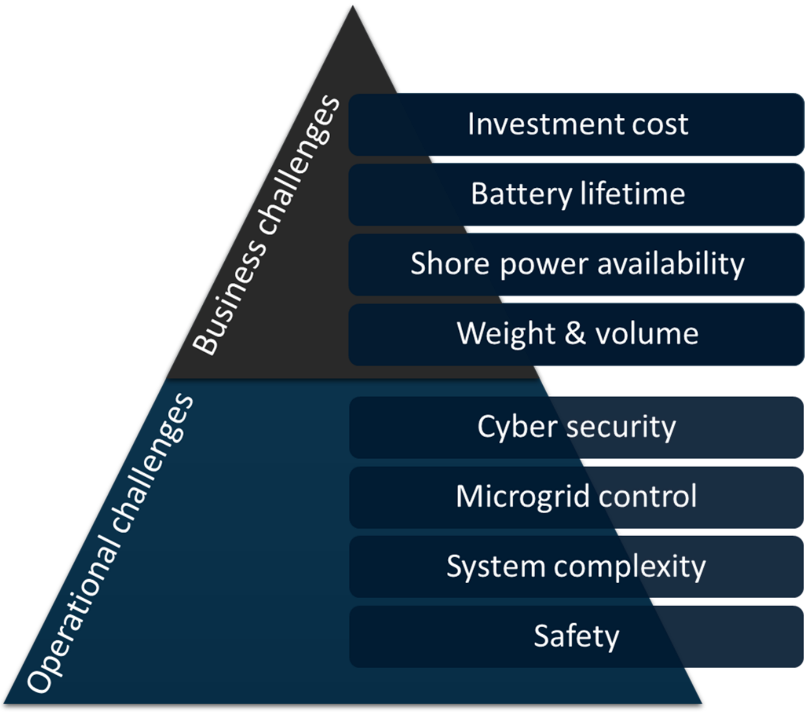

Figure 18. Hybrid power supply challenges

Safety is the most important operational challenge to address when implementing batteries on a floating city with up to 10 000 people onboard (Golden, 2022). Well-designed battery systems are considered as a relatively safe power source, but they have their own risks. Two main safety concerns are thermal runaway resulting in fire hazard and electrolyte off gas which creates the risk of explosion. Both of these risks are critical but they only happen as a result of an operational or design issue. Examples of these issues are overcharging or -discharging, overcurrent, overheating, excessive cold, external short circuit, mechanical damage, external fire, and internal defect. Too high or low battery voltage and too high current affect the system control and internal heating. Battery space temperature and humidity can decrease efficiency and cause thermal runaways. External factors like mechanical damage or fire affects the battery operation and can cause malfunctioning and explosion hazard. Finally, internal defects are particularly dangerous as they are issues that cannot be detected by the BMS, for example sensor malfunction or data issues. Most of these challenges can be addressed with proper and safety-focused battery and vessel design, implementation, usage, and BMS. (Det Norske Veritas, 2016; European Maritime Safety Agency, 2020)

Microgrid control challenges are closely related to complexity, as the whole power system needs to take many additional variables and optimization elements into account. The complexity refers to having a proper BMS in place for each battery pack and connecting them to the PMS through power converter and finally to the EMS (Figure 10). The data flow is an inevitable piece of the system, creating control and management challenges. Vessel's data volume, velocity and veracity are so high that it is sometimes referred to as big data, even though it's still mostly numerical and more or less structural. However, the variety and variability of the vessel data are expected to become more relevant in the future when audio, image and video data are increasingly included in the function. On top of handling the complexity, a microgrid control strategy has to be defined and balanced between the trade-offs, as emissions, engine running hours and battery degradation factors must be included in the optimization strategy in addition to fuel consumption. Also, the more variables are aimed to be optimized, the more complex the multi-objective control system gets. (Geertsma et al., 2017)

The fourth listed operational challenge is cyber security, which relates to all of the previous challenges. Cyber security and data reliability need to be addressed as the vessel is connected to the internet and controlled based on data more or less automatically. Vessel power control, being dependent on the real-time data flow, also requiring high data quality, and at same time being connected to the internet, creates threats of both internal and external data breaches. Even the total blackout of a vessel or its power generation would be critical, not to even mention the situation where the control of the power system would be hijacked through a cyber-attack. The probability of these risks is quite low but due to their possible critical impacts they must be thoroughly addressed and handled. (Skjong et al., 2016)

The four challenges on top of Figure 18 pyramid are more related to the business side of hybrid power supply. First concrete challenge is the battery weight and volume. As the power demand of a cruise vessel is very high, the required battery capacity, especially for zero emission operations, is massive, leading to large and heavy BESS installation. The additional weight results in increased draft which then increases the frictional resistance between the vessel's hull and water leading to even higher propulsion power demand. Battery weight and placement must also be considered from the vessel stability point of view. (Ritari et al., 2020) This is especially challenging in retrofitting because the vessel hasn't originally been designed to include batteries and most likely some less important systems such as water tanks need to be removed to make space for batteries. Battery packs can also be located separately to help the integration and vessel stabilization. (Souza, 2023) Newbuilds can be better designed for batteries, maybe even having one engine less onboard to enable more space and weight for the battery (Bennabi et al., 2021). This relates to business value directly by having less cabin space available, leading to lower revenue, unless the customers are willing to pay more for the “greener” cruise. Advanced future battery technologies might be able to tackle the weight and volume constraints better than the solutions currently available.

Shore power availability in ports can be viewed as an operational challenge related to battery charging, but in the big picture it is a matter of business value. Shore power infrastructure is a huge multimillion investment for the port and it has to be beneficial both for the cruise line and for the port (Rantio, 2015). Charging large cruise vessel batteries, possibly even multiple cruise vessels at a time, would require tens of mega-watts of shore power, which is a real challenge for the local utility grid. Ports would need massive energy storage systems also on the shore side to sufficiently supply the vessels’ power demand. (Chin et al., 2019) The number of shore power capable commercial vessels with GT over 5000 has increased rapidly to almost 4500 vessels globally, and projected to continue increasing widely, depending on the vessel type. This transformation is driving ports to invest in shore power, which is not yet extensively adopted on a global scale, but has shown signals of improvement. However, larger shore power availability would be required for cruise vessels to be able to consider all-electric port stays and manoeuvring with large capacity batteries. (Michaux, 2021; United States Environmental Protection Agency, 2022)

Investment cost and battery lifetime are the biggest business challenges regarding hybrid power supply. Considering the limited operational fuel savings potential, battery investment cost is very high. As the load fluctuations on a cruise vessel are relatively small during sailing and main engines can most of the time be operated optimally, the payback time of a BESS investment might be very long. (Geertsma et al., 2017) Payback time is of course affected by the possibility of removing one of the engines and its cost from the total cost of the power generation system. This is also where the battery degradation comes into consideration because the design lifetime of batteries is only around 10 years (He et al., 2022). Some maritime battery suppliers state that with optimal usage their BESS could last up to 20 years, but the reality is probably something in between the 10 and 20 years (Perry, 2022). As discussed in the chapter 2.2.3 battery operating conditions and usage, such as rapid charging or discharging with high C-rate, have major impacts on the battery lifetime which directly affects the investment's profitability. By combining ESSs such as battery and supercapacitor into a HESS, power system's lifetime and efficiency could be improved enabling higher lifetime profitability. Decreasing trend in battery prices and the increasing trend in fuel prices are factors affecting the battery investment profitability, making it more justified in the future. (Mutarraf et al., 2018; Skjong et al., 2016)

3.5 Battery life-cycle sustainability impacts

As sustainability and environmental benefits are one of the main drivers for implementing batteries onboard vessels, the total life-cycle sustainability impacts must be evaluated. Commercial operation is the time when batteries can generate sustainability benefits by fuel and emission reductions, but these benefits must exceed the negative impacts deriving from other parts of the battery life-cycle to justify its usage. Figure 19 below visualizes the life-cycle phases of a battery from raw materials to end of life.

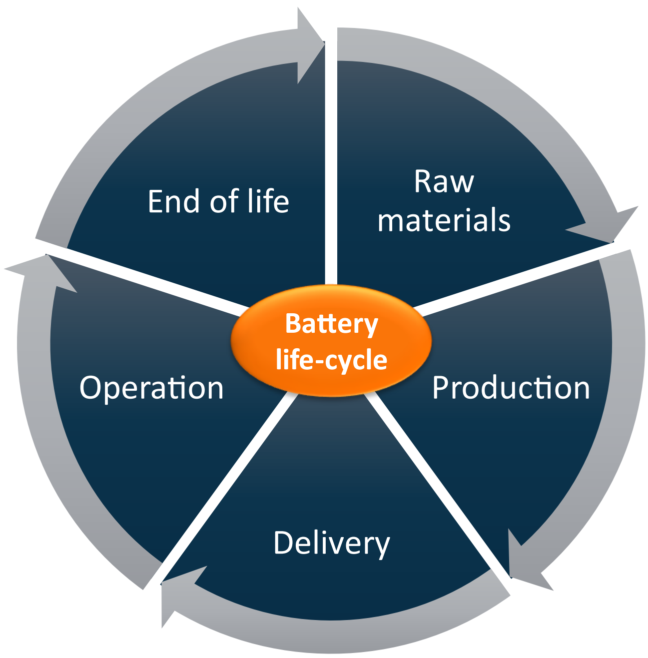

Figure 19. Battery life-cycle phases (adapted European Maritime Safety Agency, 2020)

Battery life-cycle begins from raw material extraction and processing. Typical battery chemistries, such as li-ion and lead-acid, require heavy metal mining which is a polluting and high energy and water consuming process. Some materials like lead are poisonous, creating harms and risks for the environment. (Rapier, 2020) Another sustainability challenge of batteries is the limited availability of rare and non-renewable raw materials. Lithium batteries contain only little rare materials, but supply shortages are expected on lithium, nickel and cobalt as the global battery demand is increasing rapidly. Also, the planet's raw material reserves will eventually run out and new battery solutions have to be found from recycling and alternative materials. (European Maritime Safety Agency, 2020; Melancon, 2022) Recycling is a far more sustainable approach for battery material extraction than mining and processing, and it is expected to be emphasized in the near future (Rapier, 2020). Another viable solution through technological development is using sustainable raw materials that are more common or renewable. New battery types such as metal-air and solid-state consist of common materials, the extraction of which isn't as energy consuming and polluting. (European Association for Storage of Energy and European Energy Research Alliance, 2017) There is also a lot of research going on around sustainable battery technologies, one example being Stora Enso's Lignode® solution. Lignode is a hard carbon electrode, made of renewable lignin fibre obtained from trees, replacing the fossil based graphite anode of li-ion batteries. Besides being a sustainable, renewable and very common material, lignin offers advantages such as higher C-rates and better performance at low temperatures. (Stora Enso, 2023)

Battery manufacturing has an even bigger environmental footprint than the material extraction, as battery packs consist of many components, the quality of which is highly important regarding safety and performance (European Maritime Safety Agency, 2020). Raw materials are refined to components, e.g. cathodes, anodes and electrolytes, which are assembled to cells, which then are combined into battery packs and modules. (European Association for Storage of Energy and European Energy Research Alliance, 2017) Peters et al. (2017) conducted a large investigation regarding the environmental impacts of li-ion batteries. Study results indicate that manufacturing 1 Wh of battery capacity requires on average 328 Wh of energy. This consumption was found to correspond to 110 g of Carbon Dioxide Equivalent (CO2eq) GHG emissions. In comparison, the manufacturing of a 1 W fuel cell emits 700 – 950 g of CO2eq, but it's also worth noticing that the fuel cell technology and manufacturing is not as mature and developed as li-ion (Nease and Adams, 2015). Battery manufacturing energy could be produced sustainably from renewable sources, but the study estimates an electricity mix of 50 – 70 % fossil-origin being used. (Peters et al., 2017) Battery manufacturing site location greatly affects the sustainability impacts of the delivery phase. Current li-ion manufacturing is dominated by China, followed by North America, Europe and the rest of the Asia. In the worst case, batteries are transported from a factory across the world to be implemented on a vessel. However, as merchant shipbuilding is focusing on Asia, China has a central location to provide batteries. Similarly, European battery manufacturing countries Sweden and Germany are able to supply batteries to cruise vessels built nearby in European shipyards to minimize delivery emissions and energy consumption. (Berti, 2020; Tsiropoulos et al., 2018)

After the battery system has been manufactured and delivered, it can be deployed into the vessel's power supply system and start creating benefits. The typical lifetime of an onboard battery is 10 years of operation, depending on the usage and vessel's operating profile. The two main ways for a vessel to create environmental savings through a battery are improving engine efficiency and charging with shore power. The fuel efficiency of a conventional power supply system is around 40 – 45 %, while the energy efficiency of shore power from utility grid to propeller is ~80 %. (European Maritime Safety Agency, 2020) Producing and burning MGO emits about 0.33 kg of CO2eq per kWh of energy content, whereas the European electricity mix is estimated to produce 0.47 kg CO2eq per kWh. In a direct comparison, the GHG emissions from MGO are lower, but when taking into account the engine and battery efficiency differences, shore electricity is the more sustainable option. Additionally, some countries like Norway already lean heavily towards renewable electricity production, having the average GHG emissions of only 0.03 kg CO2eq per kWh, and the trend is expected to continue globally. (Maritime Battery Forum, 2016) Ritari et al. (2020) conducted a study on a hybrid cruise ferry which saved over 250 tons of fuel annually due to improved engine efficiency. During the estimated 10 year lifetime, the battery saves ~2500 tons of fuel, corresponding to over 6500 tons of lifetime CO2 emissions. The studied battery had the capacity of 940 kWh and its production emitted ~180 tons of CO2eq emissions, meaning less than 3 % of the emissions saved during the lifetime operation, which justifies the production and usage of battery from the environmental point of view. (Ritari et al., 2020)

Battery degrades during operation and after time when the battery SoH drops to 80 %, it is considered to have reached end of life (Mongird et al., 2020). This however doesn’t necessarily mean the end of operation for the battery. At 80 % SoH the battery might no longer be suitable for its original purpose, but still has good potential to store energy in some other application, such as utility grid stabilization. This reallocation is known as the second life of the battery, the duration of which is hard to predict but can still be several years. However, as the battery technology hasn’t been designed for second-life usage and the low SoH affects the available battery voltage and current, safety aspects are emphasized. (Maritime Battery Forum, 2016) Besides creating environmental benefits, giving a second life to a battery can be an economically strategic decision since the value of an end-of-life battery can be as high as 50 % of its original price. Thus, reselling a battery for a second life can have a significant impact on the investment feasibility. (Lehmusto and Santasalo-Aarnio, 2022) After the final end of life, batteries still contain a lot of re-usable materials that can be processed for producing new batteries. For example, the recycling process of lead-acid batteries is highly developed due to the technology being mature and lead being a poisonous material, and almost 99 % of lead-acid batteries are recyclable. On the other hand, li-ion technology is relatively new and since the lifetime is long and materials aren’t as toxic as lead, an efficient recycling process isn’t yet in place. (Rapier, 2020) However, it has been estimated that 70 – 97 % of the weight of li-ion batteries could be recycled (European Maritime Safety Agency, 2020).

The sustainability impacts of an onboard battery system can be evaluated with the help of Sustainability Awareness Framework (SusAF). SusAF is designed for companies and stakeholders to analyse the effects and consequences of their services or products. The goal of SusAF is to identify possible chains of effects that could be caused by the studied products, and compare the positive impacts to the negative ones. These impacts can be analysed on the five dimensions of sustainability: technical, economic, environmental, social and individual. This sustainability impact analysis can be visually presented with a five dimensional three layer radar chart. Dimensions represent the sustainability categories and layers (1 – 3) represent the impact level, first (orange) layer being the immediate impact, second (grey) being the enabler, and third (blue) being the higher level structural impact. (Porras et al., 2021) The main positive and negative sustainability impacts of battery hybrid cruise power supply are visualized in Figure 20 below.

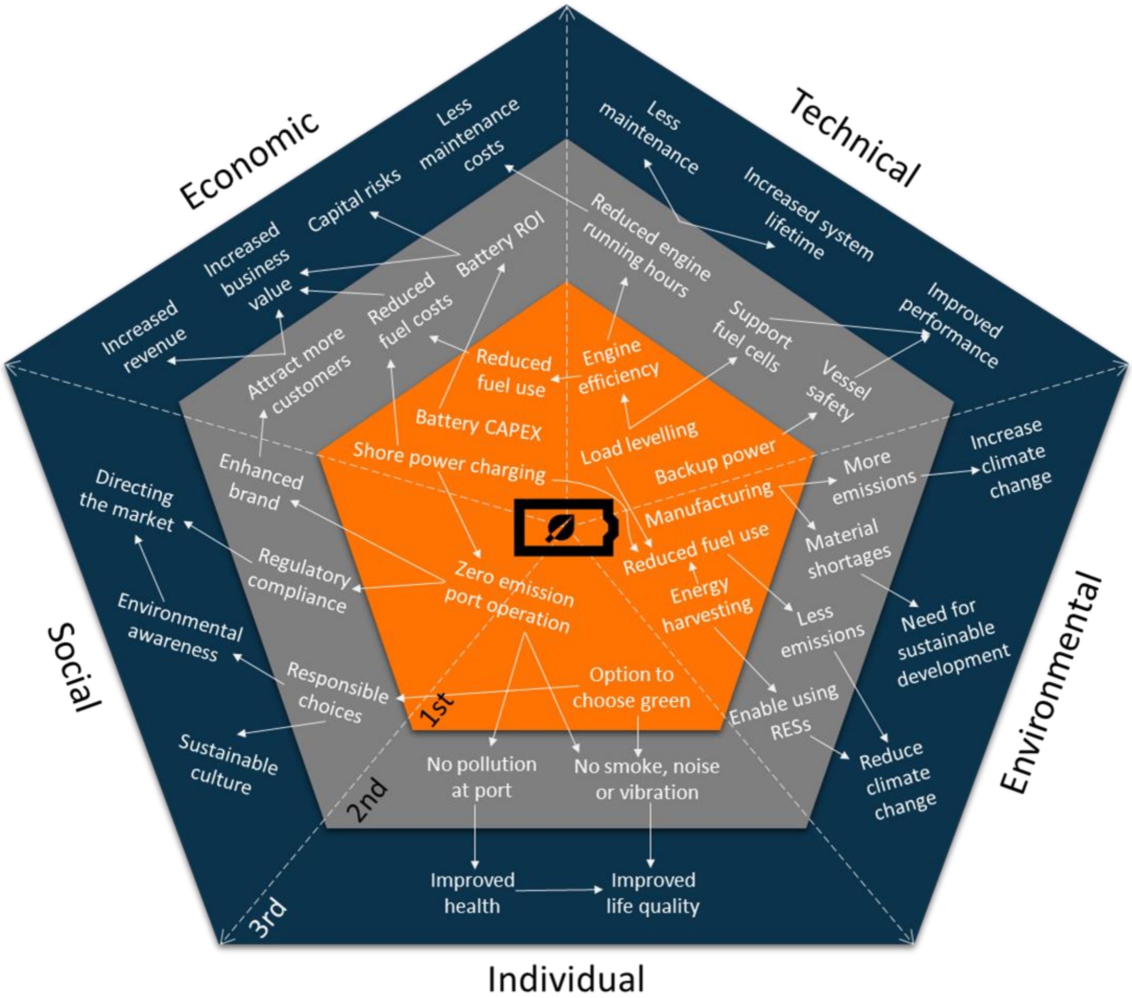

Figure 20. Sustainability impact analysis of battery hybrid power supply

The impact analysis begins from the 1st layer of immediate sustainability effects and the chains go to higher levels and can cross the dimensional borders. Immediate impacts are deriving from the battery life-cycle, negative impacts coming from the battery manufacturing process and positive impacts from the battery operation. Starting from the environmental effects, battery manufacturing requires energy and raw materials. The process creates emissions and material shortages, which then in a big picture increases climate change and the need for sustainable and renewable battery material development. Batteries allow energy harvesting which then works as an enabler for using renewable energy sources with no emissions, reducing the vessel's environmental footprint. Besides energy harvesting, battery use cases such as load levelling and shore power charging reduce the vessel's fuel consumption which directly reduces the emissions and through that hinders the climate change. Overall, the battery is estimated to reduce total emissions and footprint, even though the manufacturing process has negative effects.

Load levelling can also be seen as a technical impact as it improves the engine efficiency, which enables decreasing engine running hours and mitigating load fluctuations, leading to reduced need for engine maintenance and increased system lifetime. Battery-powered load levelling and peak shaving also enable the use of fuel cells, which are not capable of handling quick load fluctuations. Fuel cells have other benefits than batteries, and their HESS combination would improve the vessel performance greatly. Battery working as an UPS and backup power increases the safety of the vessel, which can be seen as a technical performance improvement, also affecting the required power supply configuration. Improved engine efficiency and charging with shore power, reducing fuel consumption and running hours, can be also viewed as a major economic impact, improving business value and reducing maintenance costs. The economic downside of batteries is the high investment cost (CAPEX), affecting the ROI and payback time, creating business and capital risks.

Zero emission manoeuvring and port stay are mainly linked to social and individual dimensions, because unless the port stay is powered with shore connection, batteries can only move the time and place of the emissions, without actually reducing them. The main benefit achieved with emission-free operation from the cruise line’s point of view is enhanced brand and image, attracting more customers and leading to an increased revenue and business value. It can also be seen as a business enabler, ensuring compliance to possible future regulation of for example tightening ECAs or forbidding the usage of engines completely within port area. Zero emission operation also cuts the pollution at port, leading to major health benefits for local people. Availability of hybrid cruises allow individual customers to make greener choices, which together with regulation can steer the market towards more sustainable and environmentally aware direction, also enhancing a sustainable culture. Finally, choosing to sail with a battery hybrid cruise vessel increases the individual’s life quality by being less affected by smoke, noise and vibration coming from the engines.

4 Qualitative interview

Qualitative interviews are done within the scope of this thesis to gather information on the market situation of hybrid cruise vessels. Market insights obtained from different perspectives are compared and analysed to build a picture of the interest towards alternative vessel power sources and their future outlook in the cruise business. This chapter introduces the methods and objectives of qualitative research, focusing on interviews. Also, the background, topic, questions and targets of the interviews are discussed and finally the main findings are summarized.

4.1 Interview as a qualitative research method

The term qualitative research includes multiple investigation methods that have similar characteristics. The main factors separating qualitative research from quantitative are data and material, and how they are utilized. Quantitative research aims to find patterns or exceptions from numerical data to explain the studied phenomenon. Qualitative research in turn utilizes written or visual material, such as documents, interviews, figures or videos, to create new or enhanced understanding of the topic based on human experience. The goal of qualitative research is to answer the predetermined research questions from a specified point of view in the form of consistent conclusions derived from the qualitative data analysis. (Saldana et al., 2011)

Interviewing is the most common research method for collecting qualitative data about a phenomenon. This is explained by its benefits compared to other approaches like written or digital surveys. Having a face-to-face communication with people to learn and understand their thoughts, feelings and experience about the studied phenomenon enables accessing a lot deeper information and knowledge than would be possible for example through an email survey. (Brinkmann, 2013) The reliability of the answers is typically higher and easier to assess in an interview where all the gestures and behaviour can't be hidden behind a computer. Also, unlike in surveys, in interviews the interaction flows in two ways. The questions can be further detailed and made sure that the interviewee has understood them correctly, and on the other hand the interviewee has the possibility and lower threshold to ask for clarification on the questions. Although having many advantages, interviewing has certain limitations and challenges that must be addressed. The sampling size of qualitative interviews is typically very limited, as interviewing takes a lot of time and effort. Due to the small sampling size, the risk of relying on biased information by poor interviewee selection is higher than in other research methods with higher quantities. Another challenge affecting the reliability of the results is that the analysis is based on the interpretation of the interviewer. Even though interviewer has the opportunity to ask clarifying questions, his understanding might differ from the respondent’s experience. (Saldana et al., 2011)

Interviewing enables multiple ways to gather qualitative data. The traditional method is to take notes of the insights and experiences shared by the interviewee. This approach has the benefit of summarizing key points without taking too much time or focus away from the interview, but it results to not having a full record or transcript of the interview which could be reviewed or cited in detail. Two more modern ways, made easy by digitalization, are audio and video recordings. These have the advantages to capture the entire interview, video also including the body language, acts and behaviour, letting the interviewer return to the interviews when forming the analytic synthesis. These methods might face technical challenges leading to missing some or all of the recording, as well as requiring considering data privacy aspects and the possibility of interviewees losing their anonymity. (Atkins and Wallace, 2012)

The two main styles of interviews are respondent and informant interview. The former relies on the interviewer keeping the conversation strictly within the predetermined question list following the agenda and schedule. The latter one in turn is more relaxed and free, leaving room for open discussion around the topic and creating the possibility to access such information that might have otherwise been left out by only following a defined question list. Informant interview might build a better overall picture of the topic for the interviewer, but on the other hand some questions might be left unanswered leading to lower comparability of interviews. The style selection depends fully on the topic and goals of the interview, both styles having their preferred use cases. (Atkins and Wallace, 2012)

4.2 Interview background and questions

The purpose of the interviews in this thesis study is to build a picture of the current and future market situations of hybrid cruise vessels. The goal is to understand the main drivers and motives for implementing alternative power sources and ESSs from different parties' point of view. Interview results will give insights on the interest towards hybrid vessels in near future and beyond, based on the main benefits and challenges linked to the different power supply technologies. The collective question aimed to be answered by the interviews is:

How does the market development of hybrid power supply look like from the cruise segment point of view?

Interview was selected as the qualitative research method in this thesis as it enables finding the deeper motives for hybrid power supply systems as well as facilitating open discussion around the future interests and predictions of market development. The chosen style will essentially be respondent interview, led through a pre-defined agenda and question list by the interviewer. However, to be able to capture all relevant insights and experiences around the topic, the interview will include informant style characteristics such as possibility for wider and more relaxed discussion with clarifying questions. Gathering answers to all questions enables the comparison of answers and concluding a reliable understanding of the selected topic. The question list consists of two sections: current market situation and future outlook. Former aims to investigate the current possibilities, drivers, benefits and challenges of alternative power sources for cruise vessels, focusing on batteries. The latter one opens discussion about the future of batteries and other power sources in cruise segment, divided into short-term and long-term, border being the year 2030. This time split was chosen based on the IMO's emission targets set for 2030 and 2050, also considering that the orderbooks of many shipyards are already visible for the next couple years. Interview question list is available in Appendix 1.

The interviewed parties were selected from different segments of the maritime field to include insights from varying perspectives. The three segments involved are cruise lines, shipyard and a system and solution provider. Cruise lines are considered as the main source of information as they have the best knowledge on the drivers and interest towards hybrid power supply. Shipyard is included to get a more concrete perspective on the topic, and the system and solution provider company behind this thesis study has a lot of insights on the benefit and optimization possibilities of alternative power sources affecting the feasibility and market interest. Interviewees were chosen based on contacts and suggestions for the best knowledge about the topic in each of the contacted companies. The predefined question list was shared with the contacts beforehand to find the right interviewees, also letting them prepare their answers to enable access to even deeper knowledge. People names are not relevant for the analysis which is why they are left out and only interviewee roles and years of experience around the power supply topic are mentioned. Shipyard and cruise line companies are also anonymized as it allows them to share deeper insights on their future plans regarding cruise power supply. The target companies and interviewees as well as the time and duration of the interviews are presented in Appendix 2.

4.3 Interview summary

The answers and insights gathered from the interviews form a comprehensive picture of the overall hybrid cruise vessel market situation and drivers for the future development. The interview question list was split into two sections, current situation and future outlook. Insights and expectations in the latter section were surprisingly similar between all interviewees, whereas the answers in the former part had much more variation. Interviews are beneficial to be compared between each of the three viewpoints, but the emphasis must be given to the cruise lines' answers.

Alternative power supply options for cruise vessels were well recognized by all parties and the most suitable and potential ones are commonly identified, including batteries, fuel cells, shore power and alternative fuels. The shipyard seemed to have investigated all of the possible ESS and power supply technologies and having a good understanding of their physical challenges and limitations. Wärtsilä and the cruise lines were more focused on the few main technologies that are believed to gain ground and offer the best efficiency in the future. The prioritization of drivers for the power supply change shared opinions a lot more.

Interviewees were asked to identify the major business related drivers and rank them in a priority order from one to five from the cruise line point of view. However, most of the interviewees mentioned less than five drivers that would actually have an impact on the decision making when considering other power sources than fossil fuels. Over half of the interviewees, regardless of business segment, mentioned regulation as the main driver whereas the other half emphasized brand image and money. Reasons for the small number of onboard batteries seen on the cruise segment so far were found in their operational limitations and physical constraints. Main challenges mentioned in most of the interviews, also identified in the literature review (Figure 18), were the added volume and weight due to high power and energy demand, and high costs compared to the economic benefits. Additionally, Wärtsilä and the shipyard saw the global availability of shore power and the conservative nature of the maritime industry as major challenges, while cruise lines emphasized the risks and concerns related to safety. Battery feasibility was also sharing thoughts even within the interviewed parties, some believing in great fuel and emission savings potential with multiple use cases, some seeing no benefit or use cases at all, and the rest laying somewhere in between. In the big picture, BESS was seen as a beneficial system for power supply support purposes improving vessel’s performance and engine efficiency through majority of the use cases also identified in the literature review (Figure 17).

As mentioned, the vision of the future cruise power sources was surprisingly identical between all three interviewed maritime segments. Only two interviewees didn’t believe in the popularization of batteries in the cruise segment, but all the rest saw the potential and predicted several battery pilot and development projects already in the near future, and wider adoption as a supportive power source after 2030. Combustion engines were still seen as the main power source for cruise vessels in the long run, however being powered by green fuels already in the near future. Fuel cells were listed in most of the interviews as an interesting and potential technology that will be piloted in the near future and might popularize after 2030. Shore power was also believed to become widely adopted already in the near future due to its great environmental benefits and possibly tightening emission regulation at ports. The final question regarding fully electric cruise vessels was again unanimously answered. Batteries and RESs are believed not to be capable of powering large ocean-going cruise vessels even in the future. However, when talking about future technological development, most of the interviewees emphasized to never say never.

5 Hybrid vessel market analysis

Hybrid power supply has been introduced in vessels already in the change of the millennium. First onboard batteries, with the capacity of 20 – 200 kWh, were installed on passenger vessels including ferries, yachts and submarines. Nickel-cadmium and lead-acid were the most popular battery technologies until the introduction of maritime lithium-ion batteries in 2010. Since then, the number of battery-powered vessels has increased greatly and the technological competition has been mostly between different li-ion chemistries. The average installed battery capacity has also increased significantly since the beginning of li-ion era, being almost 500 kWh already in 2011. Apart from small tug-, fishing- and workboats, merchant vessels joined the hybrid power supply transformation only in 2016 and have shown increasing interest during the past few years. Cruise segment has so far seen only couple battery piloting hybrid vessels, but the benefits and opportunities are constantly being investigated. Europe, led by Norway, is the leader of hybrid vessels with an almost 75 % share of the global market. (Hoedemaker, 2022) Lithium and nickel based technologies are currently the most suitable ones for maritime applications as they provide high energy and power density with relatively long lifetime and high safety which is another aspect that is emphasized especially in passenger vessel batteries. (European Maritime Safety Agency, 2020) Some of the older battery types such as lead-acid and nickel-cadmium are no longer used in new cruise battery installations because of the increased energy density and safety requirements (Hoedemaker, 2022).

Marine Battery Forum, established in 2014, is promoting the use of batteries in the maritime industry and together with DNV keeping a register of battery powered vessels. This ship register data is highly useful and informative when investigating the historical development of battery systems on different technologies and vessel types. Ship register also has data about the vessels currently being built or ordered that will feature onboard batteries or other alternative power sources. (Hoedemaker, 2022) Power generation in the maritime field is at turning point, as regulations and values are driving green transformation globally. Vast majority of vessels are still powered by diesel engines, but numerous alternative power sources have been introduced to contribute to the power supply (Figure 5). Cruise vessels are no different, rather the opposite, as their business relies greatly on the brand image and customer satisfaction. This chapter aims to create a vision of the current and future maritime power sources. To be able to predict the power supply development in the cruise segment, current market situation must be investigated and drivers of the transformation identified to build the ground for the analysis. This is done by gathering insights from different sectors of the maritime industry with qualitative interviews. Ship register data from DNV and Clarksons databases is also analysed to support the market study.

5.1 Hybrid vessel market development

The history of battery-powered vessels begins in the late 1990s. The first onboard battery installation was done in 1998 on a small all-electric ferry, Le Passeur, with the battery capacity of 20 kWh. Small ferries were a natural starting point for vessel batteries since they operate at slow speeds on short and fixed routes. (Hoedemaker, 2022) Few more electric ferries and small passenger vessels were built in the early 2000s, after which other small ships, like tugs and fishing boats that have relatively low power demand, joined the trend and installed hybrid power supply systems. It took until 2011 for the first larger size merchant vessel to incorporate batteries in propulsion. (Clarksons Research, 2023) The threshold of 100 battery vessels was reached in 2016 and after that the number has grown rapidly, being close to 600 in 2022. Based on the registered newbuild vessels and ordered battery retrofits the trend of hybrid power supply only seems to get stronger in the near future. (Det Norske Veritas, 2022b) Data for the following graphs is acquired from the Clarksons Research (2023) and it only contains ships registered with an IMO number, meaning that it is mainly limited to vessels with the gross tonnage over 100. For this reason, the shown timelines begin from 2009 and don’t contain the first small electric ferries. Also, all data shown after 2023 is based on vessels or retrofits under construction or being ordered. Not all vessels that will be built in the next few years have yet been ordered, reported or registered with an IMO number, which is why the graphs can be misinterpreted as showing a declining trend.

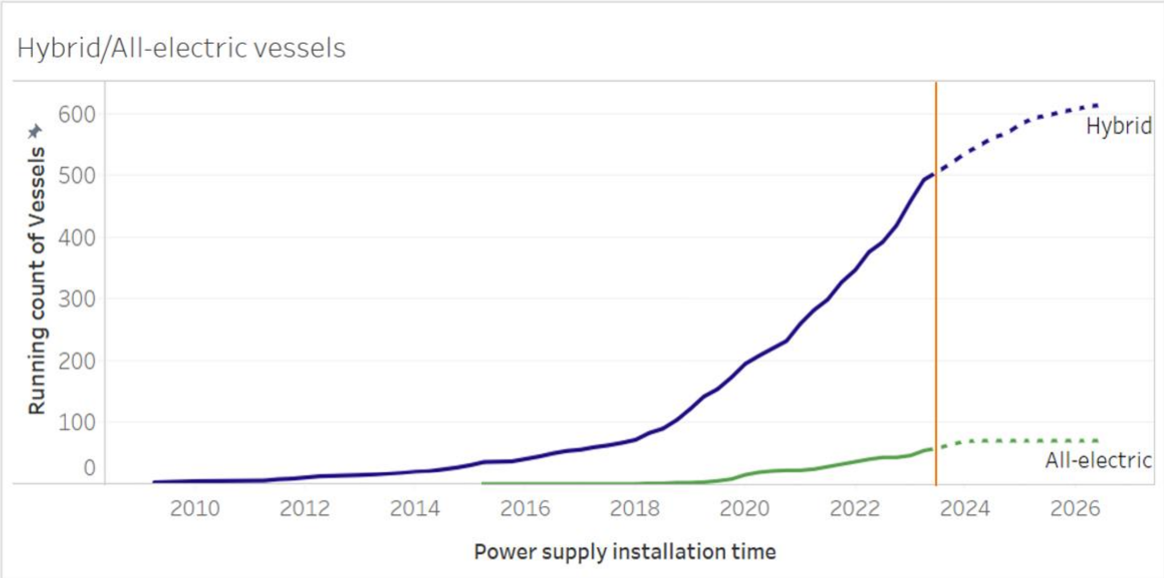

Figure 21. Development of hybrid and all-electric vessels (Clarksons Research, 2023)

The accumulating count of hybrid and all-electric vessels of over 100 GT is visualized in Figure 21 above. The blue line represents the development of hybrid vessels, containing both battery and fuel cell installations. There is a significant increase visible since 2018, after which the worldwide hybrid vessel fleet has increased fivefold. Similar but milder increase can be seen in the count of all-electric vessels, represented by the green line, since late 2019. The orange vertical line marks the market situation at the time of writing this thesis, after which the dashed lines visualize the near future development in the light of ordered vessels and retrofits. The increasing trend of hybrid vessels seems stable, although in reality it is expected to grow even more rapidly as more vessel orders and their power supply configurations get confirmed. The number of all-electric vessels is also expected to increase, but much more slowly due to the technological and characteristic limitations and challenges, such as power and energy requirements, weight and volume, and shore power infrastructure availability. (Clarksons Research, 2023)

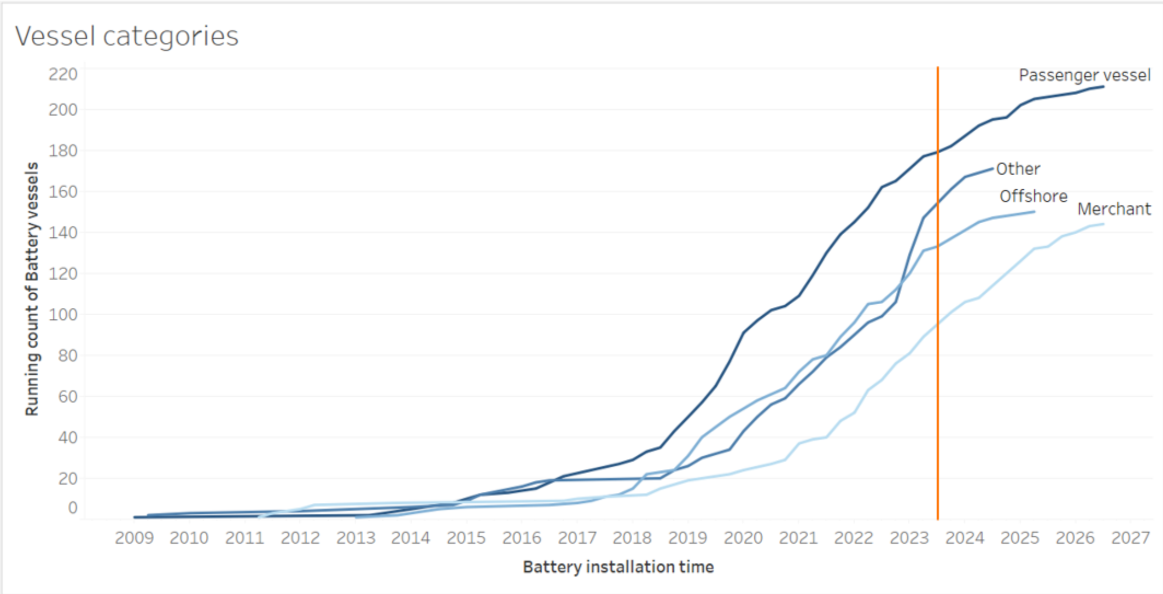

Figure 22. Battery installation timeline per vessel category (Clarksons Research, 2023)

Figure 22 above shows the development of maritime battery installations, separately for each vessel category, "Other" including for example tugs, fishing boats and inland vessels. Passenger vessels, consisting of yachts, ferries, cruise vessels, and other passenger ships, started the trend and have led the hybrid transformation. As mentioned, the wider adoption of vessel batteries began in the mid-2010s, after which the popularity has increased vastly. (Clarksons Research, 2023) Offshore vessels typically have a highly fluctuating power demand profile, due to which they benefit greatly from battery or supercapacitor enabled peak shaving. Merchant vessels have adopted batteries slightly slower, most likely reasons being the long distance and stable speed operating profile, vessel ownership dynamics, and investment feasibility. (European Maritime Safety Agency, 2020). Figure 23 below breaks down the battery installations inside the passenger vessel category. Even though yachts and catamarans, under the "Passenger vessel" type, started the transformation within the over 100 GT vessels, ferries have faced a much greater increase since 2013. Ocean going cruise vessels featured their first batteries only in 2019, after which the number has increased to ~15 vessels. (Clarksons Research, 2023)

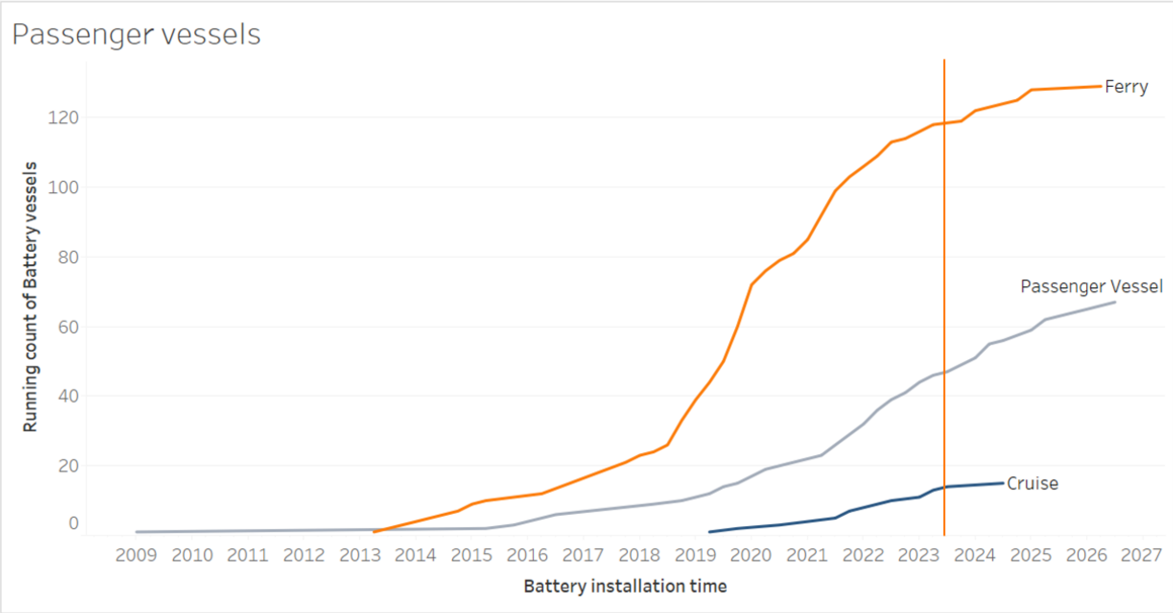

Figure 23. Passenger vessel battery installation timeline (Clarksons Research, 2023)

The operating profile, size, safety, power and energy requirements together with the uncertain investment feasibility have held back the wider battery adoption in the cruise segment, but several smaller size cruise ships have piloted batteries with different use cases. Cruise vessels have already transitioned to using electric propulsion as the main propulsion type, which makes it easier to incorporate batteries or other alternative power sources to the network than for example on mechanical propulsion. (European Maritime Safety Agency, 2020) Hurtigruten is a Norwegian cruise line that ordered the first battery hybrid ocean-going cruise vessels, Roald Amundsen and Fridtjof Nansen, in 2019. Both of the sister vessels feature a BESS with the capacity of 1.36 MWh, delivered by Corvus Energy, which is one of the leading maritime battery suppliers. Both of the 20 000 GT vessels can host 530 passengers plus the crew, while doing expedition cruises along the Norwegian coast. Besides strategic loading and peak shaving, the vessels are capable of short period all-electric manoeuvring, offering passengers a complete and natural experience of the fjords of Norway with maximized comfort. (Corvus Energy, 2023b, 2023c) AIDAprima is a 125 000 GT and 300 m long cruise vessel operated by the German-American AIDA Cruises, which is part of the Carnival Corporation. After being retrofitted with a record setting 10 MWh battery system in 2022, she is one of the latest additions to the list of hybrid cruise vessels. 10 MWh is the largest onboard BESS the maritime industry has seen so far. AIDAprima is also showing the way as the first large size cruise vessel to install batteries and being capable of cold ironing through shore power connection. (Beyer, 2022)

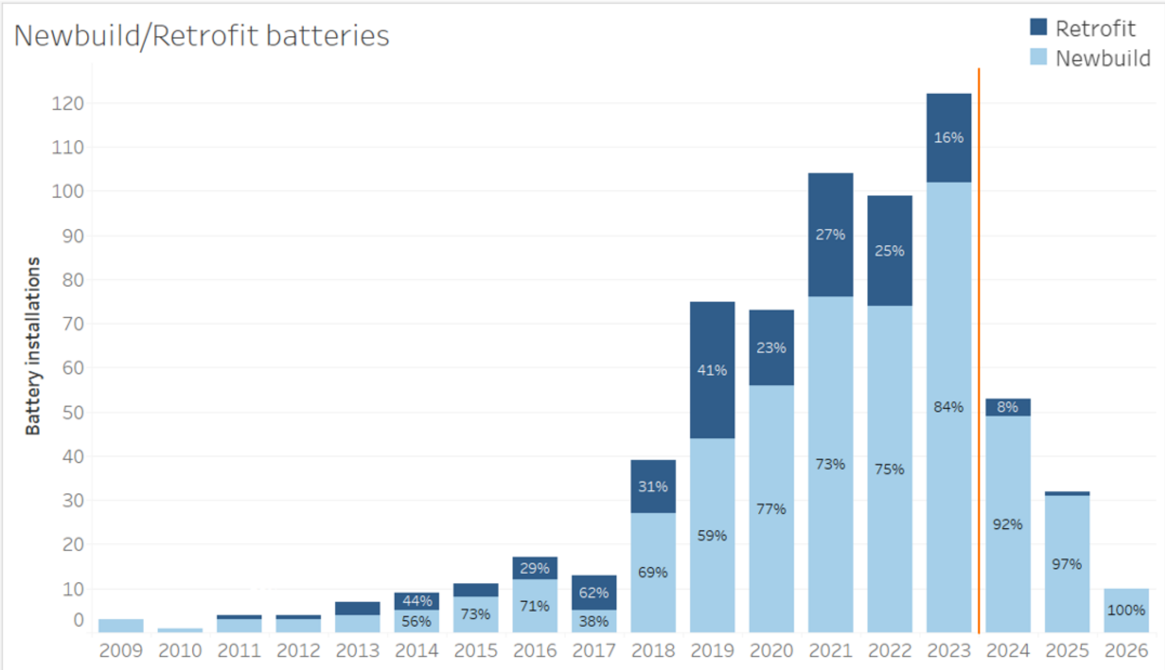

Figure 24. Newbuild and retrofit battery installations (Clarksons Research, 2023)

Another interesting element of battery installations is the installation time relative to the vessel construction time, as batteries can be installed both to existing and newbuild vessels. Figure 24 above shows the development of newbuild and retrofit battery installations over time. Apart from 2017, newbuild installations cover majority of the vessel batteries. This trend is understandable as finding the space for batteries and balancing their weight is much easier in the vessel design phase than implementing them into an existing vessel. Also, the engine configuration and total installed power supply capacity can be better adjusted on newbuild projects. Retrofitting can help on improving the energy efficiency of existing vessels, for example to comply with the new Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations, but as seen in the Figure 24, newbuilds are increasing their share of all battery installations. Based on history data, the average age of a vessel being retrofitted with batteries is 10.5 years. This number is reasonable as the life expectancy of vessels is around 25 – 35 years, meaning that the retrofitted battery can with optimal usage last for the rest of the vessel’s lifetime. For passenger vessels the average age of battery retrofitting is 15.5, more precisely 20.6 for cruise vessels, supporting the theory of batteries lasting the vessel’s remaining lifetime and helping the older vessels to comply with the evolving regulation. (Clarksons Research, 2023) As we go into the future, more and more vessels will already have batteries installed onboard, leading to the expectation of decreasing share of hybridization retrofit projects. This trend is already visible in the newbuild and retrofit orders, although the share of near future retrofits can still increase as the decision of battery retrofitting can be made much faster than designing and ordering a newbuild hybrid vessel. Additionally, as the newbuild vessels' lifetime is typically over two times longer than batteries', the number of battery replacement retrofit projects is expected to increase in the long run.

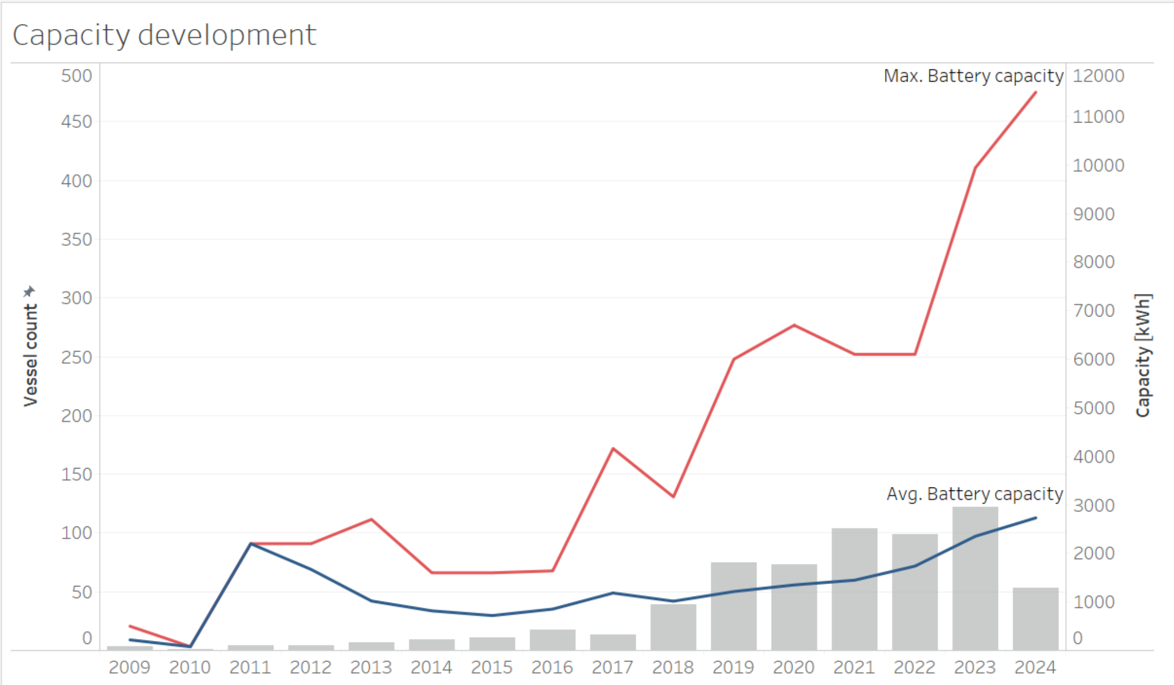

Figure 25. Vessel battery capacity development (Clarksons Research, 2023)

Hybrid vessel market can also be studied with the yearly development of average and maximum vessel battery capacity, which is visualized in Figure 25 above. The grey bars show the number of battery installations for each year, including vessels that have not reported the battery capacity. Years 2011 and 2012 show biasedly high battery capacities due to only few hybrid vessels being registered, but since the years of wider battery adoption both the average and maximum capacities have increased steadily. This trend signals the development of battery technology and rising awareness and interest towards battery possibilities in the maritime field. (Clarksons Research, 2023) However, the energy density of li-ion batteries has not seen such radical improvements that it would be possible for this increasing capacity trend to continue far in the future as the space inside vessels is limited. The only way to keep the capacity increasing is developing a battery chemistry with even higher energy density than li-ion can offer. Couple promising technologies are zinc-ion and solid-state metal-air batteries that are still being investigated and developed, but have shown positive signals regarding maritime battery requirements. (European Maritime Safety Agency, 2020) The battery supplier and system integrator market has become highly competitive during the past years. Companies like Corvus Energy, Leclanché, EST-Floattech and CATL are the market leading battery suppliers in the capacity and number of installations. Kongsberg, ABB, Siemens and Wärtsilä on the other hand lead the competition as battery system integrators. Li-ion has so far been a clear technological choice for maritime batteries, vast 76 % majority of them using the Nickel Manganese Cobalt (NMC) chemistry. In the cruise segment all reported batteries use the li-ion NMC technology. (Det Norske Veritas, 2022b)

5.2 Cruise vessel power supply possibilities

Approximately 95 % of the existing cruise vessels in early 2020s rely on diesel fuels in their power supply (Clarksons Research, 2023). However, due to multiple environmental and business drivers the use of fossil fuels is aimed to be reduced and eventually stopped in the whole maritime business, led by cruise and ferry segments. There are multiple technological possibilities, most of which are listed in the power supply side of Figure 5, that could be applied to cruise vessel's power supply system to support or replace diesel engines. The pros and cons of alternative power sources were discussed in the qualitative interviews done within this thesis study.

Alternative fuels were mentioned by all interviewees as one of the most suitable options for reducing vessel emissions. Even though burning a cleaner fuel in a combustion engine doesn't count as a hybrid system, it is worth mentioning since it's seen as the fastest and most feasible solution for cutting emissions in the near future. LNG has already gained ground as a much cleaner fuel than diesel, but it is still fossil-based and needs to be replaced in the long run. Methanol, e-methane, hydrogen and biofuels are sustainable options that can be produced without emissions by utilizing renewable energy. The challenges related to these fuels are price, availability and storage. Ammonia was also brought up in the discussions but it was found unsuitable for passenger vessels as it is highly toxic. Batteries and fuel cells were mentioned as the next most investigated power sources for cruise vessels.

They are both considered as a supportive power source, not capable of totally replacing the need for combustion engines at least in short-term. Li-ion batteries are seen as a more mature technology than fuel cells, but they both still require development to reach wider market adoption. Majority of interviewees saw peak shaving and engine support as the main purposes of batteries, whereas fuel cells were initially linked to emission-free hotel power supply during port stays. Interviewees that believed in the development of fuel cells were unanimous that they need to be coupled with batteries, creating a HESS, to handle the load variations. Technological immaturity, shore power availability, hydrogen storage, safety concerns, and volume and weight limitations are the main challenges of cruise vessel batteries and fuel cells.

Two power sources closely related to batteries and fuel cells are shore power and waste heat recovery. Based on the interviews, shore power is a highly beneficial technology especially for cruise vessels that stay long periods at ports, also having a high hotel load. Especially Wärtsilä and the interviewed shipyard saw potential in charging the onboard batteries with the shore power to enable actual emission-free operation for a short time, for example enabling all-electric port departure. Cruise lines found shore power beneficial mainly for cold ironing. Challenges linked to shore power were high power requirement, low global availability and increased electricity price due to covering the large investment cost for ports. Waste heat recovery was mentioned only by few interviewees, most likely because it is not seen as a proper alternative power source, rather as an efficiency improvement for the main power sources. However, it is a very important technology to consider in cruise vessels because combustion engines and especially fuel cells produce a lot of heat as a by-product, significantly lowering their energy efficiency. With WHR the efficiency of fuel cells can be increased by even 20 – 40 % (Melancon, 2022).

Multiple other power sources have also been investigated, piloted and even used on cruise vessels but due to having lower suitability or efficiency they are not seen as feasible as the technologies mentioned above. Gas and steam turbines have already been used onboard cruise vessels for a long time. The role of gas turbines is diminishing as engines offer higher and more economical performance as the main power source, and new technologies like batteries are capable of providing support power for load fluctuations and demand peaks. Steam turbines in turn are used to improve the vessel's energy efficiency by converting waste heat back to electricity, but there are also other WHR possibilities such as thermal ESS, which has been investigated by the interviewed shipyard. Other energy storage systems like supercapacitors, flywheels and compressed air have been considered but rejected as batteries have been found to be the most suitable, efficient and easiest solution to implement on a cruise vessel. Renewable energy sources, mainly solar and wind power, have also been considered by all interviewees but so far found unsuitable for cruise vessels because of their low efficiency, low and varying power levels, space constraints and architectural challenges. Half of the interviewees believe that solar power will popularize in the cruise segment, but mainly for image and branding purposes instead of actually becoming a notable power supplier. The final power source considered for cruise segment is nuclear power, which has already been used for a long time on naval vessels and submarines. Nuclear power raises a lot of concerns when linked to passenger vessels visiting the largest ports and cities in the world, but with new safer technologies nuclear power is also seen as a possibility for the cruise segment in the long run.

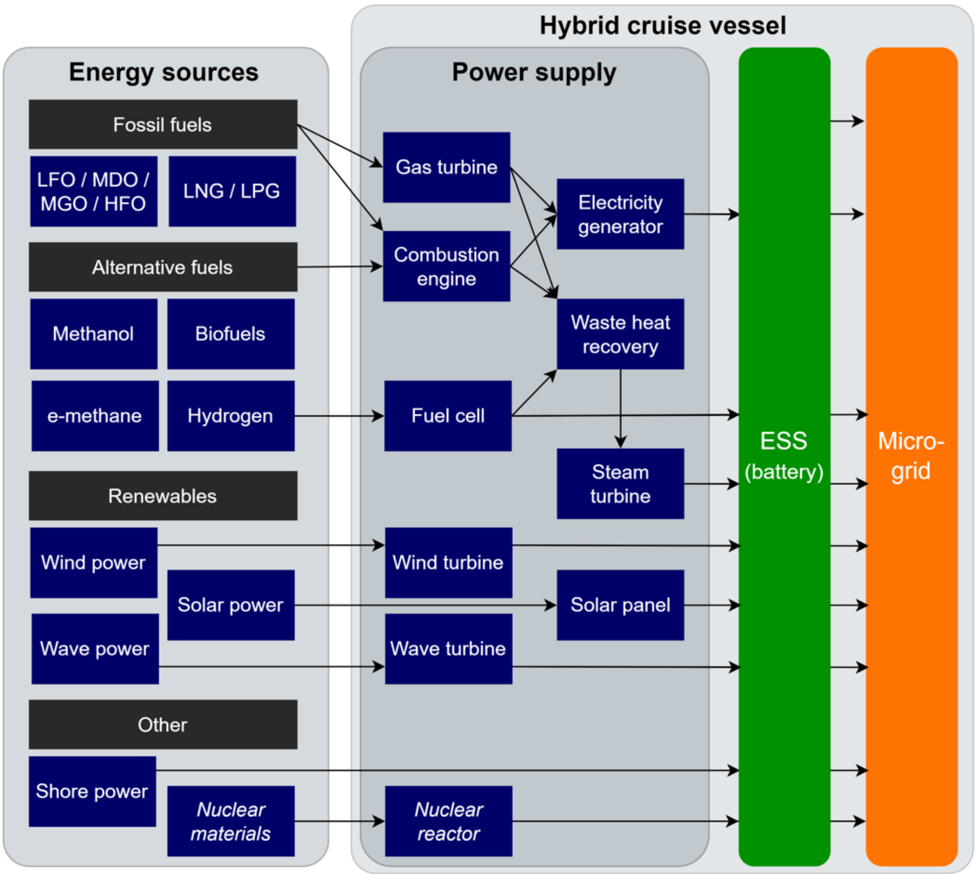

Figure 26. Hybrid cruise vessel energy sources and power suppliers

The connections between energy sources and power suppliers, based on the literature review (Figure 5) and qualitative interviews, are visualized in Figure 26 above in the context of a hybrid cruise vessel. The energy sources listed on the left side of the figure are used by the vessel to supply onboard power consumers through the electrical network. Fossil and alternative fuels are mainly consumed by combustion engines or gas turbines and transformed into electricity by a generator. The electricity can then be either stored to an ESS, in this case to a battery, or supplied straight to the microgrid. The heat that has been generated as a by-product of the combustion process can be directed to the steam turbine by the WHR to generate more electricity and to improve the energy efficiency. Hydrogen, besides being an emission-free fuel for combustion engines, can also be used in fuel cells to produce electricity to the system, again capturing waste heat with WHR for the steam generator. The renewable energy sources can be transformed to electricity with turbines and solar panels, either to be stored or immediately consumed. Shore electricity is the only source of energy that can be directly used in the microgrid without any onboard power supply process in between. The last considerable energy source mentioned in the figure is the nuclear materials, which could in the future be transformed to electricity with an onboard nuclear reactor. As seen in the figure, in an electrical propulsion system ESS can be used to store energy from any source, also being capable of supplying energy to any consumer through the microgrid.

5.3 Drivers for alternative energy sources

Several factors are driving the maritime field towards using alternative energy sources instead of fossil fuels. The growing trend of hybrid vessels in shipyards' orderbooks is a reaction to both pushing and pulling factors deriving both from the operating environment and business perspectives. Shipping industry is mainly directed by the pushing elements like regulation, whereas decision making in the cruise segment is also heavily steered by the pulling factors such as customer and stakeholder values. This chapter identifies the drivers and barriers for hybrid power supply and then discusses their pushing and pulling effects. The effects of operating environment are discussed in the form of PESTEL-analysis, after which the cruise lines' business related hybridization drivers are analysed based on the qualitative interviews.

5.3.1 Global operating environment analysis

The drivers for alternative energy sources, rising from the global operating environment, can be identified and analysed in six macro-environmental dimensions: Political, Economic, Social, Technological, Environmental, and Legal (PESTEL). PESTEL-framework is used to study the relevant factors for a selected topic from these six aspects. (Song et al., 2017) Drivers and barriers for cruise vessel hybrid power supply are summarized in Figure 27 below.

Figure 27. Hybrid power supply PESTEL-analysis

Political

Climate change and sustainability are the main carrying factors affecting more or less all of the PESTEL-dimensions. Global warming and other negative impacts of climate change are challenges that have risen political discussion and concern worldwide. Tackling climate change has been placed on the priority list of the United Nations and agreed on globally in the Paris climate conference in 2015. Common climate targets were set in the Paris agreement by 193 countries which are all legally committed to reduce their GHG emissions to limit the global warming to 2 °C, also pursuing efforts to limit the increase even further to 1.5 °C, in the 21st century. Other elements in the agreement were strengthening the ability to deal with climate change impacts and financially supporting the developing countries with the same challenges. (United Nations, 2015) This global initiative also drives sustainability in maritime business which is responsible for several percent of the global GHG emissions. IMO, operating under the United Nations, has set clear emission reduction targets for the maritime field which require immediate and innovative actions and solutions to improve vessels' energy efficiency. (International Maritime Organization, 2018)

Two other political elements affecting the adoption of hybrid power supply are the impacts of Coronavirus Disease (COVID19) and the war in Ukraine. COVID19 struck the maritime industry hard, biggest hit taken by the cruise business which was totally halted for around 15 months due to the safety restrictions. Even though the restrictions were released after majority of people received the vaccinations, COVID hasn't disappeared and its effects are still posing challenges to cruise companies both economically and technologically. (Det Norske Veritas, 2022c) The Russian invasion of Ukraine, started in the beginning of 2022, has been a massive drawback as the maritime field is still recovering from the COVID19. Numerous vessels and ports are out of commission and the exports from both Russia and Ukraine are halted. Besides consuming resources and creating uncertainties and political tension, the war is affecting vessel and battery material availability and supply chains globally, as well as the price and availability of fuel and energy. (Allianz, 2022)

Economic

Continuously increasing fossil fuel prices are driving the development of alternative maritime power sources. Typically, environmentally friendly fuels have been more expensive than fossil fuels, but due to the fuel availability and constantly tightening taxation for example the low-emission LNG has already undercut the average price of MGO and is approaching the price of LFO. Improved fuel efficiency of hybrid power supply is also becoming more and more justified by the fossil fuel price increase. (Det Norske Veritas, 2022b) Another driving element for hybrid vessels is the increasing affordability of batteries. As discussed in chapter 2.2.4 li-ion prices have decreased steadily, up to 20 % annually, and have been forecasted to continue decreasing in near future (Tsiropoulos et al., 2018). However, the limited availability of raw materials can affect the price trend and especially the 2020s challenges of declining global economy, high inflation, constrained supply chain and issues in logistics pushed the li-ion battery prices up ~7 % from 2021 to 2023 (Colthorpe, 2022; The World Bank, 2023). The price trend is still expected to drop and settle around 2030 but the global situation might appear as a setback for vessel battery installations in short-term (Tsiropoulos et al., 2018). Also, impacts of the coronavirus pandemic are still substantial especially in the cruise segment where cruise lines' revenue streams were completely cut off and companies had to lay people off and take massive loans to survive from the running expenses. The income streams have slowly reopened after the COVID restrictions were released, but the debt ratio of cruise companies is still high and less money is available to be allocated to innovation and investments such as retrofitting cruise vessels with batteries. (Baldi et al., 2022; Det Norske Veritas, 2022c)

Social

Global operating environment offers both drivers and barriers for hybrid vessels also from the socioeconomic point of view. The main driver deriving from the increasing environmental awareness and concern among customers is a "green mindset", which together with other drivers is pulling maritime field towards decarbonization. This effect is clearly visible particularly in the cruise segment where customers' market negotiation power is strong and the brand image is mostly formed by people's experience of the grand vessels visiting ports and cities around the world. Being capable of zero emission port stays is an easy way for cruise lines to differentiate from competitors, avoid being associated with negative feelings evoked by the engine smoke and noise, and possibly attract a wider customer base. Green mindset is also gaining ground among shareholders and other stakeholders and it’s starting to reflect in the cruise lines’ company values. (Meek, 2018) Health concerns are another social aspect driving emission-free power sources to be used during port stays. According to Sofiev et al. (2018) study, people living close to busy ports have been found to have much more health issues and higher mortality rate, corresponding to the emissions of vessels visiting the port. Cleaner fuels, hybrid power supply and cold ironing are capable of reducing the port stay emissions, thus improving public health (Corbett et al., 2007; Sofiev et al., 2018). Social drawbacks of batteries come from the ethics of battery material extraction and manufacturing. Besides the large amounts of energy and water required for the process, most of the battery materials are obtained from Africa, for example Democratic Republic of the Congo being one of the biggest cobalt producers in the world, where the working conditions aren’t necessarily prioritized and social sustainability is neglected. (Fastmarkets, 2023)

Technological

IoT, digitalization and technological advancements are great drivers and enablers in the field of hybrid vessels. First of all, the development of high power and high energy density li-ion technology has made it possible to consider battery installations also on cruise vessels. Besides li-ion, new battery chemistries like solid-state metal-air are under development and have shown high energy density and safety potential to be used in maritime applications in the future. (European Maritime Safety Agency, 2020) New sustainable materials, like Stora Enso’s Lignode, are also being introduced in the battery field to address the environmental concerns and availability issues of traditional raw materials (Stora Enso, 2023). Secondly, data collection, sharing and analysis have enabled the creation of intelligent control and optimization technologies, like EMS, digital twin and AI-based solutions such as power demand prediction through machine learning. Having a more complete view of the vessel’s operation, and optimization strategies already being available, drives the use of BESS for increased energy efficiency and improved technical performance. (Baldi et al., 2022; Geertsma et al., 2017) Third global driver for investing in onboard batteries is their ability to support other decarbonization technologies like fuel cells and green fuels. Battery can complement other power suppliers as it is capable of power load levelling by absorbing high power demand fluctuations, which isn’t possible or optimal for example on fuel cells. (Melancon, 2022)

Global environment is also setting technological challenges for hybrid vessels. Due to the economic impacts of COVID19, maritime industry and especially the cruise segment has had little to no money to invest in technological research and development. This has led to a possibly slower adoption and innovation of new power supply technologies, also shifting the focus more to the safety aspects. (Det Norske Veritas, 2022c) Shore power availability is another challenge for wider battery adoption. All-electric vessels require shore power for charging, but hybrid vessels could also benefit from charging batteries during port stays, especially when considering zero emission arrivals and departures. The global shore power availability isn’t yet sufficient for cruise vessels to rely on, as they sail on highly varying routes and would at least need to know in advance whether the destination port offers shore power or not since it affects their power supply decision making. However, the adoption of shore power is spreading among ports worldwide, which will drive the maritime battery installations in the near future. United States Environmental Protection Agency’s (2022) recent study states that 68 ports around the world have already implemented the required infrastructure for providing shore power connection, majority of them locating in Northern Europe. Globally tens of ports have committed to building the infrastructure and offering shore power by 2028 (Howard, 2022). Specifically in Europe, EU regulation is requiring, with few conditions, European ports to provide shore power already by 2025 (European Union, 2014).

Environmental

Environmental concerns of climate change and global warming are the main drivers behind all other PESTEL dimensions. They are directing the regulation, customer and stakeholder values, political decision making, as well as technological development. Batteries’ capability of improving fuel efficiency has direct effects on cutting maritime emissions. Battery powered zero emission operation only shifts the time and place of creating emissions, but when combined with shore power and other environmentally friendly power sources, they are able to cut down the total emissions. Onboard BESS enables utilizing RESs both in the form of green shore power as well as renewable energy produced onboard vessel, for example by solar panels. Along with the changing customer and stakeholder values, environmental aspects have also become emphasized in maritime company values. This drives the adoption of hybrid power supply, allowing companies to build a greener brand that will attract both customers and employees. The main environmental concern related to batteries is their high energy and water consuming manufacturing process, which has so far been dependent on the partly toxic raw materials.

Legal

Hybrid power supply has raised a lot of discussion also from the legal aspects. Regulation appears mostly as a pushing driver for considering alternative power sources, but it has also limiting effects on new technologies. Maritime field includes multiple actors that are taking legislative actions with different approaches. United Nations, through IMO, is the main player pushing the environmental change with emission and efficiency requirements for all vessels above 5000 GT. Energy efficiency is measured and controlled with Energy Efficiency Design Index (EEDI) for newbuilds and with Energy Efficiency Existing Ship Index (EEXI) for existing vessels. EEDI requires new vessels to be designed and constructed to have higher efficiency than a set baseline, which depends on the vessel type and size. EEXI on the other hand is a one-time calculation for existing vessels, built before 2023, to rate their energy efficiency and plan for improvements. Carbon Intensity Indicator (CII) is another new mandatory measure for commercial vessels, aiming for continuous reduction on carbon emissions by annual reporting. Carbon intensity is calculated by dividing the total mass of CO_2 emissions with the annual transport work, meaning the vessel’s capacity multiplied by the distance sailed. The CII rating is then the result of dividing the measured carbon intensity with the vessel type specific carbon intensity requirement, which is tightening annually. Based on the CII rating, vessels are labelled from A to E and improvement actions are required on poorly rated vessels (D and E) to continue operation. These regulations aim to address the IMO’s carbon emission reduction target of 40 % by 2030, compared to the baseline of 2008. (International Maritime Organization, 2023a)

DNV is another global actor which is keeping the ship register and setting safety standards for vessels that need or want to receive a DNV classification. Safety is a critical aspect, especially on passenger vessels, shaping the development and adoption of new power sources. Safety requirements of for example battery or fuel cell design, installation, usage, power limits, temperature, ventilation, fire integrity detection and extinguishing measures must be met in order to be approved for the DNV classification register. There are also multiple other actors setting rules related to the hybrid vessel power system, such as IMO, International Electrotechnical Commission and International Organization for Standardization. (European Maritime Safety Agency, 2020) Even though legislation is driving the use of hybrid power supply, the complexity and uncertainty of the continuously evolving regulation is increasing the threshold of investing into the new technologies.

IMO has set several global Emission Control Areas (ECA) where the sulphur or nitrogen oxide emissions are limited, requiring the trespassing vessels to either switch to burning cleaner fuels, wash exhaust gases with scrubbers, or utilize alternative power sources. ECAs aim to protect the nature and people on selected areas by lowering or preventing maritime pollution. (International Maritime Organization, 2023b) Examples of current ECAs are the coast lines of USA, the Baltic Sea, and Hawaii. The Mediterranean Sea has also been approved to be added to the list of ECAs, starting from May 2024. (International Maritime Organization, 2022) Besides multiple global actors, local authorities like countries, coast guards and ports are setting their own requirements for visiting vessels. Some countries, like Norway, are setting their own ECAs on important locations. Norwegian Maritime Authority has proposed listing all fjords of Norway as zero emission zones. This regulation would prohibit vessels from using fossil fuels when sailing on these areas. Zero emission operation is possible with sufficient onboard BESS and supported by the fact that Norway is the forerunner on port shore power availability and renewable electricity. These local regulations drive hybrid vessel solutions that enable the exploration of exotic destinations. (Norwegian Maritime Authority, 2023)

5.3.2 Business drivers for cruise lines

Drivers for the transformation towards sustainable maritime energy sources were discussed in the qualitative interviews from the cruise business perspective. In total seven different drivers were mentioned by the interviewees. These drivers can be put in a weighted ranking order by calculating their priority score with the formula (1) introduced below, in other words giving the weight of 5 for the highest ranked driver of each interview, 4 for the second highest and so on, and then taking the sum of the weighted rankings to get the total priority score for each driver. Hereby the maximum priority score based on the twelve interviews is 60.

$$Driver\ priority\ score = \sum_{Rank=1}^{5} Driver\ occurrences \times (6 - Rank) \qquad (1)$$

The highest ranked driver by all interviewed segments, visualized in Figure 28 below, was regulation with the priority score of 52. It was selected as the top driver by over half of the interviewees, also being placed within the top three by the other half. The effects of regulation were discussed from multiple angles. The new vessel specific CII and EEDI/EEXI measurements force cruise lines more than ever to consider energy efficiency improvements and increasing the share of alternative energy sources in their fleet to cut emissions. Even though regulation is considered as a pushing driver in the global operating environment, it is directly linked to the cruise business as vessels must comply with the requirements to be allowed to sail and create revenue. In an isolated situation the investment cost of improving vessel's energy efficiency would only be compared with the achieved monetary benefit of the reduced fuel consumption. However, because of the new regulation, vessels could be threatened by emission fees or even being forbidden to sail, which then acts as an alternative cost for the investment and makes it much more feasible to take action towards reducing the emissions. Many of the interviewed cruise lines approached the regulation driver more from the perspective of future changes, for example tightening emission requirements or demanding zero emission manoeuvring or port stays. As the regulation can evolve relatively quickly, it was seen beneficial to be proactive on piloting different technologies and making improvements before the whole fleet's power supply is required to be updated. Some of the interviewees who didn't see regulation as the highest priority driver specified that they were considering the present market situation and believed that due to possible upcoming changes the regulation might become the main driver for alternative energy sources in the future.

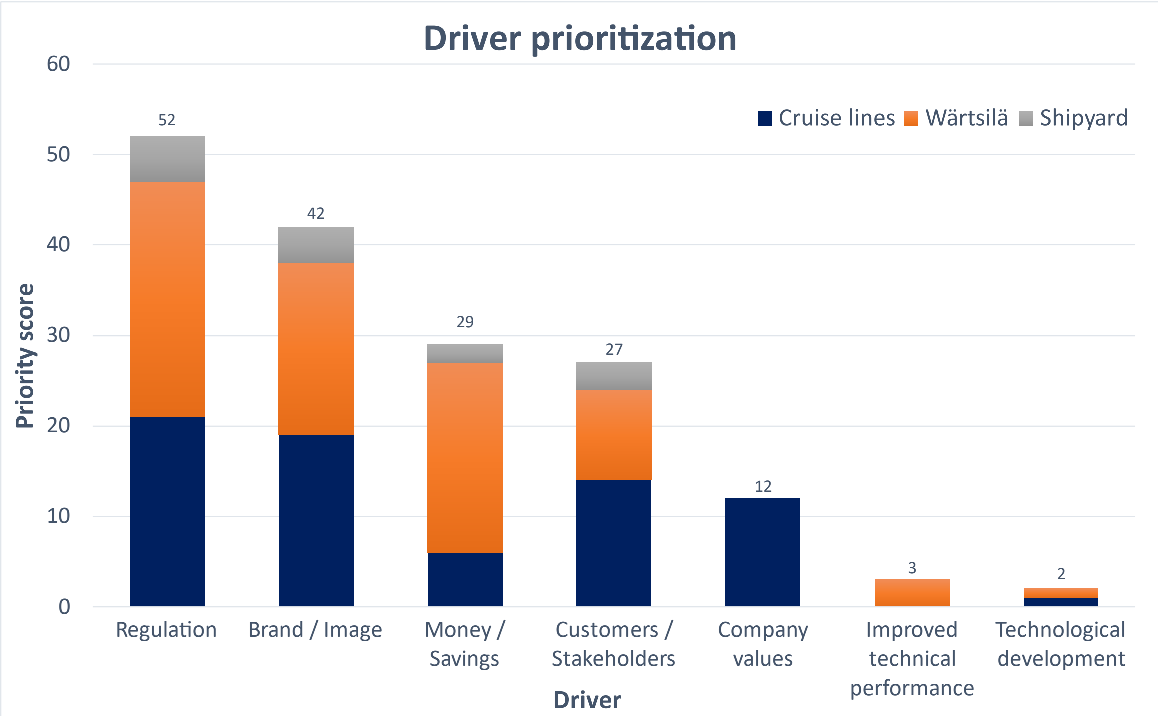

Figure 28. Power supply transformation driver priority

Brand and image was selected as the second most important business driver for the power supply transformation trend, especially in the cruise segment. Five of the twelve interviewees placed image on rank 2 with no deviation between the three interviewed segments. The reasons for seeing branding as such an important driver comes from the low feasibility and long payback time of most of the alternative energy sources. Batteries and fuel cells are still in the development and piloting phase with low to no expected Return On Investment (ROI). On the other hand, RESs like solar power have such low efficiency and minor impact on power supply in the scale of a cruise vessel that they are only used for promoting a sustainable image of the cruise line. The benefits of building a sustainable brand image lay in gaining competitive advantage over competitors by differentiation and increasing revenue by attracting a wider customer base. In the future the importance of branding as a driver might decrease as alternative energy sources are expected to become more feasible due to technological development, improved efficiency, decreased investment cost and increasing fuel prices.

The third place on the weighted driver ranking belongs to money, more precisely on the direct savings achieved from implementing hybrid power supply. As seen in the Figure 28, cruise lines didn’t see notable monetary savings potential in hybrid system that would justify the investment cost and appear as an independent driver. Interviewees from Wärtsilä and the shipyard saw clearly more savings potential in cruise power supply supported by alternative energy sources. While cruise lines’ estimates for savings achieved by battery-based power supply optimization varied mostly between 0 and 3 %, many other interviewees believed in 4 – 7 % monetary savings, however dividing opinions inside the interviewed parties. The main sources of monetary savings were fuel savings due to engine efficiency improvement through load levelling, and lower maintenance costs due to reduced running hours through battery-powered spinning reserve. Money overall is of course another background element which together with the environmental concerns is mirrored in many other drivers. For example, growing the revenue through attracting more customers is eventually behind the branding and image promotion driver. Also, even though regulation has been set to take responsibility of the nature, money is the factor driving cruise lines to follow it, since without complying with the regulation their revenue streams would be cut of as their vessels would be prohibited to sail.

Next driver on the weighted ranking in Figure 28 is customers and stakeholders. This driver includes both the pushing and pulling effects of the cruise lines’ surrounding parties, such as customers and other stakeholders like ports. This driver shared opinions between the interviewed segments, cruise lines emphasizing the pulling effect, especially from their customers’ viewpoint, while others mostly mentioned the pushing effect of the stakeholders. The globally increasing environmental awareness has led to customers demanding more sustainable cruising options to the market. Customer values and green mindset are closely related to branding and image promoting, but some cruise lines saw them separately, green brand driving competition in the market, and meeting customer values improving customer relationships and engagement. Ports and the European Union were considered as the main non-customer stakeholders related to alternative energy sources, mostly from the local regulation point of view. They can control the fuel usage and emissions during port stay and manoeuvring, and are even able to prohibit the ship from entering the port, or for example a fjord, if she doesn’t meet the requirements. However, this driver is separated from the global regulation as it only has local effects and can be avoided, unlike the previously mentioned

CII and EEDI/EEXI regulations. Also, the pulling effect of stakeholders was identified by few of the interviewees, for example through shareowner values and receiving public financial support which is lowering the threshold of investing in the energy efficiency improvements.

The last of the important drivers, mentioned only in the cruise line interviews, was company values. The urge for doing the right thing for the planet and showing the way within the maritime industry were included in the cruise lines' core values and vision. However, the other interviewed segments didn't see cruise lines' own values as a real driver for the change. Rest of the drivers, mentioned only by few interviewees, were improved technical performance and global technological development. Besides improving engine efficiency, batteries can improve the overall technical performance of the vessel for example by grid management and stabilization, and configuration optimization of the power supply system. Technological development on the other hand refers to the availability of alternative energy sources which is driving them to be used for support purposes. For example, fuel cells and engines running with sustainable fuels are not capable for handling power load fluctuations well, which drives the demand for better performing hybrid power supply including onboard batteries or supercapacitors.

5.3.3 Summary of hybrid power supply drivers and barriers

Both the business and operating environment drivers of hybrid power supply together with their effects are summarized in Figure 29 below. The elements listed in the upper part of the figure are considered as motivating drivers, categorized into pushing and pulling factors. The major pushing element for the power supply transformation is the environmental concern which is mirrored in many of the drivers. Emission targets and regulation are the most visible drivers, but also the increasing fossil fuel prices together with company and stakeholder values signal about the shared goal of environmental sustainability in the cruise industry. The pulling factors in the upper right corner of the figure consist mostly of the hybrid power supply benefits, but also include external drivers like decreasing battery price trend and technological development. Performance and efficiency improvements, power supply configuration optimization and reduced engine running hours and maintenance are examples of the direct benefits, whereas brand image, customer values and leading the way in the maritime field are indirect business drivers for cruise lines.

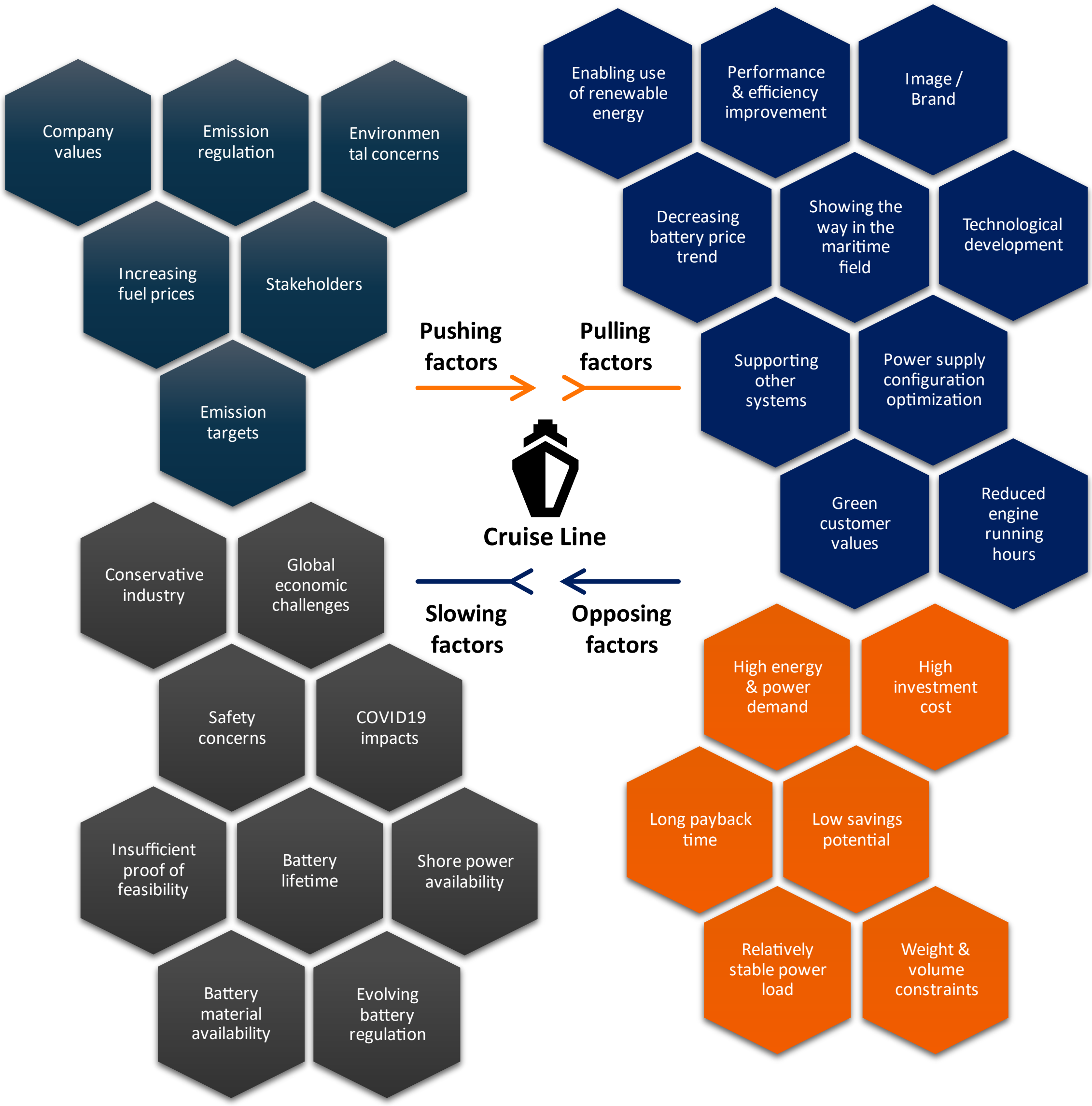

Figure 29. Summary of hybrid power supply drivers and barriers

The elements on the lower part of the Figure 29 in turn are considered as the barriers of hybrid power supply, divided into slowing and opposing factors. Slowing factors rising from the operating environment are global economic challenges, mainly as a consequence of COVID-19 restrictions, evolving battery regulation and battery material availability which can temporarily be seen in the battery prices. From the business perspective the major challenges relate to safety concerns such as fire hazard, global shore power availability which limits the battery charging and usage possibilities, and battery lifetime which greatly affects the investment feasibility and payback time. Insufficient proof of feasibility is hindering the wider adoption of hybrid power supply as per the interviews there are still many energy efficiency development areas on cruise vessels that offer better ROI with lower investment cost. Besides the high CAPEX cost, the weight and volume constraints due to cruise vessel's high power and energy demand are seen as barriers for placing more responsibility on alternative energy sources. Also, the relatively stable power demand profile and high efficiency of diesel engines, even in sub-optimal operation, has opposed the need for investing in hybrid power supply, so far.

5.4 Future of cruise vessel power supply

The power supply in maritime industry is in front of a massive transformation that has already began. The use of fossil fuels will be ran down and replaced with new, renewable, sustainable and emission-free energy sources. The drivers for this transformation are also evolving and shaping the time frame of the change. Rising power supply trends and future technological development can only be guessed, but the predictions can be supported by analysing the drivers and investigating the interests and plans of the market leading companies. This chapter explores the near future hybrid vessel expectations and long-term power supply and energy source trends and technologies in the cruise segment, based on the qualitative interviews done within the scope of this thesis. The threshold between near future and beyond was set on year 2030, which is the first strategic step of IMO's emission reduction plan.

5.4.1 Near future hybrid cruise vessel market expectations

Near future market development of cruise vessel power sources can be forecasted based on newbuild vessel orders, agreed retrofit projects, expert insights and the outlook of technological advancements. Clarksons Research (2023) vessel database already contains a few ordered cruise vessels that will feature onboard batteries, fuel cells or both. However, the orderbook data is only visible for the next few years and might change radically when new orders are placed or plans are changed. Therefore, the market predictions until 2030 are based on the qualitative interview study which combines insights from different maritime segments and companies.

The near future expectations for cruise power sources were incredibly unanimous, even though there was variation in driver prioritization and alternative energy sources under consideration. All interviewees saw combustion engines as the main power source for cruise vessels in the near future, major transformation happening on the fuel side. LNG was already seen as the new standard fuel for the next few years, but the piloting and adoption of truly renewable and sustainable fuels, mainly methanol, e-methane, hydrogen and biofuels, was believed to take place already before 2030. The engine technology for alternative fuels already exists so the main barriers slowing down the adoption are fuel efficiency, availability and cost. Interviewees were also quite unanimous regarding the near future expectations for cruise batteries. Besides the two interviewees that didn’t consider batteries as a feasible investment in the cruise segment, all others believed that the market is going to see more and more battery pilot projects and slowly a wider adoption as a support power source when approaching the year 2030. In the beginning of the adoption, cruise vessel batteries are believed to have small or medium energy capacity, hence the natural use cases are power load levelling through strategic loading and peak shaving, and uninterruptible power supply.

Another reason for battery adoption in the cruise segment was seen in supporting the popularizing fuel cells. Due to the technological immaturity of fuel cells and challenges with hydrogen storage and availability, the schedule expectations for fuel cell adoption were a bit more conservative than for batteries, which is also why green fuel powered combustion engines are currently considered as the highest technological priority. However, majority of the interviewees guessed that we would see multiple smaller size fuel cell pilots before 2030 but the wider adoption will take longer. Fuel cells shared opinions a bit more than batteries, few interviewees discarding the idea almost completely and few others believing in fuel cells taking a major responsibility of service power supply, at first during port stays, already in the near future. Third power source believed to popularize in short-term was shore power, which of course is limited to port stays. However, the impact of shore power is believed to be substantial as it could cut down the port stay emissions completely and also create monetary benefits by reducing fuel costs. Rest of the mentioned alternative power sources were not considered feasible in the near future without significant technological development. Some interviewees predicted small implementations of solar panels to take place in the near future, but their effect on the power supply is extremely limited and the only real driver is the brand image.

5.4.2 Future outlook of cruise power supply technologies

The evolution of cruise vessels' power supply in long-term is unknown. Many factors, currently the most important of which are summarized in Figure 29, affect and steer the adoption and innovation of sustainable power sources. The pulling drivers such as customer and company values lead the development of new technologies, whereas pushing drivers like regulation force the industry to stop the use of old and unsustainable energy sources. The time frame and direction of cruise power supply will evolve over time, but predictions can be made in the light of current knowledge and expert insights. Figure 30 below visualizes a high-level estimation of the diffusion of cruise vessel power supply technologies, based on the market analysis and qualitative interviews. The Y-axis of the figure describes the estimated share of responsibility in newbuild cruise vessel's power supply for each power source.

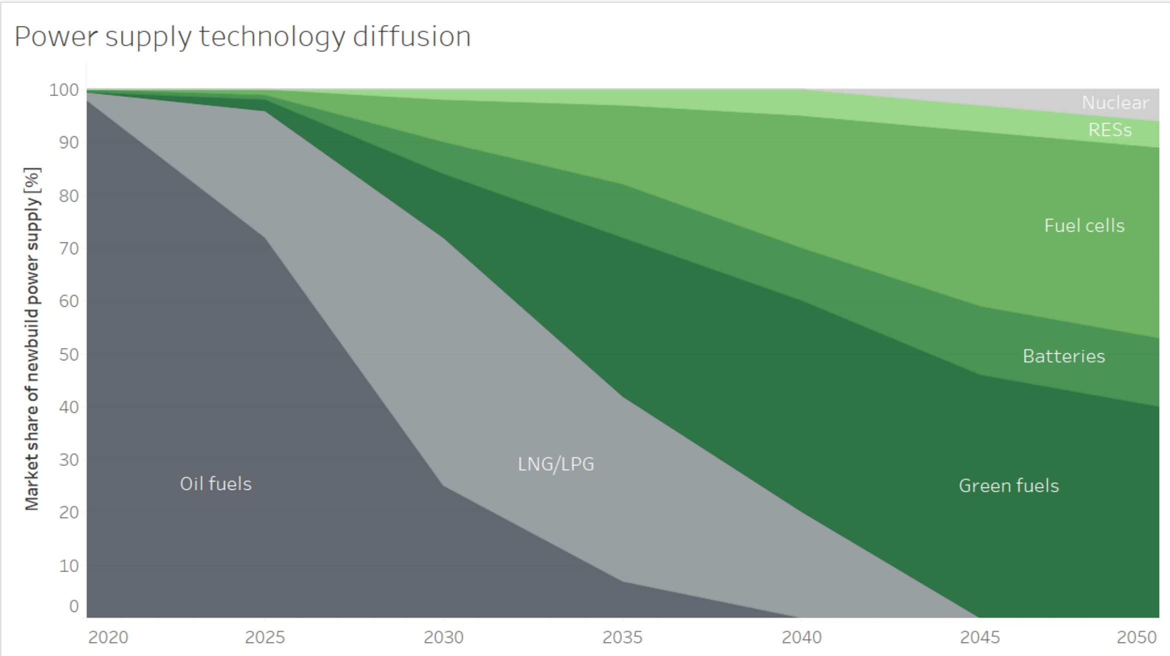

Figure 30. Diffusion of cruise power supply technologies

The first major transformation of driving down the use of fossil fuels has started already during the first decades of the 21st century. Although LNG and green fuels are taking over the market in the near future, the end of fossil fuel powered newbuild cruise vessels will take longer. Based on the vessel orders for the next few years, green fuels, batteries and fuel cells will be piloted on multiple vessels and LNG is starting to compete with the traditional oil fuels. In 2030 the share of oil fuels is expected to drop even below 30 % of the total power supply on newbuild vessels, meaning that vessels could have for example four main engines running on LNG or green fuels and two smaller engines running on oil fuels. The timing of leaving oil fuels completely behind is hard to estimate, but it’s expected to require the final push from the regulation. LNG will act as a temporary fuel while moving towards the sustainable green fuels like methanol, hydrogen, e-methane and biofuels, the adoption of which has already began but is expected to accelerate around 2030. One interviewee also commented on the staggered transformation within the existing fleet, depending on the vessels’ age. Because of the tightening regulation like CII is also targeting existing ships, the oldest vessels are going to retire as it would be unfeasible to update them with new expensive power supply systems that wouldn’t financially break even during their last years of service. Middle aged vessels are expected to be retrofitted with LNG or biofuel capability, for example by Wärtsilä’s dual fuel engines, to boost the energy efficiency and meet the emission requirements for several years (Wärtsilä, 2023d). Newest and cleanest technologies like methanol and hydrogen engines are then implemented in the newbuilds that have long lifetime ahead and act as the flagships for the green transformation.

As green fuels are taking over the market, batteries are also predicted to popularize greatly as a supportive power source. Battery capacity is expected to increase and use cases to expand in the future, also including the possibility of all-electric manoeuvring and in theory even battery-powered port stay. Even though cold ironing is a much more feasible solution for zero emission port stays than utilizing BESS, the increasing global availability of shore power will also drive the adoption of batteries as they enable using onshore produced renewable energy also during sailing. However, the responsibility share of batteries in the Figure 30 is limited as they are not seen as a possible main power source for cruise operation, even in long-term. On the other hand, fuel cells are forecasted to gain ground in the future after the technology matures and is capable for providing higher power levels. Wider adoption and increasing power supply responsibility of fuel cells still requires solving the availability and storage issues of large amounts of hydrogen. Few options to overcome these challenges are the onboard conversion of the easier to store methanol to hydrogen via a reformer, or developing further the competing fuel cell technologies that utilize other fuels such as LNG or methanol. With these advancements, fuel cells could potentially take a bigger role in the cruise power supply, even replacing few engines, if combined with batteries for handling the load fluctuation. Some interviewees also saw that with great technological development cruise vessels could be capable of operating fully on battery supported fuel cells in the future.

Last two energy sources mentioned in the Figure 30 that are expected to be part of the cruise industry's future are nuclear and renewables, meaning solar and wind power. RESs are not believed to be capable of handling the whole power demand of a cruise vessel, rather working as accessory energy, mainly for branding purposes. The space, efficiency and architectural constraints related to RESs are still hindering the adoption in the future, but with technological development and innovative solutions, such as the EU-funded Envision solar panel windows, they could in long-term popularize in the cruise segment. Wind power was seen as a technology with higher impact on the power supply, but with even lower applicability to cruise vessels. Nuclear power was sharing opinions but great future potential is associated with it. Due to regulation, safety risks and public concerns, nuclear is not expected to make an appearance in the cruise segment before the year 2040, but modern versions of nuclear power, such as molten salt reactor, were considered as a real possibility. Nuclear energy offers high power with relatively low volume and weight and it could be coupled with batteries to even out the load fluctuations. Batteries, fuel cells and nuclear power were seen as the only possibilities for all-electric engineless cruise vessels in distant future, but there wasn't expected to become the need for engineless operation as the new green fuels could be utilized with zero life-cycle emissions.

6 Battery savings potential analysis

Expectations of high popularization and various benefits through multiple use cases have been linked to maritime battery systems, also in the cruise segment. Wider market adoption of hybrid power supply is taking place among ferries and small passenger vessels, also starting to reach the merchant segment. As cruise vessel's operating profile poses challenges for the utilization of onboard BESS, cruise segment hasn't yet adopted batteries widely, but has shown rising interest by investigating and piloting batteries. One factor slowing down the cruise hybridization is the insufficient proof and research on battery investment feasibility. Since there is only few large size vessels utilizing batteries in power supply, the operative savings through reduced fuel consumption and engine running hours are difficult to estimate for a cruise vessel. However, digitalization and new advanced technologies create possibilities for analysing the savings potential.

Few cruise hybridization savings potential estimations can be found in the academic literature, all of them suggesting a maximum 5 % reduction in fuel consumption. Cruise vessels have the lowest potential among all vessel types, since the average savings in the market are around 10 – 20 % and the highest potential of 100 % is associated with ferries and tugboats that can be fully electrified. (European Maritime Safety Agency, 2020) Operational monetary savings achieved through battery-based performance optimization must exceed the battery CAPEX cost during its lifetime to justify the investment financially. However, batteries also create other benefits such as emission savings and possibly increased revenue due to improved brand image. For example, besides saving over 900 tons of fuel annually, Hurtigruten's Roald Amundsen is estimated to cut its yearly CO2 emissions by 20 %, meaning around 3000 tons, by power load levelling and peak shaving enabled by its 1.36 MWh BESS (Corvus Energy, 2023b; Lockhart, 2019). These non-monetary savings are more difficult to include in the calculations, but must be taken into account in the investment decision making.

One option for analysing cruise battery savings potential and assessing the investment feasibility is simulating BESS onboard a cruise vessel. Digital twin technology enables making a copy of a vessel or its system which can then with IoT sensor data be simulated in real-life or imaginary scenarios to assess its operational performance. Digital twin can also be used to virtually estimate the effects of changing vessel systems or configurations, for example by simulating a BESS onboard the vessel or by removing one engine completely. This technology enables estimating battery installation's impact and feasibility for both newbuilds and retrofits, for example to support the decision making of upgrading vessels to meet regulatory emission requirements. This chapter introduces the background, configurations and limitations of the hybrid cruise vessel simulations done within this thesis. The simulation process is described and demonstrated with a simple case example, after which the full simulation results are summarized and analysed both from the monetary and emission point of view. Finally, the results are used to estimate the fuel and emission savings potential on a cruise vessel.

6.1 Background of the simulation

A battery simulation is conducted within this thesis study to estimate the battery savings potential for cruise vessels. The analysis is done by utilizing Wärtsilä's internal simulation tool which uses digital twin technology and real-life vessel data to enable as accurate savings estimates as possible. The simulation process is visualized below in Figure 31.

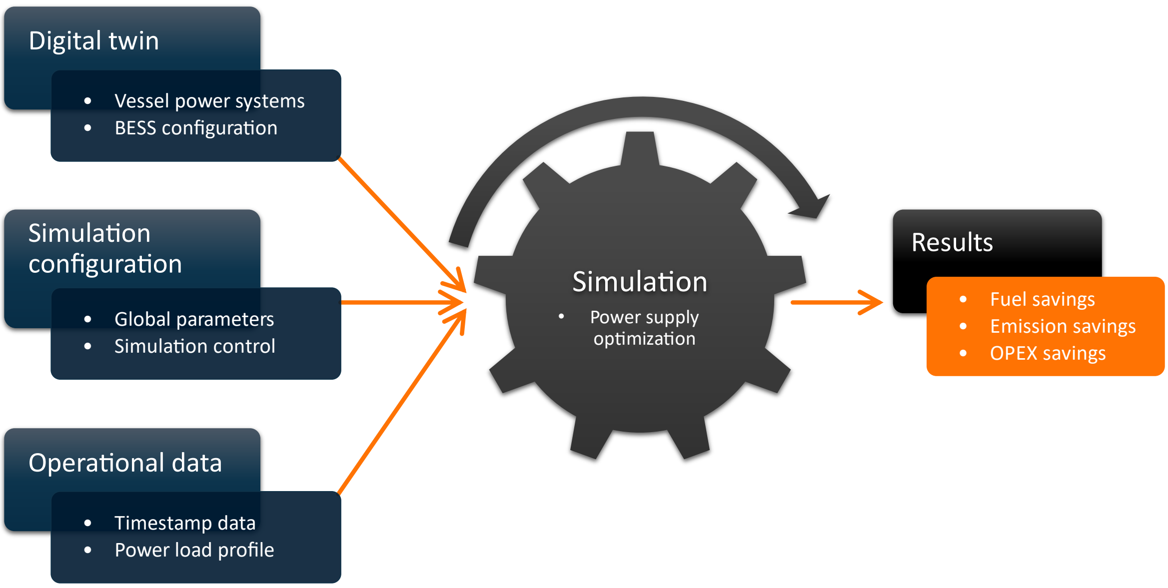

Figure 31. Battery simulation process

The simulator requires three types of inputs: digital twin of the vessel, simulator control configuration, and vessel's operational data. Digital twin of the vessel is created by modelling the vessel's whole power train from suppliers to consumers. In practice it means inputting all relevant information related to the engines, propellers, thrusters and service power. Based on the given data, the simulator builds a modular end to end digital copy of the vessel's power system. The digital twin can also be extended with the studied systems, in this case modelling BESSs with different characteristics, to enable scenario comparison. The second input needed for the simulations is the control configuration. This includes choosing time steps and power limits and controlling the use of engines, batteries and shore power. Another part of simulation configuration is defining global parameters such as fuel prices and emission factors, shore electricity price, maintenance and running costs. Final piece of inputs is the case vessel's operating profile, which is given as time series data. This data is queried both from the vessel's AIS and IAS systems, containing for example speed, draft and location data, vessel's operating mode, and power demand profile.

After configuring the simulator and giving all required input data, the simulation can be run. Simulator combines the defined power supplier and consumer modules into a digital power train and begins going through the given time series data. At each time stamp, the optimal power supply combination is chosen based on the power demand, available power sources and price data. For example, during sailing the simulator runs the vessel on optimal engine combination to reach the lowest possible SFOC of the engines, and then uses batteries to absorb the load fluctuations as much as possible considering the C-rate and remaining SoC. Another example can be given from port stays, where the cost of shore electricity, if available, is compared to the cost of burning fuel and the decision is made by minimizing the costs. However, the simulation control options enable forcing the use of shore power if it's available, for example if the destination port has forbidden burning fuel during port stays. The simulation takes into account losses in power transmission and conversions, also estimating the amount and cost of consumables such as engine lube oil and urea, which is used for reducing the vessel's nitrogen oxide emissions (Yara, 2018).

When the simulation is complete, the results can be reviewed and summarized from the processed time series data. The results include the chosen power sources and power supply loads, as well as their costs, at each time stamp. This data can then be analysed to build a picture of the simulated systems' differences in fuel consumption, engine running hours, emissions and operating costs. The average savings achieved in the simulated time frame can be extrapolated for one year of operation, and even over the battery or vessel lifetime to enable investment feasibility assessment. However, the selected time frame must represent the vessel's typical operating profile as well as possible, and still the savings results must be considered as rough estimates because of the long extrapolation and possible simulation inaccuracies. That being said, the results can give valuable information for the investment decision making, especially by increasing the insightfulness with sensitivity and scenario analyses. The simulator can be used for estimating the feasibility of both newbuild and retrofit battery installations, also enabling the optimization of the existing power supply system.

6.2 Case simulation configuration

Battery simulations in this thesis study are done for two case vessels from the newbuild battery perspective. Even though battery retrofitting can be a feasible option for improving existing cruise vessels' energy efficiency, the investment profitability assessment can be more accurately done for newbuild vessels where the installation costs have less variation and engine configuration can also be modified without additional costs. Case vessel selection was done based on vessel characteristics, data quality and availability. Two relatively new cruise vessels from different size ranges and with different engine configurations were chosen to enable comparison of similar battery systems in different scenarios. Case vessel characteristics together with their engine configurations and simulated battery systems are summarized below in Table 4.

Table 4. Case vessel characteristics

Vessel	Age [y]	Capacity [GT]	Length [m]	Number and size of engines [max MW]	Battery capacities [MWh]	Battery C-rates
Vessel X	< 5	< 150 000	> 300	2 X 14 2 X 10 1 X 7	2, 6, 10	1, 2, 3
Vessel Y	< 5	> 200 000	> 350	2 X 19 4 X 14	2, 6, 10	1, 2, 3

Vessel and engine configurations were done precisely based on the information available on their characteristics and operation, for example on engine specific fuel consumption from the SFOC-curve. Other element that was defined precisely is the battery options. In this case study three battery capacity sizes, each with three different C-rates, were simulated. Rest of the configurations and global parameters are assumptions based on available information. Detailed configurations are summarized in Appendix 3. Both of the case vessels burn HFO and MGO, the prices and emission factors of which are taken from the global averages (Engineering ToolBox, 2009; PBT International NV, 2023; Wu et al., 2018). For simplicity, the maximum power and price of shore connection are fixed and two separate scenarios are simulated: one without shore power and one with shore power available on all ports. Reliability of the savings potential analysis is also increased by simulating multiple routes with port stays in between within the voyage.

Power supply OPEX and battery CAPEX are two assumption elements having a major effect on the results, which is why they will be included in the sensitivity analysis. BESS investment cost is assumed to be 850 €/kWh, which is supported by the literature review results summarized in Table 2. However, slightly increased prices are used for batteries with higher C-rates in the analysis. Around 2.7 % share of the battery's total life-cycle costs, referring to ~3000 €/year, is used to calculate the annual maintenance costs for the 2 MWh batteries, but the maintenance cost increase for C-rate and capacity upgrade on bigger batteries is assumed to be limited. It is worth mentioning that the battery OPEX only includes maintenance costs, and shore power costs are calculated separately. Engine investment costs are assumed to be around 5 – 10 million euros depending on the engine size, price per kilowatt being between 450 and 650 €. Power supply OPEX consists of multiple elements, main ones being fuel costs, engine maintenance and other consumables like lube oil, urea and caustic soda. Fuel costs will be analysed separately in the simulations, and engine OPEX will include maintenance costs of around 40 – 60 €/h_r, depending on the number of cylinders, and non-fuel consumable costs of 90 – 130 €/h_r depending on the engine size. Hereby the total OPEX of the power supply consists of fuel costs, engine running and maintenance costs, battery maintenance costs and shore power costs.

One more assumption done for the simulations is using the same power demand profile data in all scenarios. In practice this means ignoring the battery's possible negative effect on the vessel's power demand, except for the battery charging. Installing a battery to support the engines adds weight to the vessel which increases the draft and results in increased power demand through increased frictional resistance between the water and hull. However, the weights of the simulated batteries, are less than 0.1 % of the case vessels' gross tonnage and therefore assumed to have only a limited effect on the power demand. The cells of a 10 MWh battery are estimated to weight around 70 – 80 tons based on the li-ion energy density shown in Table 1, and the weight of the whole BESS could be over 100 tons according to Corvus Energy (2023d). Also, the weight of the vessels can be controlled for example by emptying ballast water tanks of removing engines or water tanks completely. Additionally, energy efficiency improvement technologies such as the air lubrication system could be installed to reduce the water friction (Silverstream Technologies, 2023). For simplicity, the power demand effect of the increased weight from the battery is in the simulations assumed to be zero.

6.3 Simulation case example

The simulation of both case vessels with different voyages and multiple battery and shore power combinations is a large exercise that would not add to the understanding of the basic idea of the simulation. The simulation process (Figure 31) can be more clearly demonstrated in-detail with a one route example that reveals insights of the battery usage and benefits. Vessel X is configured and used for this case example to visualize the idea of the simulation. The selected example route contains all vessel operation modes (at port, manoeuvring, and sailing) and all battery use cases (peak shaving, strategic loading, all-electric manoeuvring, and shore power charging) that will be incorporated in the full simulation. Final simulation results are then calculated from the combination of selected scenarios on a longer voyage consisting of several sailed routes and port stays.

Case route: Road Town - Nassau

Figure 32. Case example route

Figure 32 above visualizes the sailed route from Road Town in British Virgin Islands to Nassau. The example begins with a port stay and ends to a port stay, including manoeuvring phases in both ends and stable sailing in between. These types of straight routes have typically lower battery savings potential due to low load fluctuations, but the benefits can be seen during the manoeuvring phases. The power demand profile of the case example, given as a time series input data for the simulator, is visualized in Figure 33 below. Power demand categories are coloured and divided into propulsion, thruster, and hotel powers, where hotel power includes all service power components (Figure 5) except for the thrusters. The graph clearly shows that the hotel power demand is continuously high, even during port stays, thrusters are used only during the manoeuvring phases, and propulsion power is high but relatively stable on an optimally sailed straight route.

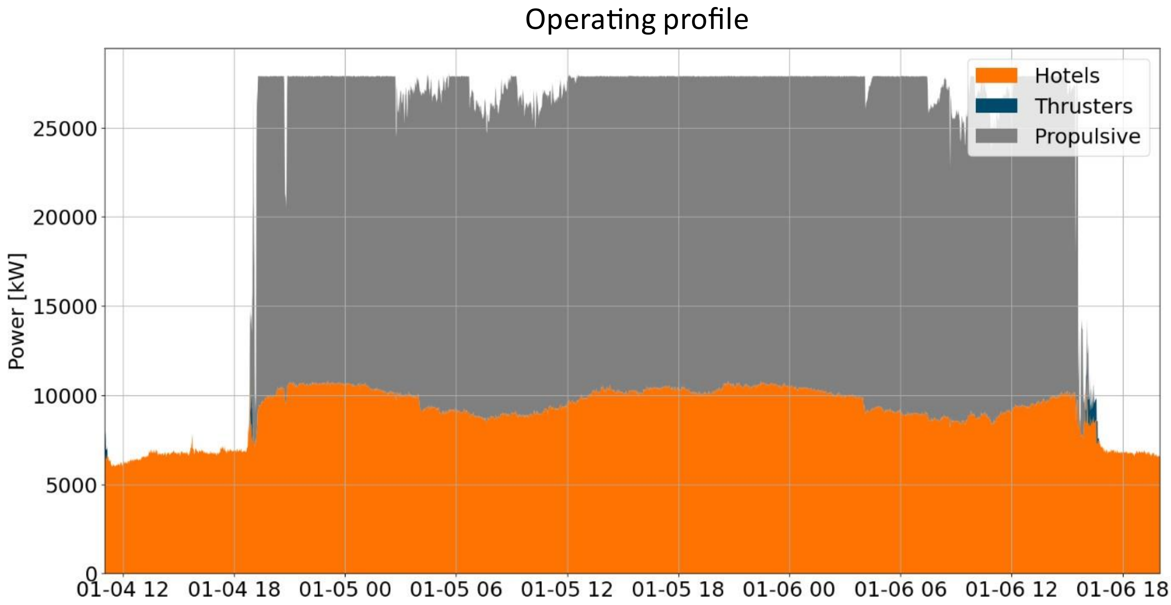

Figure 33. Case power demand profile

After receiving the required configuration and input data, simulator optimizes engine and battery usage to minimize operational expenses such as fuel consumption and engine running costs. Figure 34 below visualizes the power levels and power sources of the simulated 6 MWh 3 C battery hybrid power supply system. We can see that the simulation starts with shore power supplying the hotel power demand. In the very beginning, the shore power consumption is higher than the total consumer power due to the battery being also charged. The total consumer power rises quickly when the vessel starts manoeuvring out of the port area, requiring the start of three of the five engines. Few engine changes are done during the load fluctuations to minimize the total SFOC, but mainly three engines, two large ones and one medium sized, are run and supported by battery-powered load levelling. When approaching the destination port of Nassau, simulator changes the running engine combination and performs manoeuvring with battery-powered peak shaving. After arriving at the port, the vessel is connected to the shore power for hotel power supply and charging the battery.

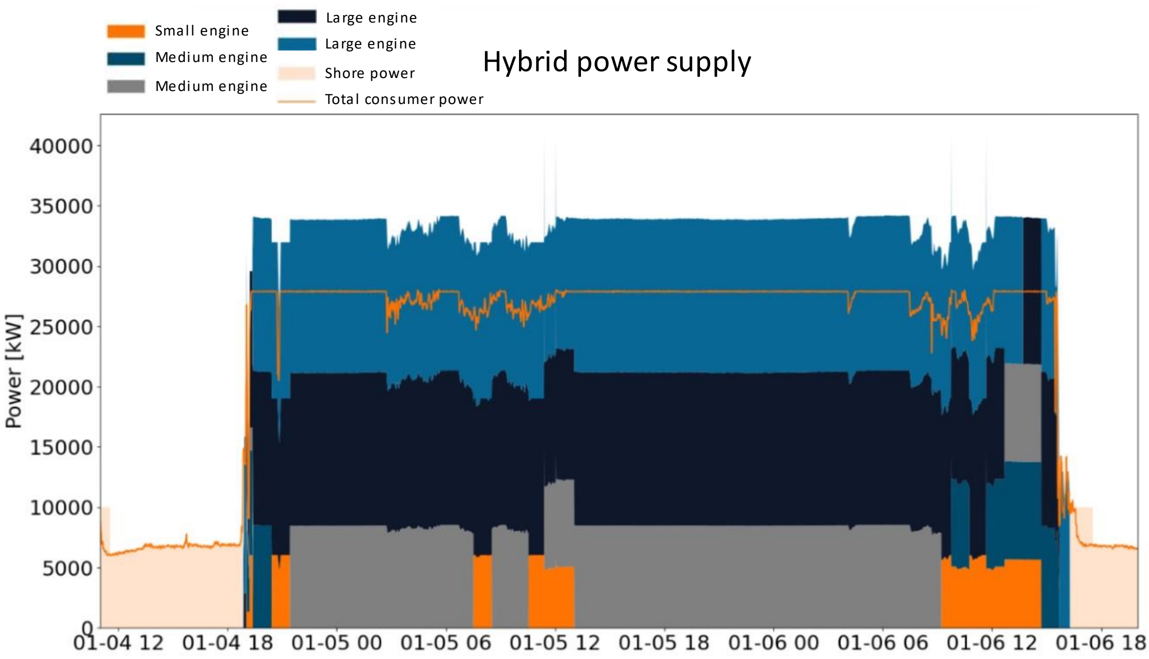

Figure 34. Optimized case hybrid power supply

Figure 35 below presents the same case example from the battery perspective, blue and green bars representing battery charge and discharge powers, and orange line visualizing the battery's state of charge. With shore power the battery SoC is increased to the predefined maximum of 80 % to enable long battery lifetime and safe operating voltage. During the manoeuvring phase battery is used for both positive and negative peak shaving. In this case the 6 MWh 3 C battery is capable of handling even the over 10 MW power peaks. During the first power load drop and engine change after manoeuvring out of the port area, the battery is being discharged to enable strategic loading by sailing with smaller engine. During the stable and straight sailing the battery is used fairly little, only to balance the slightest load fluctuations to enable optimizing engine SFOC. During the first higher power fluctuations at around 03:00 on 5.1, batteries are capable of preventing changes in the number of running engines, even though the engine loads are slightly changed. Battery's absolute low SoC limit has been set to 20 % and preferrable low SoC limit to 25 %, which can be seen as the level where battery is no longer discharged before charging it first. During the port arrival battery is again used for peak shaving and then charged back to 80 % SoC with the shore power.

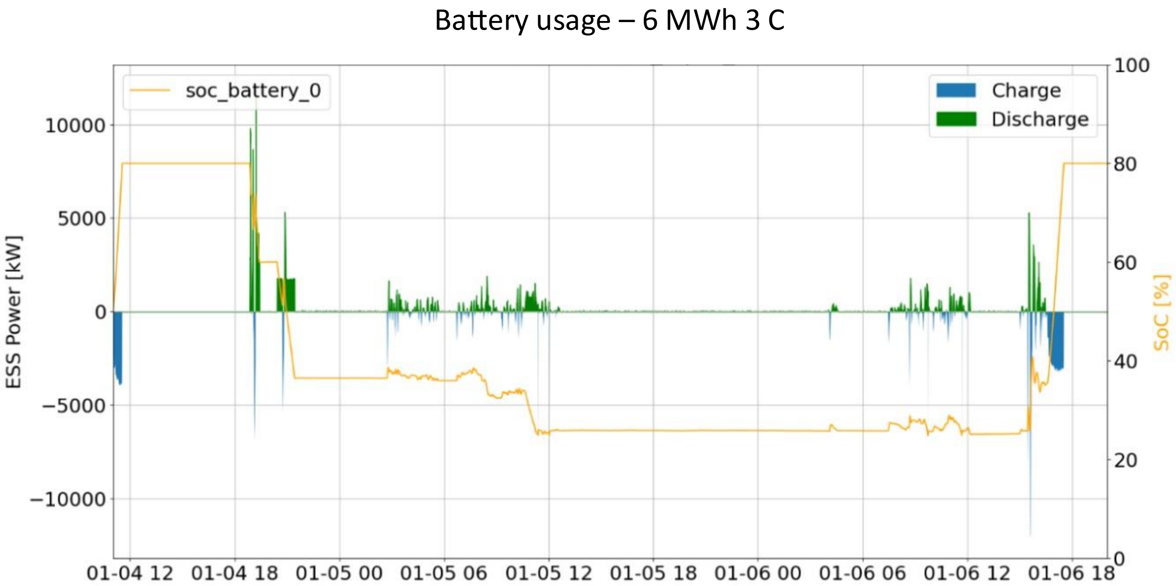

Figure 35. Case example battery usage

Simulating one route might not represent the vessel's typical operating profile and therefore isn't sufficient for reliably analysing the effects and feasibility of a battery installation. This requires the simulation of a larger data set which is performed next, each of the simulated routes following the battery usage and power supply OPEX optimisation idea demonstrated in this case example.

6.4 Simulation results

In total five simulations are done within this thesis study, with and without utilizing shore power for both of the case vessels, and one with changed engine configuration for vessel X. Each of the simulations compare vessel operation with nine different battery systems to the conventional diesel-electric reference system. To eliminate the effect of supplying service power with shore electricity from the analysis, case scenarios where shore power is available are compared to a conventional reference that also utilizes shore power. This way the scope of the analysis is kept in studying the effect of batteries instead of including the major benefits of cold ironing. However, the benefit of charging batteries with shore power, which is expected to popularize in the near future, still remains in the analysis. Overall, the simulated fuel and OPEX savings were low and in the ballpark of the estimates from existing research. It must be emphasized that the simulation is based on multiple assumptions and only showing rough estimates of the reality. The simulator only analyses direct battery savings without taking indirect savings and benefits, such as branding, into account. Main benefits of cruise batteries are achieved during manoeuvring, which accounts for around 4 – 5 % of the total time simulated, as seen in the simulation configurations (Appendix 3). However, the savings potential during sailing, which accounts for ~70 % of the time, is very low for cruise vessels operated with optimal engine configurations and loads, which lowers the total OPEX savings potential.

6.4.1 Voyage simulation result breakdown

The two main elements of the results, also acting as major drivers for hybrid power supply, are costs and emissions. Simulated vessels' operating costs consist of fuel, shore power, battery maintenance, and engine consumables and maintenance costs together referred to as running costs. Results of the conventional power system simulation are used as a reference for the battery simulations which then enables calculating the absolute and relative savings.

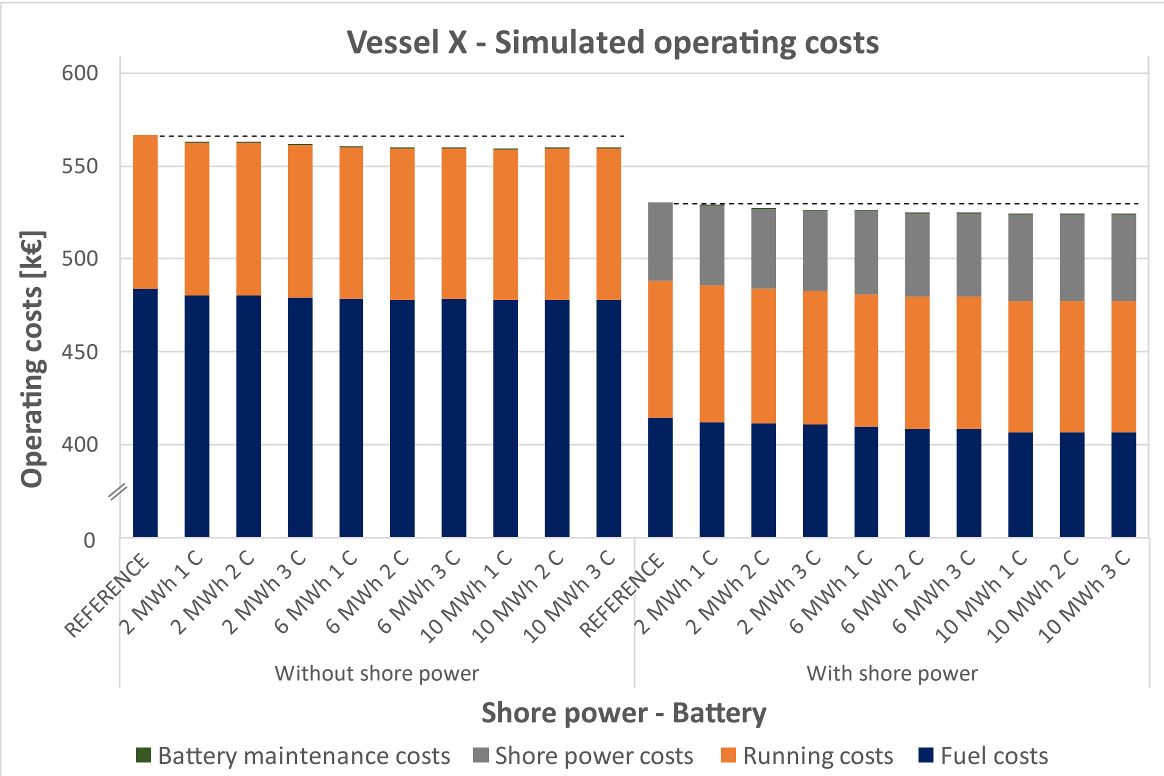

Figure 36. Vessel X - Simulated operating costs

Figure 36 above visualizes the operating costs of the simulated voyage for case vessel X with each battery and shore power scenario. The Y-axis is cut to enable easier comparison between the conventional (reference) and hybrid (battery) systems. The difference between hybrid and conventional systems' costs is marginal but visible. In the simulations without shore power, the fuel and running cost savings are bigger than the additional battery maintenance costs, which indicates small savings in the total operating costs. Much more clear insight seen in the graph is the major cost savings of incorporating shore power. Cold ironing and shore electricity powered battery charging cuts the voyage fuel costs significantly by ~70 k€ and engine running costs by ~10 k€. After adding the ~40 k€ shore electricity costs to the OPEX, we are left with ~40 k€ savings, with the assumed shore power price of 0.1 €/kWh. In the shore power simulations, increasing the battery size also increases shore power costs, but the achieved fuel and running cost reduction is larger and savings are created.

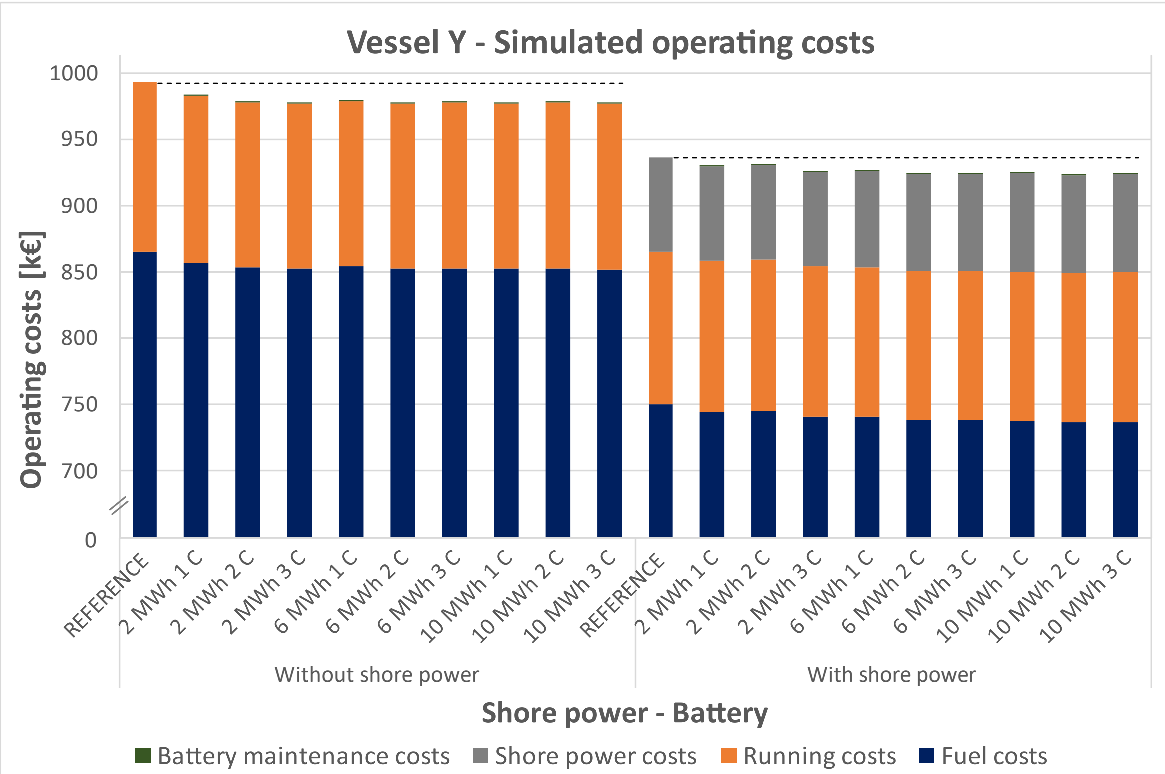

Figure 37. Vessel Y - Simulated operating costs

Figure 37 above shows the same cost information for the larger case vessel Y. Due to the vessel size and higher power demand the operating costs are almost twice as high as on vessel X. Here the difference between reference and hybrid simulation costs is clearer than on vessel X. Also, the trend of decreasing operating costs when enhancing the battery capacity and C-rate seems to be slightly stronger and continues through the entire case battery scope. The savings of incorporating shore power are also clear, but seem to have relatively smaller effect than on the vessel X. In reality, the price of shore power has a major impact on the savings equation, and the price can vary a lot among ports around the world. In this case simulation, if the price of shore electricity is doubled from the assumed 0.1 to 0.2 €/kWh, the monetary benefit of shore power would be lost and the main driver, together with the pushing regulation, would be the emission savings.

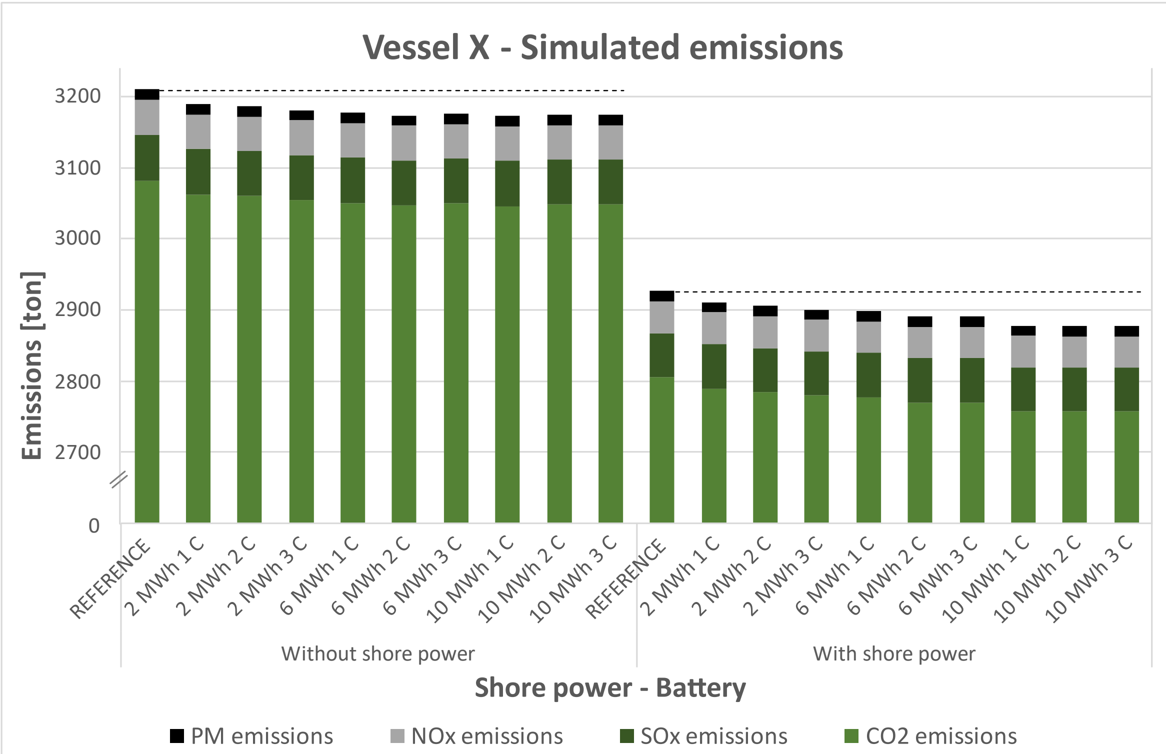

Figure 38. Vessel X - Simulated emissions

Emissions are the second important element under examination in the simulations. Figure 38 above visualizes the four main maritime emissions, Carbon Dioxide (CO2), Sulphur Oxide (SOx), Nitrogen Oxide (NOx) and Particulate Matter (PM), in tons emitted during the simulated 10-day voyage. As the Y-axis is again cut for easier comparison between the simulated scenarios, it is clear that CO2 is the major emission with over 3000 tons emitted without shore power and almost 2800 tons when shore power was available. SOx, NOx and PM emission amounts are much smaller, but their effect on the environment and health of the exposed people, especially in port areas, is substantial. Decreasing trend is visible also in the emissions when increasing battery capacity and C-rate, until reaching the highest savings potential of vessel X with the 10 MWh 1 C battery. The emission reduction when utilizing shore power is massive, in total almost 300 tons, but even more important is the fact that the emissions are cut completely during port stays by using shore connection, which eliminates the vessel's polluting effect within the port area.

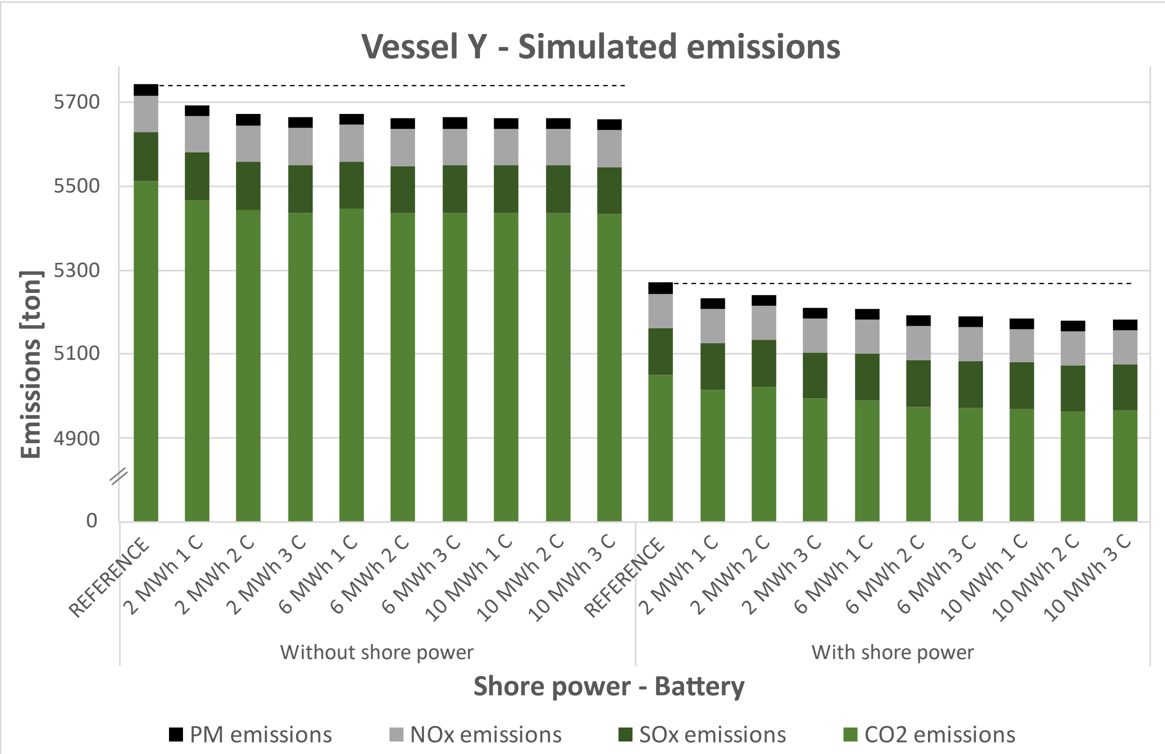

Figure 39. Vessel Y - Simulated emissions

Similar effects and trends are also seen in Figure 39 above for vessel Y. Like costs, the emissions are also almost double the amount as on vessel X because of the higher power demand on the larger vessel Y. The reduction effect of shore power is significant, in total over 400 tons, but again the relative benefit is slightly smaller than on vessel X. This difference indicates that the propulsion power demand for vessel Y is relatively higher than the service power demand, when compared to vessel X, since cold ironing only affects the service power emissions during port stays. Batteries show great potential for reducing emissions also on vessel Y, especially when coupled with shore power connection.

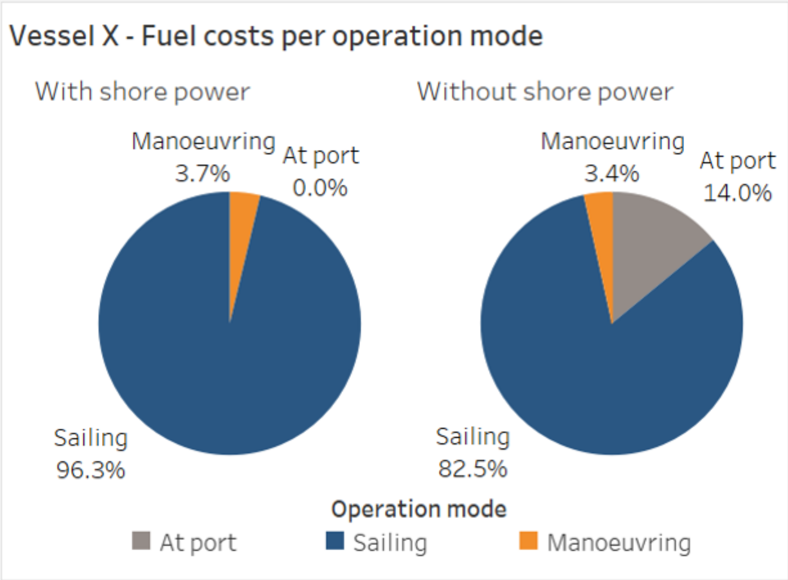

Figure 40. Vessel X - Fuel costs per operation mode

For further investigation of the battery usage and benefits, the origin of the operating costs can be broken down into the vessel operation modes which are sailing, manoeuvring, and at port. Shore power costs are fully incurred during port stays, while for example the fixed annual battery maintenance costs can be distributed evenly to all operation modes based on the time spent in each mode. The two most important operating expenses are fuel and engine running costs. They are dependent on the engine load and running hours and therefore create costs without a direct connection to the time spent in each mode, rather being connected to the power demand and its stability. The simulated fuel costs of the 10-day voyage are broken down in Figure 40 above for vessel X with conventional power supply system. We can see that without having shore power available, the fuel costs follow the time spent in each operation mode (Appendix 3), but is focused on the sailing phase. On the other hand, when shore power is available, port stays don't create any fuel costs and their share is divided between sailing and manoeuvring modes. Manoeuvring is responsible for ~3.5 % of the total fuel costs, which is a relatively small portion of the total OPEX. However, manoeuvring is the phase where engines are run least optimally due to high spinning reserve requirements and power demand fluctuations, therefore having the most potential for battery-powered optimization.

6.4.2 Battery savings potential

The OPEX savings potential, comparing hybrid power supply system to the conventional one, is calculated by dividing the achieved monetary savings with the reference costs from the conventional system simulation. Overall, the results of the simulation correspond to the expectations of increased savings potential achieved by increasing battery capacity and C-rate for both vessels. However, the average OPEX savings potentials are quite low, around 0.6 – 1.6 %.

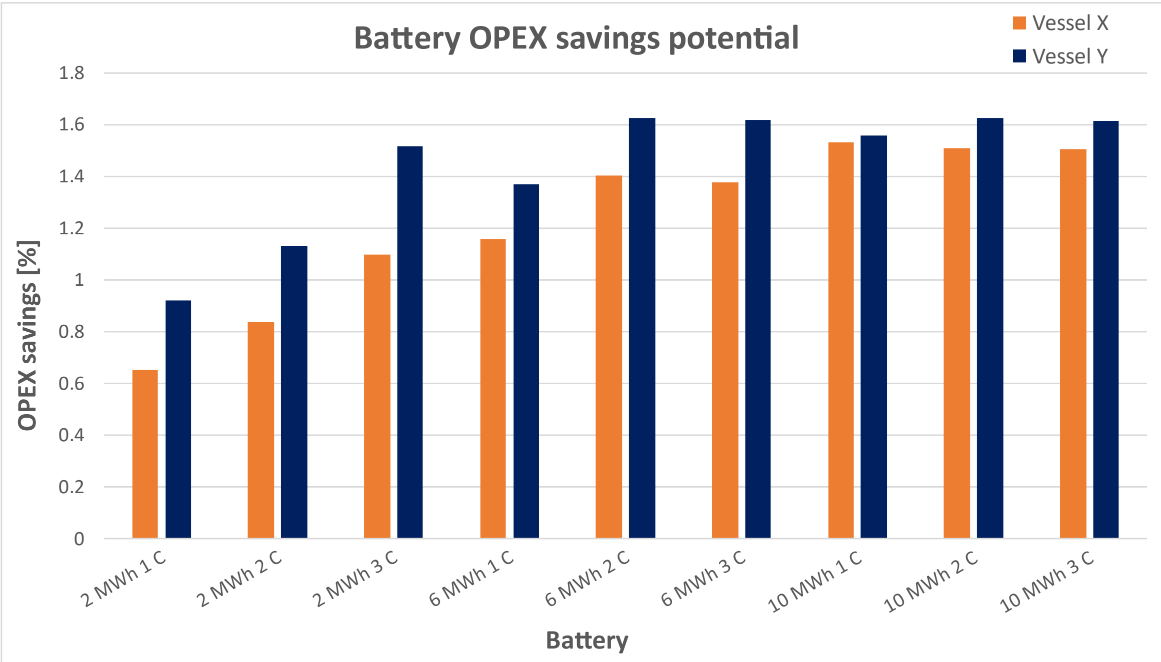

Figure 41. Simulated battery OPEX savings potential

Figure 41 above visualizes the monetary savings potential of each simulated battery system for both vessels, averaging both scenarios of shore power availability. Here it’s clearly visible that the larger case vessel Y has higher savings potential on each battery scenario. The reason for this is most likely in the engine configurations, as the larger vessel only has large and extra-large engines, which limits the possibilities of reaching the optimal SFOC in conventional power system without BESS. For the smaller case vessel X, the savings potential increases steadily to ~1.5 % until 10 MWh 1 C battery, after which the potential starts slightly decreasing. This decrease is mainly caused by the increased battery maintenance costs without achieving additional fuel or running hour savings by increasing the large battery's C-rate. For the bigger case vessel Y, large batteries show quite stable savings potentials regardless of C-rate or capacity. This indicates that slightly increased fuel and running hour savings are achieved by upgrading the battery, but they are in line with the increased battery maintenance cost which eliminates the increase of the potential.

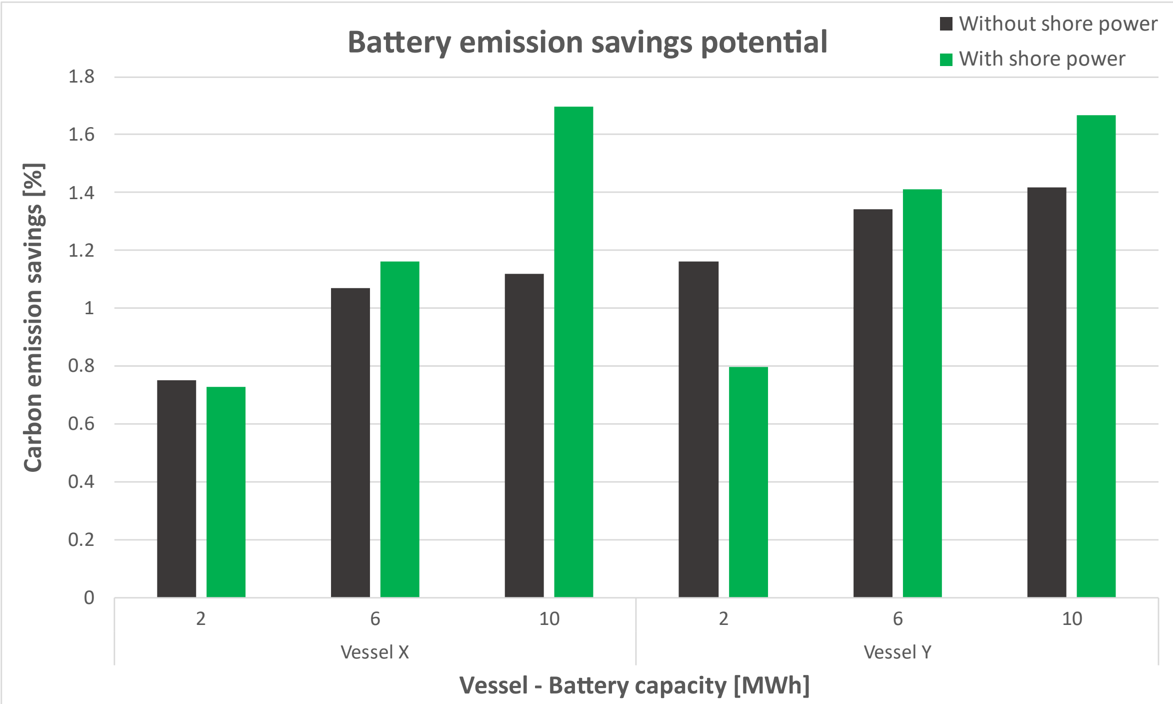

Figure 42. Simulated battery emission savings potential

Battery emission savings potential can be calculated similarly, comparing the simulated battery scenarios to the conventional reference. Figure 42 above visualizes the percentual carbon emission savings potential for each battery capacity and for both vessels with and without shore power. Emission savings follow the same increasing trend as OPEX savings when the battery size is increased. The increases of potential by upgrading the battery within the scenarios utilizing shore power are much higher than within the isolated battery scenarios. This can be explained by the batteries being charged with green shore power, the emissions of which are excluded from the analysis. The bigger the battery, the more it can benefit from the shore energy during the voyage by replacing engine power with green battery power. What is interesting is that for both vessels the 2 MWh battery seems to have higher emission savings potential in the isolated scenario than when shore power is available. This difference can be explained by the challenges of the simulated small batteries that are not capable of fully supporting strategic engine loading and caused new engines to be turned on unnecessarily often. Also, small batteries don't benefit as much from the shore power charging than larger batteries so the overall savings remain low. These insights indicate that 2 MWh battery doesn't enable harnessing the full potential of hybrid power supply on large size cruise vessels.

One interesting insight from the emission aspect is the hybridization's effect on the vessel's carbon intensity indicator. Based on the simulation result extrapolations, the annual CII rating can be calculated and compared between the conventional and hybrid systems to illustrate the battery's emission benefits, also from the regulation point of view. The simplified formula (2) for calculating CII is presented below (adapted Det Norske Veritas, 2023b). The correction factors are vessel type specific constants and same for all cruise vessels. The CII rating is received by dividing the calculated CII with the vessel type's required CII, which tightens by 2 % every year, and comparing the result to the rating limits from A to E. (ClassNK, 2021)

$$CII = \frac{Annual\ CO2\ emissions}{Annual\ distance\ travelled\ \times Gross\ tonnage} \times Correction\ factors \qquad (2)$$

The CII calculation also considers emissions produced during port stays even though no distance is travelled, which drives strongly towards the use of shore power. However, as shore power cuts the port stay emissions completely, both of the simulated case vessels would reach the highest CII rating A, which is why studying the scenario without shore power gives more insights on the hybridization's effect. Annual development of the estimated CII rating for both of the simulated case vessels without shore power is visualized below in Figure 43, coloured by the power supply system. The rating limits are shown on the Y axis and labelled for each scenario, based on the annual CII requirement. The figure clearly shows that the smaller vessel X has a much better CII rating than the larger vessel Y. However, as already seen in the emission savings potential (Figure 42), hybridization has a slightly higher impact on the emission efficiency of vessel Y when shore power is not available. Even though the battery's emission savings potential is only 0.7 – 1.7 %, Figure 43 shows that it can have an impact on the CII rating. For vessel Y, the CII rating of 2023 with conventional system is C, but incorporating a BESS would be able to improve the rating to B. In the following years with tighter CII requirements, vessel Y falls into the rating C regardless of the power supply configuration. On vessel X in turn the CII rating is A for the first two years, but with hybrid power supply she's able to stay one year longer in the highest rating before falling to B. Based on the simulations, both of the vessels are on the higher end of the CII rating scale, but even with the small effect achieved from the hybridization the rating can be improved, which can have a higher significance in the future.

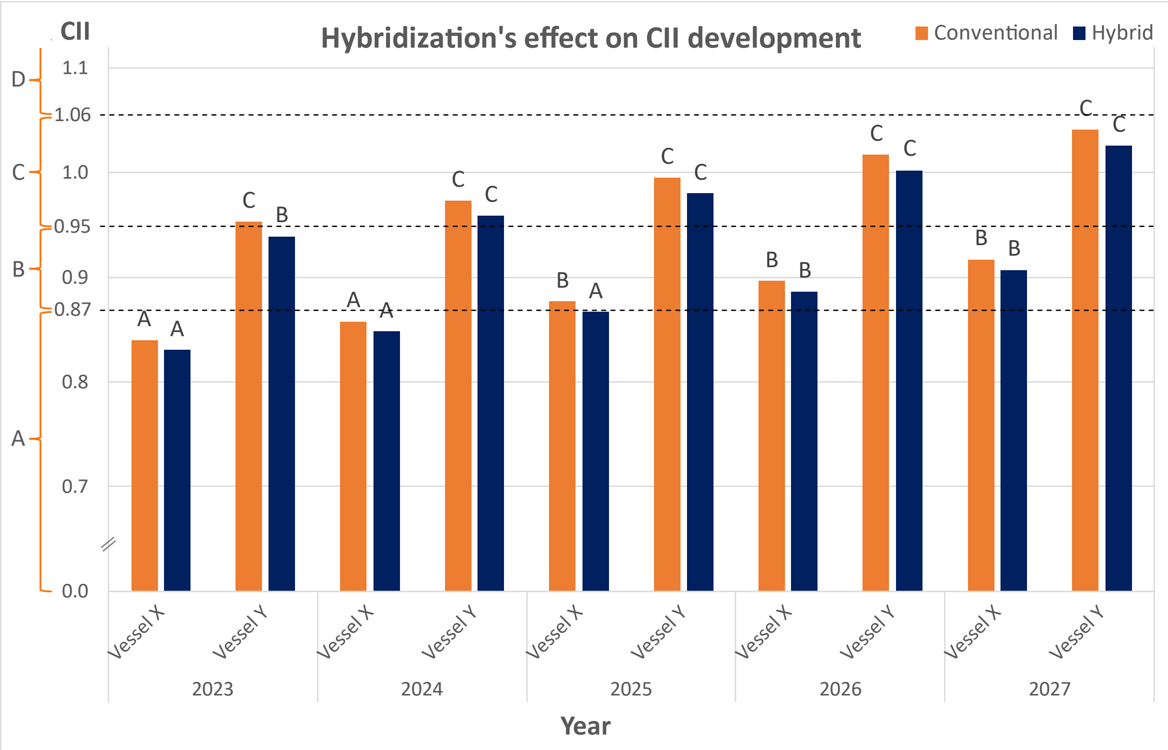

Figure 43. Hybridization's effect on CII development

Annual OPEX and emission savings extrapolated from the simulations are summarized in Appendix 4. OPEX savings of 0.6 – 1.6 % correspond to 100 – 600 k€ savings per year. On the emission side the annual reduction in carbon emissions varies between 700 – 3000 tons. Two other elements included in Appendix 4 are the percentual reduction in total engine running hours and annual battery cycles. Without changing the engine configuration, batteries show potential for 1 – 4 % reduction in running hours, which through running and maintenance costs are responsible for a significant share of the vessel's operational expenses. Battery cycles on the other hand are closely related to the battery lifetime profitability through SoH degradation. Smaller batteries are obviously put through much more cycles in the simulations than larger batteries, which leads to an earlier need for battery replacement.

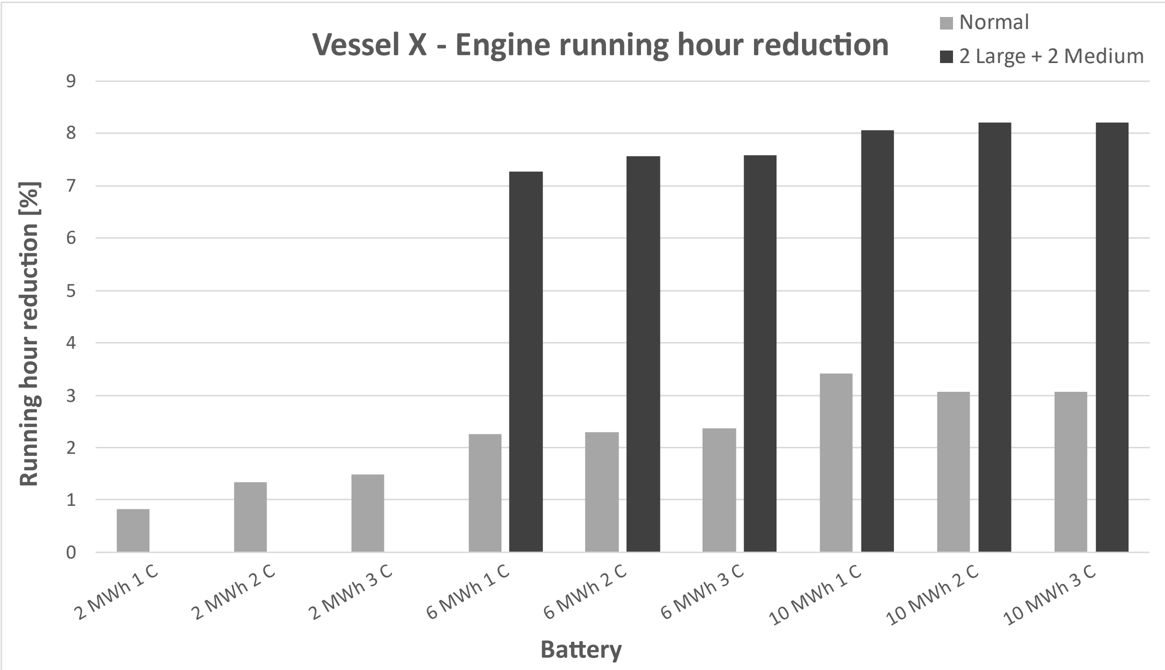

Figure 44. Vessel X - Engine running hour reduction

The results of the fifth simulation investigating hybridized vessel X with changed engine configuration are included in Appendix 4. Smallest of the five main engines was removed and replaced with a battery in the simulation. This scenario is considered realistic since the vessel practically never runs all five engines simultaneously and the smallest engine is only capable of producing 6.7 MW of power. To comply with the safety and reserve power requirements, the four engine scenario is only simulated with 6 and 10 MWh batteries that could realistically replace the smallest engine, and shore power is assumed to be available at every port. As seen in Figure 44 above, the total engine running hours are reduced significantly compared to the normal hybrid configuration. This additional 4 – 5 % reduction corresponds to over 40 k€ annual savings in engine running and maintenance costs. However, as seen in Appendix 4, the OPEX savings are more or less the same as in the normal five engine configuration. The reason for this is found in the much lower fuel savings. This indicates that the removal of one engine makes it more challenging for the vessel to reach the optimal SFOC on the remaining engines, which would enable sailing as fuel efficiently as possible. However, when considering hybrid newbuild vessels, the engine configuration could be designed more optimally taking the battery system into account, which would enable even higher OPEX savings potential and increase the feasibility of the battery.

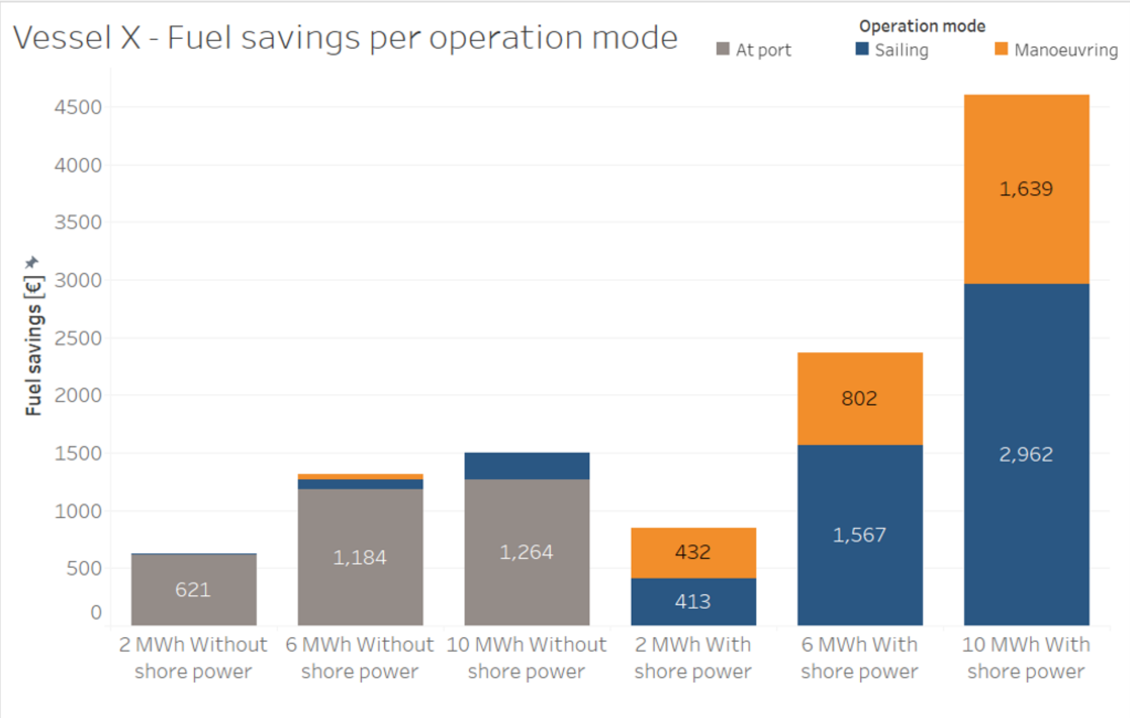

Figure 45. Vessel X – Fuel savings per operation mode

The battery savings potential is also insightful to be studied from the vessel's operation mode point of view. Figure 45 above summarizes the achieved fuel cost savings of vessel X for each battery capacity compared to the conventional system simulation's reference costs, coloured by the operation mode. Without having shore power available, the main savings are achieved during port stays, where batteries enable engines to be run more optimally to supply the service power. Due to not being able to charge batteries with the shore power, the savings during manoeuvring and sailing are limited, but visible on the larger battery scenarios. When shore power is available, port stay fuel costs are zero, meaning that there is no savings potential. Manoeuvring and sailing phases on the other hand show much higher savings potential, especially now that the battery has been fully charged, up to the 80 % SoC limit to minimize battery degradation, and can be better used for strategic loading and as spinning reserve. Here it's also visible that the battery enabled fuel savings during manoeuvring account for ~30 – 50 % of the total fuel savings, with shore power incorporated, which is significant considering that the manoeuvring phase's share of the total fuel costs is only ~3.5 %. However, it's worth mentioning that part of the described savings, especially with the larger batteries, comes from the vessel performing all-electric manoeuvring for a short period of time during port departures, meaning that the engines are not run at all.

7 Battery investment feasibility

The feasibility of a battery investment on a cruise vessel can be analysed based on the estimated investment costs and simulated monetary savings. The resale value of a battery can have a big positive impact on the battery investment's financial profitability, but on the other hand battery replacement costs must be included in the hybrid vessel's life-cycle feasibility. Many other non-monetary elements, such as emissions and brand image, also affect the investment decision making, but their weight and effect is harder to measure and thus can't be used in the calculations. For simplicity, this battery investment feasibility analysis will only focus on the monetary elements. This chapter presents the investment and life-cycle feasibility of different battery systems based on the OPEX and CAPEX costs and estimated life-cycle savings, obtained from the literature review and vessel simulations. Life-cycle cash flows are discounted to get the net present value of the investment options, after which they are compared in terms of ROI. Finally, sensitivity and scenario analyses are performed to build a more comprehensive picture of the investment feasibility under the assumptions and varying factors.

7.1 Life-cycle cash flow

The financial side of the battery investment consists of the initial investment cost, annual OPEX savings in power supply, and the resale value of the end-of-life battery. The resale value of an ~80 % SoH battery has been estimated to be up to 50 % of its original investment cost, which must be considered in the investment decision making. The resale price depends on the battery characteristics, SoH and battery market price development, and is in this analysis assumed to be 40 % of the initial battery CAPEX. Figure 46 below visualizes the life-cycle costs and savings of a 10 MWh 2 C battery based on the vessel Y simulation results. The orange bar on year 0 represents the initial investment cost of 9 million euros, after which the hybrid operation creates ~500 k€ annual power supply OPEX savings. After 15 years of operation, the 10 MWh battery has performed over 7000 cycles and is considered end-of-life. With the assumed 40 % resale value of the original price, the final year has a positive cash flow of over 4 million euros. Without any variations in the cash flow, additional costs, battery market price reductions or regard of the interest rate, the positive cash flow within the 15 year life-cycle is ~2.5 MEUR higher than the investment cost. However, even with all the assumptions, the payback of the investment is dependent on the resale value as the annual savings are far from reaching the break-even point.

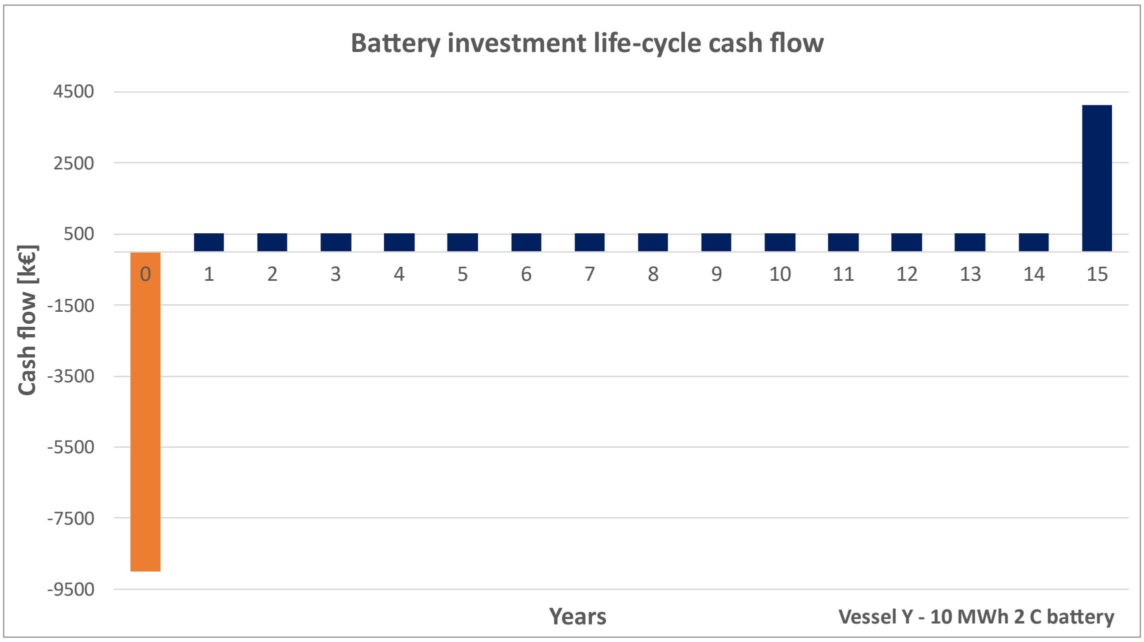

Figure 46. Battery investment life-cycle cash flow example

To extend the investigation from battery life-cycle to hybrid vessel life-cycle investment profitability, the battery replacement costs must be considered. On average (Appendix 4), the 2 MWh batteries show around 950, 6 MWh batteries 550, and 10 MWh batteries 450 annual cycles. Assuming that the batteries are used optimally between 20 – 80 % SoC and stored in cool temperatures to minimize calendar degradation, the described annual cycles would refer to battery lifetimes of 6, 10 and 15 years respectively based on the capacities. The battery replacement costs are lower than the initial investment cost since the replacement planning and installation project is assumed to be less expensive, and the power conversion and transmission systems don't typically need to be replaced. Hereby, the reinvestment cost only consists of the battery pack replacement, which in large scale battery systems accounts for 40 – 80 % of the total cost, as shown in chapter 2.2.4 , and is assumed to be 80 % of the total battery CAPEX in this analysis. The other financial element lowering the battery replacement costs is the resale value of the end-of-life battery, which in this study has been assumed to be 40 % of the original investment cost. For simplicity, here it is assumed that the new battery market prices don’t change during the studied period, even though in reality the decreasing price trend is expected to continue in the future.

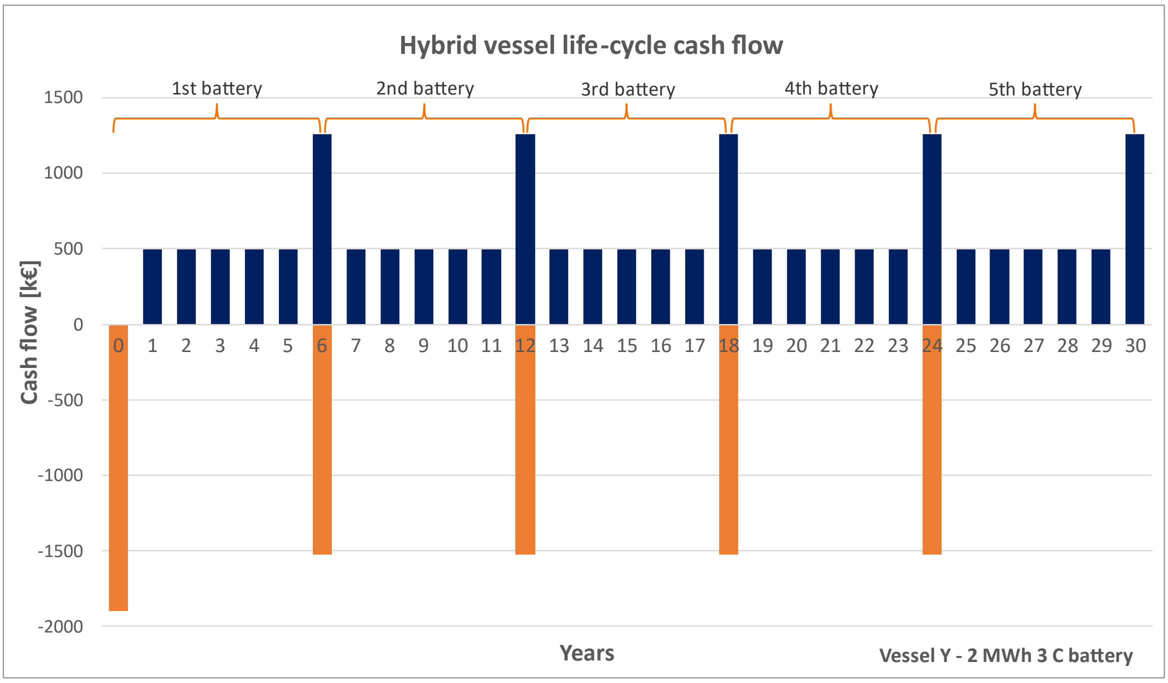

Figure 47. Hybrid vessel life-cycle cash flow example

Hybrid vessel investment’s life-cycle cash flows are visualized above in Figure 47, using the simulation of vessel Y with 2 MWh 3 C battery scenario as an example. Lifetime of the smaller battery is much shorter when compared to the 10 MWh battery in the previous example. The first six years of the investment follow the same pattern as in Figure 46, but at the end-of-life of the first battery, a replacement is required incurring a cost equivalent of 80 % of the first battery CAPEX. Same principle is followed for the next three batteries, and after 30 years and in total five battery packs, the vessel is assumed to have reached its end-of-life and the final battery pack is sold with 40 % resale price. The simulation of 2 MWh battery shows higher annual savings relative to the investment cost which is why the sum of life-cycle cash flows is ~10 million euros positive. However, the effect of the interest rate is not included in the calculation and the actual suitability and effect of a 2 MWh battery on a large cruise vessel would require further analysis.

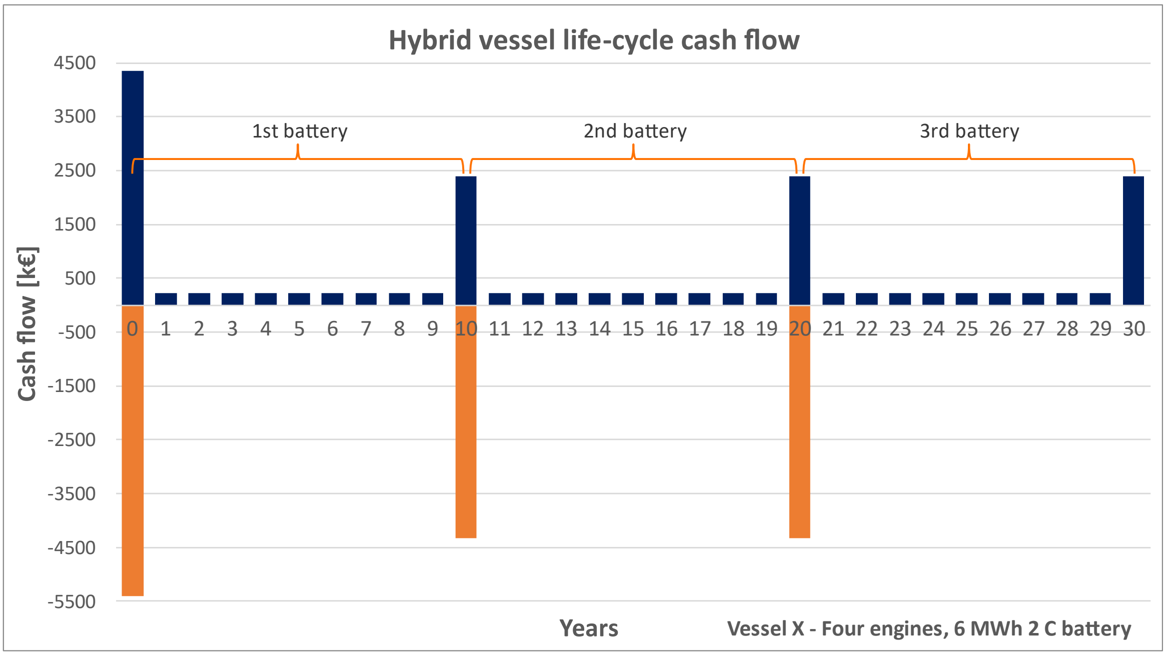

Figure 48. Four engine hybrid vessel life-cycle cash flow

A third example of life-cycle cash flows can be given from the simulation of vessel X with changed engine configuration. In this scenario, the CAPEX cost of the smallest engine can be seen as savings in the beginning of the vessel life-cycle, shown above in Figure 48. The estimated savings from the engine removal are not enough to cover the large battery investment cost, but clearly have a major impact. However, as mentioned earlier, the fuel savings achieved with the lightened engine configuration are much lower than with the original setup, which is why the payback of the investment is still dependent on the resale value of the battery. When reviewing only the life-cycle of the first battery investment, without considering future battery replacements, the savings from the engine reduction makes the investment look highly profitable. But when considering the whole lifetime of the vessel, the engine CAPEX savings are lost to cover the battery replacement costs that are higher than the resale value and low annual OPEX savings together, withering the hybrid investment's feasibility. Still, it's worth highlighting that when talking about newbuild vessels, the engine configuration could be designed more optimally with one less engine than the current case example under investigation, which would enable higher fuel efficiency through operating engines closer to optimal SFOC.

7.2 Investment net present value

To be able to realistically analyse the battery investment feasibility, the existing interest rate must be considered when calculating the future cash flows. This discounting is done with a selected interest rate, which should represent the Required Rate of Return (RRR). Different RRR ranges are typically used for different types of investments, based on the importance and risk of the investment. For example, the required rate of return on machinery replacement or cost reduction investments is usually set lower than on new product or market expansion investments. In this battery investment case, the goal is to reduce the vessel's operating costs, so the RRR can be kept moderate. (Palmer et al., 2023) One option to set the RRR when analysing cost reduction investments is using the Weighted Average Cost of Capital (WACC). WACC takes the company's capital structure into account, meaning the amount and cost of both equity and debt. This gives a realistic requirement for the investment return in order to justify the purchase cost. The formula (3) for calculating WACC is presented below. (Hargrave et al., 2023)

$$WACC = \left(\frac{Equity}{Equity + Debt} \times Cost\ of\ equity\right) + \left(\frac{Debt}{Equity + Debt} \times Cost\ of\ debt \times (1 - Tax\ rate)\right) \tag{3}$$

The WACC of three market leading cruise lines is calculated with the formula (3) above and their average is used to discount the simulated future battery costs and savings. As seen in Table 5 below, Carnival Corporation has a clearly lower WACC than its two competitors. Nevertheless, the average interest rate of 9.12 % is estimated to be a realistic RRR for cost reduction targeting investments and selected to be used in this feasibility analysis.

Table 5. Cruise line WACC calculation for 2022 (adapted Discounted Cash Flow, 2023a, 2023b, 2023c)

Cruise line	Royal Caribbean Cruises	Carnival Corporation	Norwegian Cruise line Holdings
Debt [M$]	23994	35881	13622
Equity [M$]	19259	10927	5931
Total capital [M$]	43253	46808	19553
Cost of debt [%]	4.10	4	6.70
Cost of equity [%]	18.00	16.6	18.20
Tax rate [%]	2.60	-0.20	0.30
WACC [%]	10.23	6.95	10.17
Average WACC [%]	**9.12**		

After selecting the interest rate, the Net Present Value (NPV) of the investment can be calculated as the sum of discounted future cash flows, including the end-of-life resale value. In order for the investment to be feasible, NPV must be positive, meaning that the sum of discounted cash flows is higher than the initial investment cost. The formula (4) used for calculating battery investment NPV is presented below (adapted Fernando et al., 2023b).

$$NPV = \sum_{t=0}^{\substack{Battery\\lifetime}} \frac{Annual\ cash\ flow}{(1+WACC)^t} \tag{4}$$

The initial investment cost is included in the annual cash flows in the calculation, but as the summation starts from the year 0, it’s divided by 1 and thus not affected by the interest rate. The further in the future a cash flow is, the lower its effect is on the net present value. The effect of interest rate on cash flow NPV is visualized below in Figure 49.

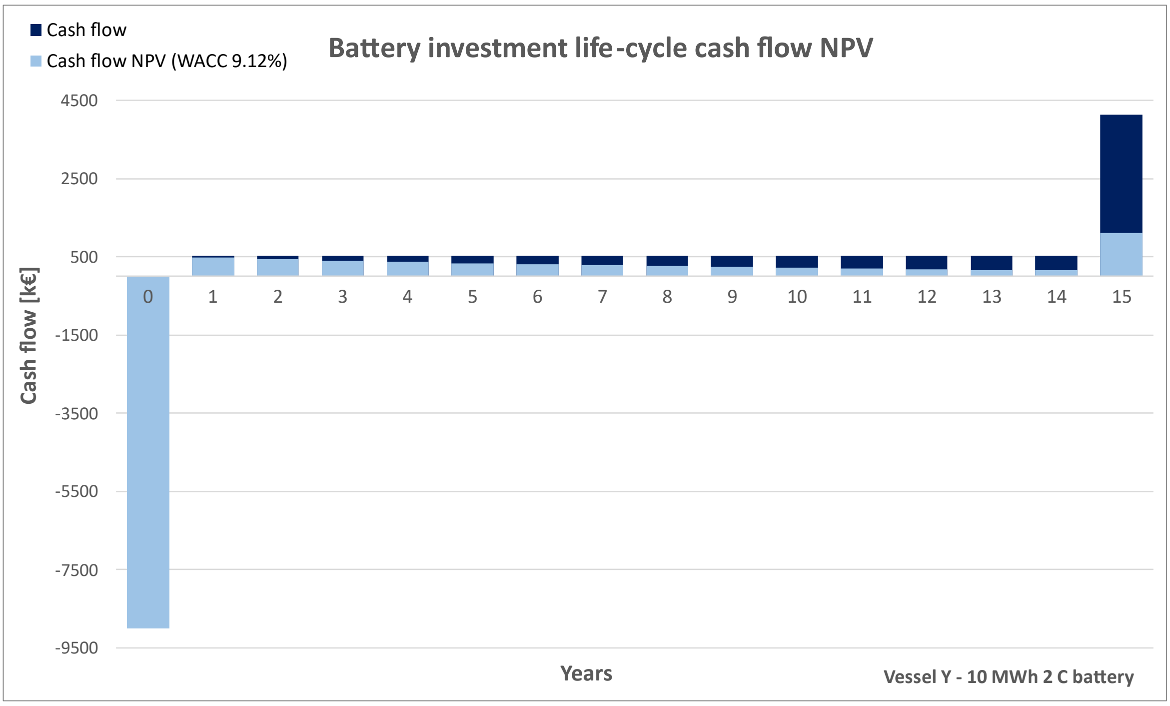

Figure 49. Battery investment NPV

The dark blue bars represent the cash flows of the 10 MWh 2 C battery investment for case vessel Y, similarly as in Figure 46. However, here the light blue bars show the cash flow's real effect on the NPV, discounted with the selected 9.12 % WACC. The initial investment cost is included in the NPV with 100 % weight, but the future savings are valued less. This is clearly visible in the resale profit of selling the end-of-life battery in the end of year 15, where its effect on the NPV is less than 30 % of its value. If the sum of undiscounted cash flows in Figure 46 was over 2 million euros positive, here it is clear that the NPV in this investment scenario is highly negative. Considering the interest rate in calculations reveals the real profitability of the investment, which in this case disclosed the unfeasibility of the 10 MWh 2 C battery for vessel Y in terms of money.

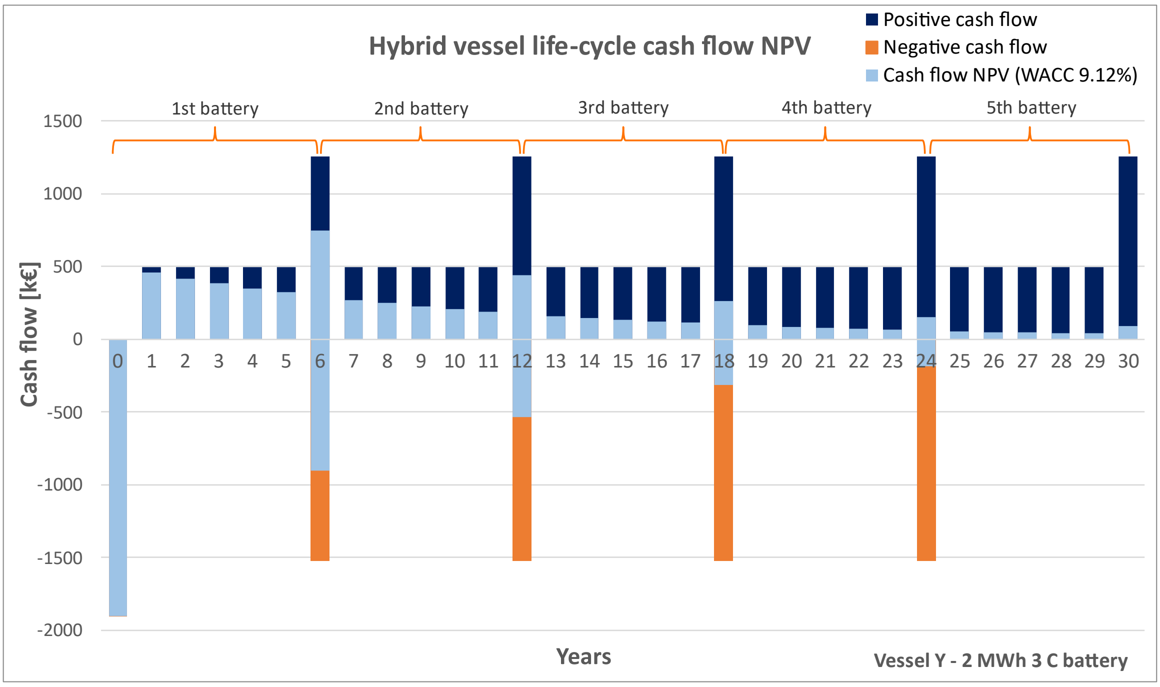

Figure 50. Hybrid vessel investment NPV

Net present value of the cash flows can also be visualized for the whole hybrid vessel's life-cycle, as seen in Figure 50 above. Savings created by the first 2 MWh 3 C battery during the first six years are valued more than the savings expected from the following batteries. Here it is worth noticing that also the negative cash flows from the battery replacements have a reduced impact on the NPV. When analysing the investment profitability over a 30-year timespan, the effect of the interest rate is substantial. Lowering the WACC by few percentages can make the investment break even or increase its profitability, and on the other hand, increasing the rate can wither the achieved monetary benefits so much that the investment becomes unfeasible.

7.3 Return on battery investment

Profitability of an investment can be viewed with many different approaches, such as payback time, net present value, and internal rate of return. Return On Investment (ROI) is a commonly used profitability measure in the business world as it takes into account the required rate of return, in the form of WACC, and evaluates the cash flows in relation to the investment cost. Besides enabling the profitability assessment of one investment, ROI can be used to support the decision making when comparing different investment opportunities.

If the RRR is set appropriately, positive ROI means that the investment is worthwhile, and on the other hand, negative ROI signals an unprofitable investment. The formula (5) used for calculating ROI is presented below. (adapted Fernando et al., 2023a)

$$ROI = \frac{NPV}{Investment\ CAPEX} \tag{5}$$

The battery investment NPV and ROI together with hybrid vessel investment NPV are calculated for a few selected scenarios, based on the simulated OPEX savings and estimated CAPEX costs. The C-rate with the highest savings potential is chosen from each battery capacity group for both vessels to be analysed and compared as an investment opportunity. This resulted into selecting the highest C-rate of 3 for the smallest batteries and either 1 C or 2 C for the larger batteries, depending on the power demand in the scenario. This signals that even though the power demand on cruise vessels is high, the load fluctuations can be handled with relatively low C-rates and the emphasis from the profitability perspective must be given to the battery capacity.

Table 6. Hybrid vessel investment feasibility analysis

Vessel	Scenario	Battery lifetime [y]	Battery replace-ments	Vessel lifetime [y]	Yearly savings [k€/y]	Battery CAPEX [k€]	Resale value [%]	Replacement cost relative to CAPEX [%]	Engine CAPEX [k€]	WACC [%]	Battery lifetime NPV [k€]	Battery ROI [%]	Vessel lifetime NPV [k€]
Vessel X	2 MWh 3 C battery	6	4	30	187	1900	40	80	-	9	-614	-32	-912
Vessel X	6 MWh 2 C battery	10	2	30	240	5400	40	80	-	9	-2963	-55	-4078
Vessel X	10 MWh 1 C battery	15	1	30	268	8500	40	80	-	9	-5440	-64	-6450
Vessel X	**Four engines, 6 MWh 2 C battery**	10	2	30	226	5400	40	80	4355	9	**1300**	**24**	**130**
Vessel X	Four engines, 10 MWh 2 C battery	15	1	30	245	9000	40	80	4355	9	-1711	-19	-2863
Vessel Y	**2 MWh 3 C battery**	6	4	30	499	1900	40	80	-	9	**779**	**41**	**2257**
Vessel Y	6 MWh 2 C battery	10	2	30	531	5400	40	80	-	9	-1111	-21	-1129
Vessel Y	10 MWh 2 C battery	15	1	30	528	9000	40	80	-	9	-3798	-42	-4338

The results of the investment feasibility calculations are summarized in the Table 6 above. The message of the analysis is quite clear, batteries in general are not a monetarily feasible investment on an optimally operated cruise vessel. The CAPEX cost of installing batteries is still so high that for example even with over 520 k€ annual savings the investment cost of

9 MEUR can’t be justified. The smaller the battery is, the higher the NPV and ROI seem to be, but still only two scenarios have reached the break-even point. For vessel X, the only feasible investment option is the 6 MWh 2 C battery when also removing the smallest 6.7 MW engine. This raises the first battery’s ROI to over 20 %, but when considering the NPV over the hybrid vessel’s whole lifetime, the savings are diminishing and resulting in a marginal 130 k€ profit. On the other hand, for vessel Y the only feasible option is the smallest 2 MWh battery with the C-rate 3. The annual savings are relatively high in relation to the battery CAPEX, especially in comparison to the other options. Here the ROI of over 40 % is healthy and acceptable, but the feasibility is again dependent on the battery’s end-of-life resale value and can’t comfortably be justified only with the OPEX savings. In this scenario, as the engine configuration isn’t changed, the profitable battery investment also makes the vessel hybridization investment feasible resulting in almost 2.2 MEUR lifetime net profit. Still, the assumptions must be acknowledged and the actual usability of a 2 MWh battery on an over 200 000 GT cruise vessel must be verified. Even though the battery investment on a cruise ship doesn’t in general seem worthwhile in terms of money, to see the big picture all the other benefits and drivers for hybrid power supply must be considered, and recognized that changes in the assumed variables can reshape the situation completely.

7.4 Sensitivity and scenario analysis

In an analysis containing numerous assumptions and evolving factors, the results only represent one possible outcome. Even though this scenario might have high probability to happen, the examination of other scenarios and effects of changing assumptions is beneficial. This can be done with sensitivity and scenario analyses. Sensitivity analysis means taking few of the most critical factors under the microscope one by one, to see how their changes affect the investment feasibility. The factors chosen to be studied in this analysis are battery price, fuel prices, battery lifetime, and resale value. In the scope of this sensitivity analysis, the aim is to test how much the selected factors should improve, ceteris paribus, for the battery investments to become profitable. After studying the effect of the improvements individually, they can be combined in a scenario analysis. Typically, scenario analysis describes the worst and best case scenarios, but as the 6 and 10 MWh battery investment options chosen for further analysis are all unprofitable, it’s more insightful to investigate how much improvement is required for them to break even. (Kenton et al., 2023)

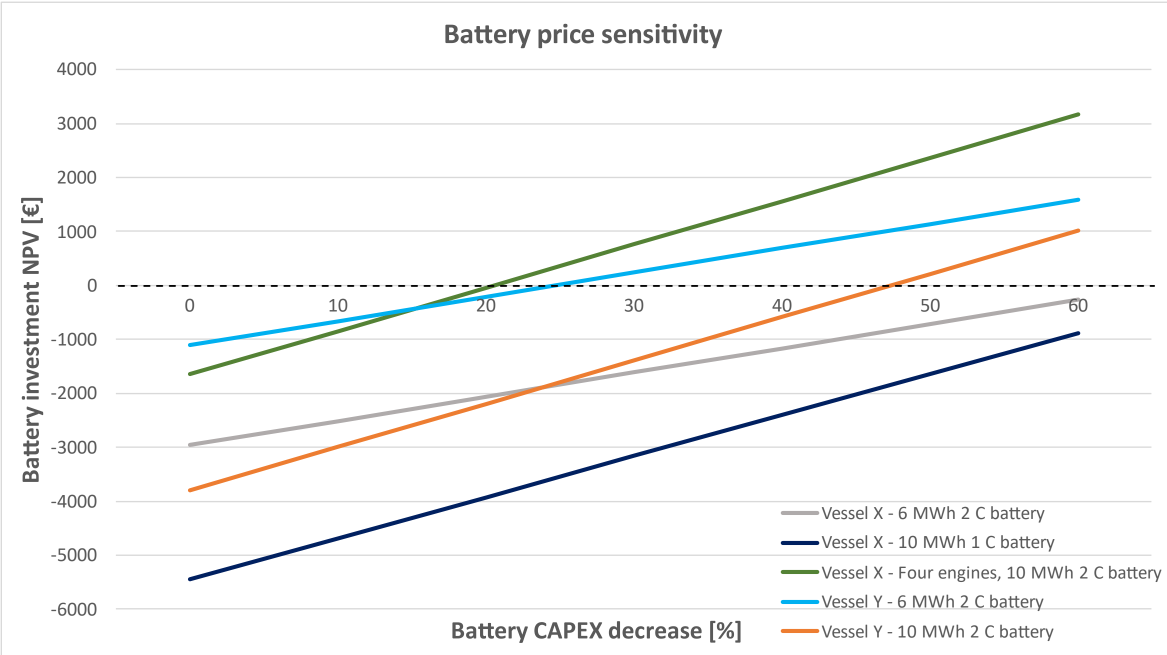

Figure 51. Battery price sensitivity

Battery price is the singe element affecting investment feasibility the most. Besides being a huge negative cash flow, it takes place in the very beginning of the investment life-cycle which means that it is not affected by the interest rate. Vice versa, the higher the RRR is set, the heavier is the cost of the battery in relation to the future savings. Figure 51 above shows the effect of battery CAPEX decrease on the investment NPV. All of the selected battery scenarios start from negative NPV, but after a 20 - 25 % price decrease both the vessel Y with a 6 MWh 2 C battery and the vessel X with lightened engine configuration and a 10 MWh 2 C battery break even. In the 6 MWh battery scenarios the price sensitivity is clearly lower, which speaks of the lower starting CAPEX in relation to the annual savings. Rest of the hybrid scenarios would need over 45 % price decrease, vessel X with normal engine configuration even over 60 %, before being considered as viable options. As discussed in chapter 2.2.4 battery prices have been in a decreasing trend which is expected to continue in the future. However, over 60 % decrease from the current level might be left unseen.

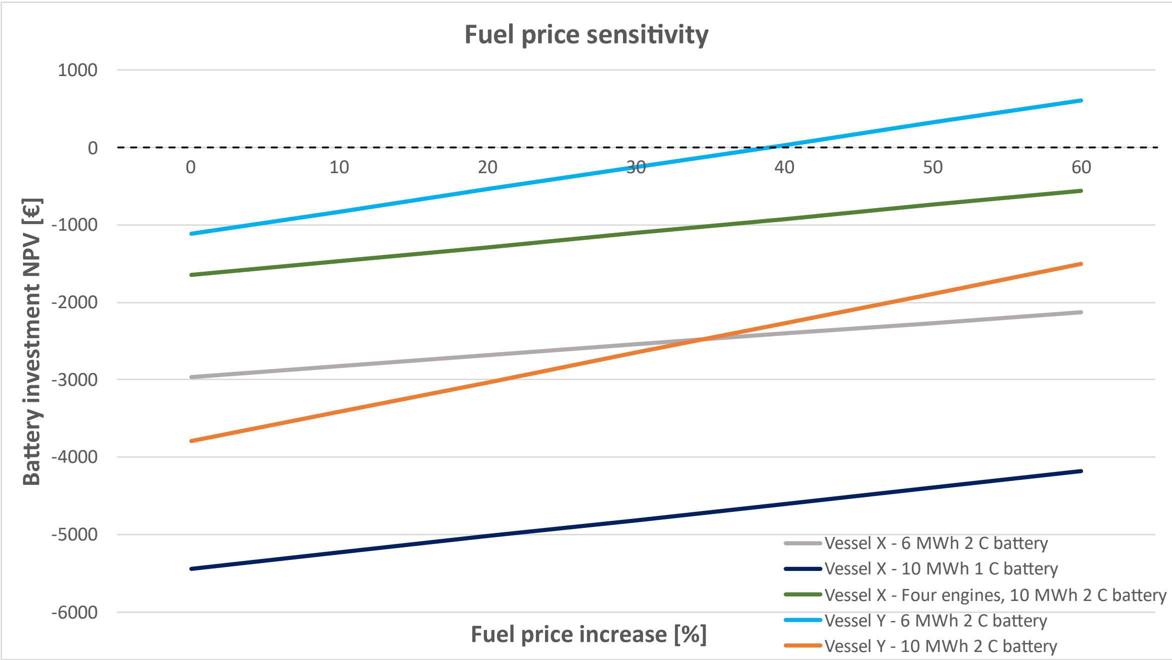

Figure 52. Fuel price sensitivity

Fuel prices are another important factor in the feasibility equation of battery investments, as the main benefits of hybridization come from fuel savings. The higher the fuel prices are, the more money can be saved with batteries. Figure 52 above illustrates the effect of increasing fuel prices on the investment profitability. The insight from the graph is clear, besides the 6 MWh 2 C battery on vessel Y, even the 60 % fuel price increase alone wouldn't make the studied battery scenarios feasible, but clearly having a positive effect on the NPV. In general, 10 MWh batteries seem to benefit more from the fuel price increase as they are capable of higher fuel savings, however remaining in the negative NPV. Also, the larger vessel Y reacts stronger to the changes in fuel prices since its fuel consumption is higher. Even though especially the fossil fuel prices are expected to increase in the future as their usage is aimed to be reduced, similarly to battery CAPEX, the sensitivity of this factor alone is not enough to make the investments realistically feasible. The price development of sustainable "green" fuels will also have a major impact on the battery feasibility in the near future, but that is out of the scope of this analysis.

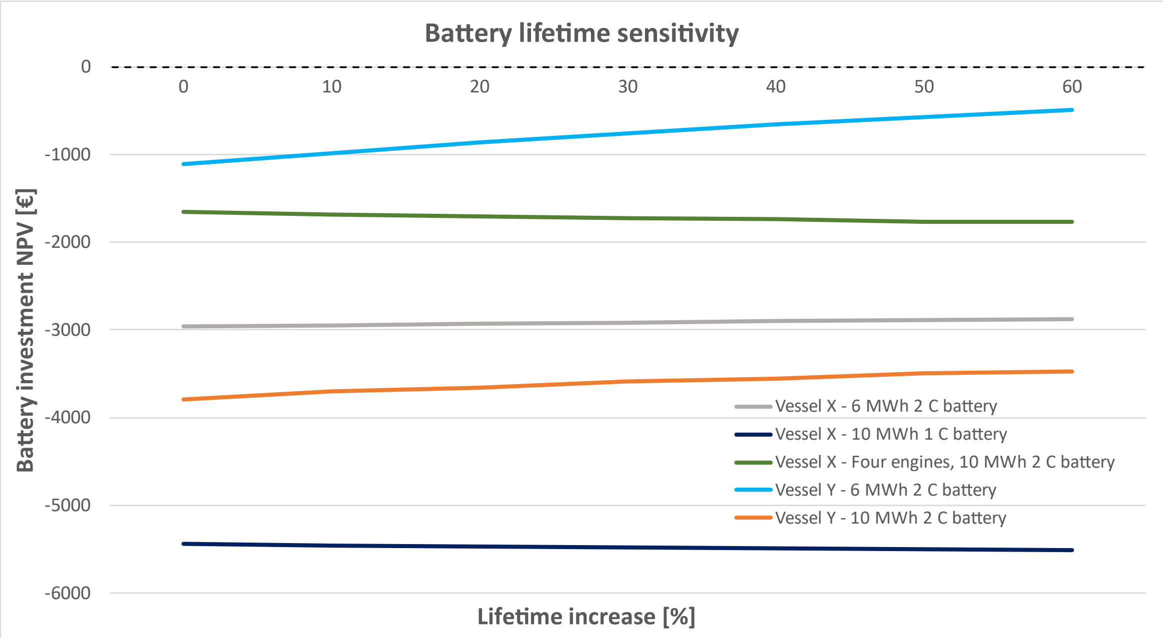

Figure 53. Battery lifetime sensitivity

Battery lifetime is the third variable under sensitivity examination in terms of investment NPV. Figure 53 above shows the almost non-existent effect on the battery NPV, even with a 60 % lifetime increase. In the scenarios with 10 MWh batteries on vessel X the increased lifetime actually lowers the battery investment's NPV, as the positive cash flow from the battery resale moves further into the future and gets more affected by the interest rate. From the vessel hybridization investment point of view the increased battery lifetime enables slightly higher NPV as costly battery replacements are needed less often, but still the NPV remains negative in all scenarios. However, if the focus is limited to the OPEX savings, increasing battery lifetime enables more positive cash flow to be created with the same initial investment cost, also increasing emission savings and sustainability. The battery lifetime increase of tens of percentages would need a lot of technological development, and is not expected to be seen in the near future, at least for the current battery chemistries.

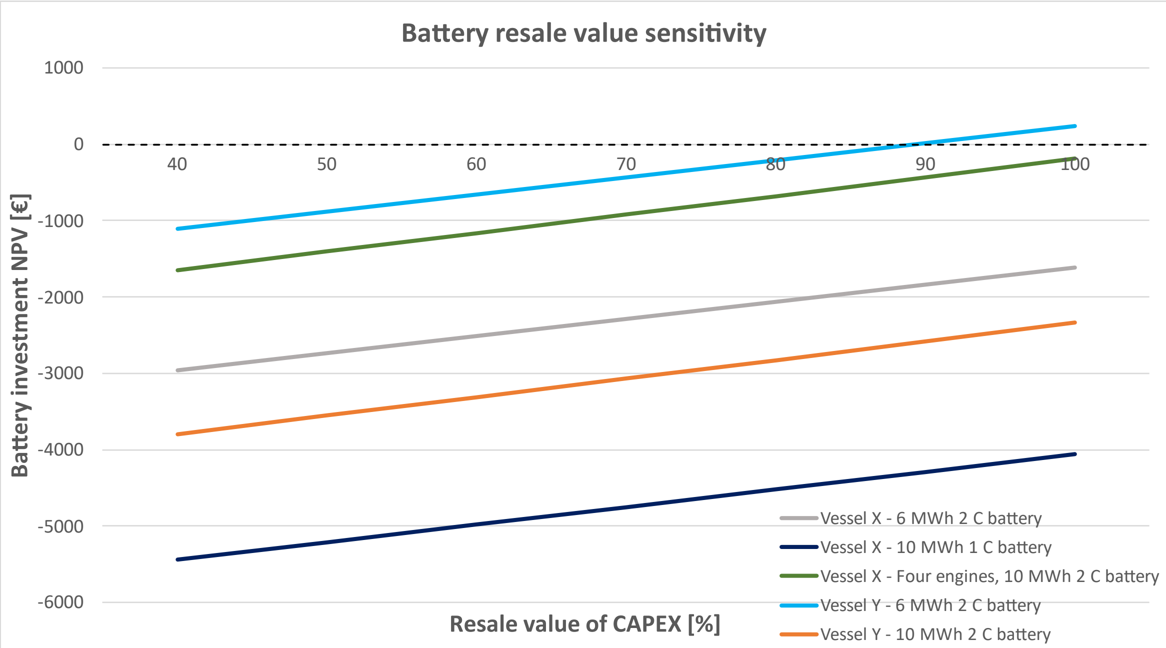

Figure 54. Battery resale value sensitivity

The last of the studied factors is the resale value of the end-of-life battery, as a percentage of the initial battery CAPEX. The visualization in Figure 54 above begins from the 40 % assumption done for the feasibility analysis, and is increased by 10 % up to 100 % resale value, which of course in practice is absurd. Here the story is the same as with other sensitivity factors that, besides the 6 MWh 2 C battery on vessel Y, even receiving the full battery CAPEX cost back in the end of the investment period, the effect of the interest rate has reduced its value so much that the NPV still remains negative. The battery resale value has potential to increase in the future as current li-ion raw materials are running low and the sustainability and second-life aspects are receiving more attention.

As a result of the sensitivity analysis, only a great battery price reduction can alone make the simulated battery investment scenarios feasible, but the effect of the other factors is limited. 6 MWh 2 C battery on vessel Y seems to be the investment option closest of becoming feasible with moderate improvements on the individual assumptions. However, ceteris paribus principle doesn’t exist in the real business world and all factors are constantly evolving. This is why combining the sensitivity of the most important factors in a future modelling scenario analysis yields more realistic and insightful results.

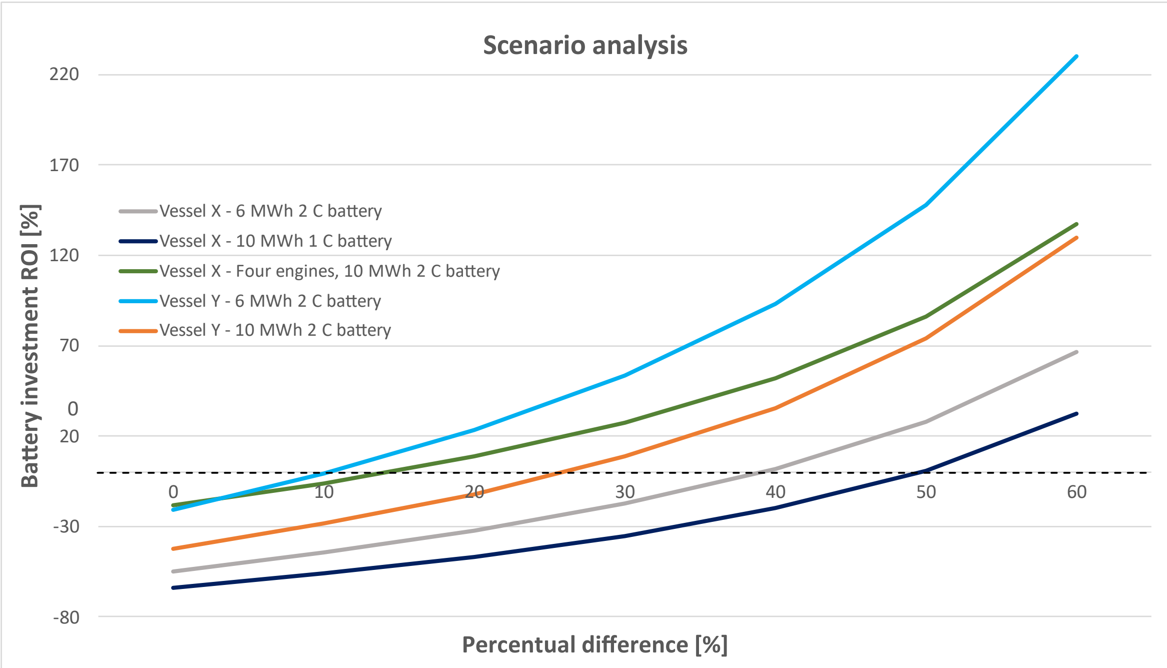

Figure 55. Battery investment scenario analysis

The combined effect of the four selected factors on the return on battery investment is summarized in Figure 55 above. The scenarios are built in 10 % increments, where battery CAPEX is decreased and the three other factors are increased by 10 % at every step. Here we can see that the ROI is on an accelerating rise on all battery investment options, each of them reaching the break-even point before the 50 % increment. The 6 MWh 2 C battery system on vessel Y becomes profitable already at ~9 % combined difference, while the four engine hybrid configuration on vessel X requires ~14 % difference. The scenario analysis is beneficial when estimating how much the assumed factors need to develop in the future for the investments to be justified. For example the under 15 % development, enough for profitable hybridization of both vessels, can be considered possible in the near future, as battery prices are forecasted to decrease and fossil fuel prices are expected to rise. Also, as the current battery raw materials are running short, the second-life of batteries might be valued higher, increasing the end-of-life resale price. In the long run, also the battery lifetime could be improved through technological development. However, there is a lot of uncertainty around the evolution of the influencing factors and the investment decision making must be based on realistic expectations and done with case-specific assumptions.

8 Conclusions and summary

Energy and emission efficiency is a global hot topic, also being a key driver for vessel hybridization from financial, environmental and strategic aspects. Cruise industry, as a technological leader of the maritime field, is fully engaged in the research, innovation, development and piloting of new advanced solutions to improve vessel performance and cut emissions and costs through reducing fuel consumption. Lithium-ion batteries are the current market leader of alternative power sources, supporting and optimizing the operation of traditional combustion engines. Even though BESS in general is a well-studied concept, knowledge about its applicability and feasibility in cruise business has been lacking. Smaller passenger vessels and ferries were a natural and suitable starting point for maritime hybridization, but due to technological advancements the time has come for also cruise vessels to incorporate hybrid power supply. Cruise vessels differ greatly from other vessel types by their characteristics and unique operating and power demand profiles. Hereby, there is a need for understanding the requirements, limitations, benefits, and challenges of installing batteries onboard the largest passenger vessels in the world. This chapter summarizes the main findings of this thesis study also concluding answers to the research questions. The reliability and validity of the research are assessed and finally the future research areas are discussed.

8.1 Summary of the findings

Hybrid power supply has been proven to have multiple valuable benefits compared to traditional diesel engine power supply. These benefits act as internal drivers, pulling cruise lines to join the hybridization trend. Pulling and pushing drivers can also be found from the external operating environment both from the operational and business perspectives. On the other side of the coin, there are multiple internal trade-offs and external challenges related to cruise hybridization that must be considered and weighted against the benefits in the decision making. All these elements are summarized in the form of a SWOT-analysis (Strengths, Weaknesses, Opportunities, Threats) in Figure 56 below.

Figure 56. Hybrid cruise power supply SWOT-analysis

Strengths

The strengths of hybrid system are identified as internal advantages in comparison to conventional power supply. The first multidimensional benefit of battery hybrid system is vessel performance optimization, which is manifested in many operational elements such as energy and emission efficiency, controllability, safety and comfort. As the vast majority of cruise vessels feature electric propulsion, all onboard power consumers can be connected to the vessel's electrical microgrid. This enables the implementation of an energy management system to optimize the power consumption and production based on a selected smart grid control strategy. The main function of an onboard ESS is grid stabilization which enables engines to be run on optimal power load, minimizing the specific fuel oil consumption. Power load levelling, in the form of peak shaving and strategic loading, creates direct fuel and emission savings compared to the conventional power supply system. Based on the digital twin simulations, the savings potential of battery hybrid power supply is estimated to be very limited, in the ballpark of 0.5 – 2.0 %. Increasing battery capacity and C-rate, in relation to the vessel size, increases the savings until a vessel specific maximum where the engines are operated as optimally as possible, minimizing fuel consumption. Besides enabling optimal engine operation, battery-powered spinning reserve and immediate uninterruptible power supply also improve the controllability and manoeuvrability of the vessel. This is beneficial especially during port arrivals and departures when thrusters are being used and power supply system faces rapid and possibly unexpected demand peaks. ESS serves also as a back-up power in case of emergency or engine failure, improving safety and system availability. Improved passenger comfort is an important benefit from the business perspective as the vessel, designed to entertain passengers, is capable of silent and smokeless operation. Onboard ESS enables the usage of renewable energy during sailing, originating for example from sustainably produced shore electricity, which directly cuts emissions and builds a greener brand image. Besides the monetary, environmental and health benefits, reducing and controlling the time and place of the vessel emissions enables compliance to both local and global emission regulations. Emission control areas, such as the fjords of Norway, are examples of local regulation, and CII rating is a global regulation example, both possible to be addressed with hybrid power supply.

Weaknesses

Even though offering valuable benefits and performance improvements, hybrid power supply isn’t believed to be a revolutionary silver bullet. Cruise vessels’ unique operating profile poses challenges for the hybrid system in terms of capacity and performance. As the power and energy demand is high throughout the varying long distance voyages, the ESS has to be balanced between weight, space and performance requirements. For example low capacity batteries are not capable of acting as spinning reserve or optimizing engine configuration, but on the other hand large batteries add weight to the vessel and take up a lot of room which is away from the revenue creating passenger space. Due to these trade-offs, all-electric engineless cruise vessels are not seen possible at least with the known technologies, and ESS is considered only as a secondary power source. ESS installation adds multiple pieces to the power supply system, including energy storage device, power conversion and transmission, and possibly battery, power and energy management systems, increasing the overall complexity. Large and not fully mature maritime ESS applications are also linked to internal safety risks such as fire hazards and off gas explosions, requiring technological development together with preventive regulatory and safety actions. Multiple actors like IMO and DNV have already issued guidelines for hybrid vessels covering for example the design, installation, operation, maintenance and disposal of onboard batteries, but the regulation is still under development. Another weakness of ESSs is the high investment cost of several million euros, which based on the savings potential analysis can't be justified only with the operational cost savings. Hybridization investment profitability is also dependent on the ESS lifetime, which can be maximized by optimizing the usage with a multi-objective EMS control strategy considering for example the state of charge limits and calendar degradation factors such as temperature and humidity. The operational savings potential of 0.5 – 2.0 % is very low for a long-term multimillion investment, which is why the WACC based required rate of return withers the net present value of future cash flows, drawing the return on investment into negative in most cases.

Opportunities

Various external opportunities and benefits are linked to implementing hybrid power supply on a cruise ship. The globally popularizing port shore power connection enables not only emission-free port stays but also battery charging, which is capable of creating cost and emission savings during sailing. Zero emission operation and utilization of renewable energy builds a sustainable and green cruise brand, answering to customers' demand which is rising from the increasing environmental awareness, climate concerns and green values. Bringing a green option to the market allows customers to make a responsible choice, attracting a wider customer base and building a sustainable culture. Onboard energy storage systems are also capable of providing concrete opportunities for the vessel, such as engine configuration optimization. Newbuild hybrid vessels can be designed, and battery retrofit vessels reconfigured, to have less engines onboard than without an ESS, which creates direct CAPEX savings, making the hybridization investment more justified. Another opportunity expected to raise interest in the near future is the second-life and recycling of ESSs, especially regarding li-ion batteries. End-of-life batteries have great potential to be reused in other applications, for example in shore utility grid stabilization, and their resale price can be up to 50 % of the original value. As battery raw materials are limited and more and more emphasis is given to sustainability aspects, the so far immature li-ion battery recycling processes are likely to develop greatly when the first large automotive and maritime battery wave reaches end-of-life. Besides second-life and recycling, new battery chemistries, more sustainable and even renewable, are being developed and expected to be capable of offering higher performance than the market leading li-ion batteries. Onboard energy storage systems can complement other new technologies such as renewable energy production with solar panels and wind turbines, or energy harvesting through waste heat recovery. Green fuels like methanol and hydrogen have been recognized as the main maritime energy source going forward, driving the use of ESS for power load levelling since the alternative fuels are not as capable of high power changes as for example diesel fuels. ESSs can also be combined into hybrid energy storage systems, harnessing the benefits of different solutions. Fuel cells combined with batteries for power load fluctuation mitigation is anticipated to be the most feasible HESS for cruise vessels in the future, piloting already in progress. The final major opportunity related to batteries is the tightening emission targets, such as IMO's emission reduction targets for 2030 and 2050, and regulation, such as CII and EEXI/EEDI. To keep up with the transformation, continuous efficiency improvement is required and onboard ESSs are identified as one viable solution.

Threats

The final dimension of SWOT-analysis is threats, which in the case of hybrid cruise vessels are versatile. When talking about a multi-layered, semi-automated and complex digital energy management system, cyber security threats such as power blackouts or even vessel control hijacking through cyber-attacks must be considered. That, together with the internal safety hazards, can create safety concerns both for the crew and passengers, raising business risks in the form of brand deterioration and revenue losses. Even though regulation is seen as a top driver for hybrid power supply from the emission point of view, the evolving ESS safety regulation is causing challenges and uncertainty, hindering the hybridization of the cruise industry. Another challenge related especially to li-ion batteries is the availability and sustainability of raw materials, which aren't sufficient to supply the continuously growing demand and production. Also challenges in the global supply chains and economy, as a consequence of COVID19 and political conflicts, affect the availability of ESS components as well as the cruise lines' financial capability and interest to invest in expensive efficiency improvement technologies. The high investment cost of installing hybrid power supply on a cruise vessel, not to even mention the cost of a fleet wide hybridization, raises capital risks for the cruise line. This combined with the uncertainty and possible inaccuracies of the savings and feasibility estimates, due to lack of research and data, holds back the wider adoption of ESS in the cruise segment.

8.2 Answers to research questions

The goal of this thesis was to gather, combine and create knowledge on the feasibility of utilizing a battery system on a cruise vessel. The main research question aimed to be answered by this study was:

How can a hybrid vessel's operational performance be optimized with battery usage?

To be able to examine the main question thoroughly, the research was divided into four sections: battery usage and optimisation review, market situation study, savings potential analysis, and investment feasibility assessment. Each of the sections was linked to a supporting sub-question, together compiling the answer to the main question.

How can batteries be used to improve cruise vessel's performance?

Batteries can be installed onboard a cruise vessel and connected to the vessel's electrical network through a power converter. As cruise vessels typically use electrical propulsion, supplying both the propulsion and service powers through the same microgrid, the full potential of batteries can be harnessed. Continuous data flow is the key enabling element of battery based optimization, as a smart grid control strategy can be implemented through an energy management system. Batteries are capable of improving the cruise vessel's performance on multiple aspects, main one being the engine efficiency optimization through disconnecting the direct link between energy production and consumption. As the maritime combustion engines' specific fuel oil consumption in relation to power output is lowest on ~85 % load of the maximum continuous rate, enabling optimal engine operation lowers fuel consumption, directly reducing operational costs and emissions. This power load levelling consists of demand peak shaving, strategic loading and battery-powered spinning reserve, all together enabling the vessel to operate on optimal number of engines running on optimal load. Other ways of vessel performance improvement are short period all-electric operation maximizing passenger comfort and eliminating emissions, energy harvesting from waste and renewable sources improving energy efficiency, and enabling onboard engine configuration optimization by serving as an uninterruptible back-up power source.

What are the limitations and challenges of onboard battery systems?

Battery technologies approved for maritime applications offer great opportunities for vessel performance improvement, but they have certain limitations and challenges that have hindered the adoption especially in the cruise segment. The exceptional characteristics in cruise vessels' operating profile, such as long distances, varying routes, long port stays and high continuous service power load, set high requirements for onboard battery systems. Due to the high power and energy demands, batteries are not suitable to be used as the main power source on a cruise vessel, considering the li-ion technology's power and energy density. Even as a secondary power source, trade-offs must be made between the battery capacity, added weight and required space. As the wider adoption of shore power is just getting started globally, batteries are mainly charged from the engines, limiting the emission and fuel consumption reduction to the efficiency improvements. High investment cost and limited lifetime due to battery degradation are also major business challenges for cruise hybridization, especially considering the low monetary savings potential. Additionally, safety concerns are associated with onboard batteries, energy storage system safety regulation is constantly evolving, and power supply system complexity is increased by adding more physical and digital layers to the configuration.

What does the hybrid vessel market look like, and how is it expected to develop in the future?

Li-ion batteries, as the market leading hybridization technology, have developed and popularized a lot in the beginning of the 21st century, also raising interest and getting foothold in the maritime industry, especially among smaller vessels such as ferries, yachts and workboats. However, the cruise segment, which typically paves the way for the adoption of new technologies in the relatively conservative maritime field, has slowly started waking up to the vessel hybridization only at the turn of the 2020s. This absence arises from the battery technology’s limitations on the uniquely challenging cruise business. Anyway, the wider adoption of batteries for support purposes is expected to take place also in the cruise segment in the near future, as based on the market study other alternative power sources such as fuel cells and green fuels are taking over the market. Also, the tightening emission regulation, green customer and company values, and promoting sustainable brand image are driving cruise lines towards the hybridization. Increasing the batteries’ role in the power supply system would require major technological development, which is not believed to happen in short-term. Hybrid power supply is expected to become the new normal, however not relying on any single technology, rather featuring vessel and purpose specific solutions and combinations of different power sources. Smaller ships and vessels operating on short and designated routes, such as ferries, are forecasted to become all-electric as ports worldwide are adopting shore power connection. With sustainable fuels and renewable energy sources available, also keeping nuclear power as a future opportunity, cruise vessels are not believed to become fully battery-powered.

How much operational savings can batteries generate and are they a profitable investment?

Operational savings achieved with batteries, mainly coming from reduced fuel consumption and engine running hours, can be measured in money and emissions. As there is only few battery hybrid cruise vessels in the world, the savings potential can’t be calculated from real data. However, new technologies like digital twin enables the savings potential estimation of cruise battery applications via comparative vessel data simulation. Based on the simulations the operational savings potential for an optimally operated cruise vessel is low and in line with the estimates of previous research, around 0.5 – 2.0 %, both from the emission and monetary perspectives. This refers to, depending on the vessel characteristics and operational profile, at highest 400 – 600 k€ OPEX savings and 2000 – 3000 ton CO2 emission savings annually. What comes to the investment profitability, the way of calculation must be defined. If only looking at the operational monetary savings, also considering the required rate of return, the multimillion hybridization investment can’t be justified. In case the engine configuration can be lightened and taken into account in the total CAPEX, the investment has higher chances to break even. The estimated return on investment is highly dependent on the assumed variables, such as fuel prices, battery CAPEX and resale value, which are expected to develop in a favourable direction from the hybridization point of view, possibly already in the near future. Even though the savings potential is low compared to other vessel types and the investment seems financially unfeasible, batteries provide many important non-monetary benefits for the vessel's performance and efficiency that must be considered in the investment decision making.

8.3 Reliability and validity of the research

A critical evaluation of reliability and validity is a core element in qualitative research, also emphasized in this thesis that combines multiple research methods and sources of information to study the hybrid cruise vessel topic from multiple angles. As this thesis examines a well-studied hot topic, the quality and timeliness of the information is important. The literature review is built on reliable academic sources, mainly from the past few years. The data analysis part of the market situation study utilizes vessel register data from two different sources, containing the possibility of invalid data but with only minor effects on the reliability of the big picture. The validity of interviews can never be fully verified, but the face to face conversations, large number of interviewees, and involvement of multiple maritime segments minimizes the risks of invalidity. The highest uncertainty in this thesis study is linked to the savings potential analysis which is based on the digital twin simulations. As there is no operational data available from battery hybrid cruise vessels, the digital model of the hybrid power supply system is built on multiple assumptions and pre-defined constant values. Even though employing actual operating data from conventional cruise vessels, the simulations are only capable of providing rough estimates of the reality. Due to the limited number of simulated vessels, voyages, and scenarios, the estimated savings potential and investment feasibility calculations can only speculate the range of monetary and environmental savings and give insights to support the decision making. It's also worth mentioning that every vessel is unique and has different characteristics and operating profile, requiring vessel specific investigation to be able to design the optimal power supply configuration.

8.4 Future research areas

As hybrid vessels are a vibrant topic and under piloting in the cruise segment, continuous research is required to better understand the benefits, limitations and feasibility of the new sustainable technologies. The future research areas, left unstudied within this thesis, are coming from the scope limitations and more in-depth analysis required on batteries in the cruise segment. Due to the assumptions and limitations in the battery simulation, further analysis containing larger sampling size and more battery scenarios would be required to achieve higher reliability of the savings potential estimation. After proper real-life battery piloting and data collection, the feasibility analysis could be done more reliably based on actual hybrid cruise vessel data. Also, as this thesis focuses on the newbuild vessel perspective, the feasibility of cruise battery retrofitting would require further research.

Since the scope of this study was limited to batteries, other power supply technologies with high expectations and potential, such as fuel cells and nuclear molten-salt reactors, were left unstudied. Based on the interviews, the HESS combination of fuel cell and battery is expected to be the most suitable for and popularise in cruise applications, which is why it would be beneficial to be studied more thoroughly. Other interesting future research areas would be the hybrid vessel's complete energy management optimization and using the vessel's hotel load "as a battery". Battery's effect on the vessel's weight, stability, depth and engine configuration was not studied in detail in this thesis and would be required to be able to, besides optimizing the power supply, optimize the power consumption for example in the form of optimal speed and trim. This would serve as the basis for building a complete multi-objective energy management strategy. Another possibility related to the energy management is controlling the vessel's hotel load proactively based on real-time IoT data and AI supported power demand predictions. In practice this would mean for example cooling the passenger spaces before a forecasted temperature rise to avoid sudden power demand peaks, or lowering the level of lighting in public areas during accelerating to enable the engines to stay in optimal operation.

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Appendix 1. Interview question list

Current state

- What alternative power sources are being considered for cruise vessels?
- What are the main drivers for using alternative energy sources?
    - Prioritize: Image/Brand, Money/Savings, Regulation, Customers/Stakeholders, Other
- Why is there so few batteries in the cruise segment so far?
- Could batteries be feasible for cruise vessels?

Future outlook

- How does the future of battery powered cruise vessels look like?
    - Short-term (before 2030)?
    - Long-term (after 2030)?
- Which alternative power source or their combination seems most feasible?
    - Short-term (before 2030)?
    - Long-term (after 2030)?
- Will there be all-electric engineless cruise vessels in the future?

Appendix 2. Interviewee information

Business	Company	Interviewee role	Year of topic related experience	Interview duration	Time of interview
System and solution provider	**Wärtsilä**	Power Supply Decarbonisation Manager	16	1 h 19 min	03/2023
		Decarbonisation Modelling Engineer	5	54 min	03/2023
		Senior Business Innovation Manager	8	1 h 12 min	03/2023
		Technical Cruise Sales Manager	10	1 h 8 min	03/2023
		Senior Energy Storage Product Manager	8	42 min	03/2023
		Business Development Manager	6	1 h 3 min	03/2023
Cruise line	**Company A**	Director of Energy and Decarbonisation Development	1,5	34 min	03/2023
	Company B	Vice President of Decarbonisation	7	37 min	04/2023
	Company C	Associate Vice President of Fleet Optimization	12	50 min	05/2023
	Company D	Director of Decarbonisation and Energy Management	17	59 min	05/2023
	Company E	Director of Electrical Department	31	45 min	04/2023
Cruise shipbuilding	**Shipyard X**	Head of Product Development	8	51 min	04/2023

Appendix 3. Simulation configurations

Simulation configurations

Global parameters

Fuels	Carbon content [%]	Sulphur content [%]	Nitrogen oxide content [%]	Particulate matter content [%]	Price [€/t]
HFO	85	3.5	1.1	0.315	450
MGO	87.5	1	0.8	0.092	800

Shore connection	Power [kW]	Price [€/kWh]
Shore power	15000	0.1

Batteries	Capacity [kWh]	C-rate	Min SoC [%]	Max SoC [%]	Starting SoC [%]	Maintenance [€/y]	Price [€/kWh]	CAPEX [€]
ESS21	2000	1	20	80	50	3000	850	1700000
ESS22	2000	2	20	80	50	3250	900	1800000
ESS23	2000	3	20	80	50	3500	950	1900000
ESS61	6000	1	20	80	50	4000	850	5100000
ESS62	6000	2	20	80	50	4250	900	5400000
ESS63	6000	3	20	80	50	4500	950	5700000
ESS11	10000	1	20	80	50	5000	850	8500000
ESS12	10000	2	20	80	50	5250	900	9000000
ESS13	10000	3	20	80	50	5500	950	9500000

Vessel X

	Type	Age [years]	Capacity [GT]	Length [m]
Characteristics	Cruise	< 5	< 150000	> 300

Engines	Number of engines	Max power [kW]	Fuels	Optimal SFOC [g/kWh]	Maintenance [€/h_r]	Consumables [€/h_r]	Engine price [€/kW]	CAPEX [€]
Large	2	14400	HFO/MGO	178	50	115	500	7200000
Medium	2	9600	HFO/MGO	179	40	100	600	5760000
Small	1	6700	HFO/MGO	180	50	90	650	4355000

Voyage	Duration [days]	Legs	Time in Port [%]	Time Manoeuvring [%]	Time Sailing [%]
A	10	7	26	4	70

Vessel Y

	Type	Age [years]	Capacity [GT]	Length [m]
Characteristics	Cruise	< 5	> 200000	> 350

Engines	Number of engines	Max power [kW]	Fuels	Optimal SFOC [g/kWh]	Maintenance [€/h_r]	Consumables [€/h_r]	Engine price [€/kW]	CAPEX [€]
Extra large	2	19200	HFO/MGO	176	60	130	450	8640000
Large	4	14400	HFO/MGO	178	50	115	500	7200000

Voyage	Duration [days]	Legs	Time in Port [%]	Time Manoeuvring [%]	Time Sailing [%]
B	10	7	26	5	69

Appendix 4. Simulation results summary

Vessel	Engine configuration	Battery capacity [MWh]	Shore power available	Yearly battery cycles	Running hour reduction [%]	OPEX savings [%]	Yearly savings [€/year]	Carbon emission savings [%]	Yearly carbon emission savings [ton/year]
Vessel X	Normal	2	Yes	973	1.2	0.8	122588	0.7	746
			No	937	1.2	1.0	172723	0.8	846
	Normal	6	Yes	548	3.2	1.3	206917	1.3	1376
			No	268	1.4	1.4	250794	1.1	1203
	Normal	10	Yes	584	4.1	1.6	253692	1.9	1944
			No	146	2.2	1.5	266583	1.1	1260
	One engine less	6	Yes	608	7.5	1.3	204717	1.0	999
		10	Yes	511	8.2	1.5	242259	1.5	1531
Vessel Y	Normal	2	Yes	973	2.0	1.0	289675	0.8	1471
			No	925	2.1	1.4	499563	1.2	2338
	Normal	6	Yes	669	2.6	1.5	441553	1.4	2604
			No	633	2.2	1.6	563324	1.3	2700
	Normal	10	Yes	596	2.5	1.6	462639	1.7	3070
			No	450	2.1	1.6	581855	1.4	2853