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Utilization of Batteries in The Momentary Load Variations of a Cruise Ship

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ABSTRACT :

The shipping and cruising industry is considered one of the most important and cheapest transportation, however, it is considered responsible for almost 2.89% of global emissions in 2018. Due to the new regulations provided by IMO, the need to reduce fuel consumption and emissions from the shipping industry becomes imperative. Several technologies have been applied to achieve those challenges, but the main focus of this thesis will be on the utilization of batteries as one of the most promising energy storage technologies, to handle the load variation rather than the operation of the auxiliary diesel engines at an economical loading range.

In cruise ship applications, the auxiliary diesel engines are utilized to supply the power required for the auxiliary loads and thruster motors, usually, thruster motors operate close to harbors. So, to ensure power availability, the auxiliary diesel engines usually run at low loading levels. The optimum operating point for the diesel engines is at 80% of loading, if that percentage decreases, both fuel consumption, and NOx emissions increased exponentially, moreover, the engine’s lifetime will be reduced and more maintenance will be required. By utilizing batteries, it will be capable of providing the required power for the operation of thruster motors or during peak loading periods rather than the operation of all available auxiliary diesel engines at low loading levels.

The presented study focused on four different scenarios with different battery-pack sizes, showing the space required for each scenario and the operating profile of each diesel engine indicating the fuel consumption with and without the presence of batteries. The first scenario utilized a 940-kWh battery pack, which increased the efficiency of the running engines close to the optimum operating level. The last scenario utilized a 3240-kWh battery pack, which enables the shutdown of the auxiliary engines during the operation of thruster motors or peak loading. By using the large battery model scenario, half the number of diesel engines will not be required in the future new builds of a cruise ship. This will not only improve the fuel consumption efficiency and reduce emissions, moreover, the maintenance and overall build cost will also be reduced. Technical and economic analysis is presented showing the payback period of the batteries with different fuel and battery price options. The payback period is highly affected by the saving associated with fuel costs and the price of batteries.

KEYWORDS: (Hybrid ship power supply, Energy storage, Cruise ship).

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Abbreviations

AVR	Automatic Voltage Regulator
BC	Black Carbon
BESS	Battery Energy Storage Systems
BOP	the balance of plant
C&C	construction and commissioning
DoD	depth of discharge
E/P	energy to power
EVs	Electric Vehicles
EASE	European Association for Storage of Energy
ECMS	Equivalent Consumption Minimization Strategy
EDLC	Electrochemical Double Layer Capacitor
EPC	engineering, procurement, and construction
ESS	Energy storage system
G&A	General & Administrative
GHG	Green House Gas
IMO	International Maritime Organization
IPSs	Integrated Power Systems
LFP	li-phosphate
LTO	lithium-titrate
MRL	manufacturing readiness level
O&M	operation and maintenance
PCS	power conversion system
PM	Particulate Matter
PMS	Power Management System
RTE	round-trip efficiency
SFC	Specific Fuel Consumption
SFOC	Specific Fuel Oil Consumption
SoC	state of charge
TRL	technology readiness level

VLA	vented lead-acid
VRLA	valve-regulated lead-acid
ZEDS	Zonal Electrical Distribution System

1 Introduction

The maritime shipping industry is considered the backbone of world trade, nowadays, it's almost utilized for transporting everything due to its huge capacity and low prices compared to other means of transportation (BitNautic, 2020). Maritime shipping is included in several civil applications such as Ro-Ro vessels, dry cargo ships, general cargo vessels, bulk carriers, reefer vessels, container vessels, liquid cargo ships, crude carriers, product carriers, chemical carriers, liquified gas carriers, specialized cargo, passenger vessels, tugs, livestock carriers, and heavy lift/project cargo vessels (Portocargo, 2022). However, the main focus of this thesis will be on passenger vessels or cruise ships. According to Statista, (2021a) the cruise ship industry was responsible for transporting almost 30 million in 2019, that number was expected to increase in 2020 but due to the spreading of the coronavirus pandemic and the associated restrictions, that number dropped dramatically to about 5.8 million in 2020, cruise travels ranged from several hours up to several months and from local to worldwide destinations. The cruise shipping industry is expected to recover in the upcoming few years, its revenue is expected to increase from $23.3 billion in 2007 to $57 billion in 2027, the industry is very promising, and as a result, there is an increased interest to utilize larger cruise ships to increase revenue and increase efficiency (Statista, 2021b). Moreover, to meet the future market demand, every year about 6 to 8 cruise ships have been built with a carrying capacity of up to 8,000 passengers accommodated onboard (Vicenzutti et al., 2017).

Based on the International Maritime Organization IMO, (2020) report, all major industries and electrical power generation are moving toward using renewable energy sources rather than conventional sources, which have a detrimental effect on the environment, causing climate change and global warming. The shipping industry is not away from this transition, it was responsible for 2.76% of global emissions in 2012, and that percentage increased to 2.89% in 2018. The total Green House Gas (GHG) emissions from the shipping industry were 977 million tonnes in 2012, that number increased to 1,076 million tonnes in 2018, with about a 9.6% increase percentage, the shipping industry was responsible for almost 15% of global NO_x emissions. The main considered

GHG emissions are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Emissions projection in 2050 is expected to be about 90-130% of 2008's emissions, if no measures are taken, the 2° C reduction target according to the Paris convention will not be possible to achieve. Moreover, all new-build ships shall be 30% or more energy-efficient than those built-in 2014. Figure 1 represents the contribution of the shipping industry to air pollution, that contribution has a severe effect on human health and the environment, especially close to harbors or ports.

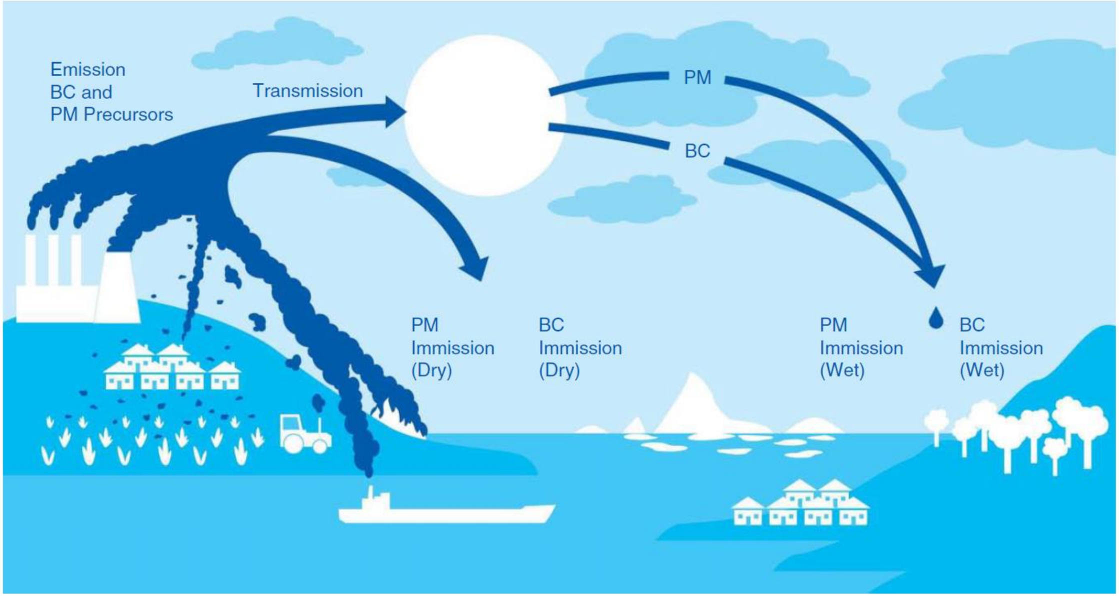


Figure 1. Shipping contribution to air pollution. BC: Black Carbon; PM: Particulate Matter (Alnes et al., 2017).

Shipping operation is highly dynamic due to the unpredicted working conditions in the sea environment, which requires the operation of reserve diesel engines as a power redundancy or spinning reserve for certain types of operations, these diesel engines are running at low speed and low efficiency with high fuel consumption. As illustrated in Figure 2, the Specific Fuel Oil Consumption (SFOC) for two diesel engines with different loading conditions, as noticed, there is about 14% fuel saving in case of running only one diesel engine in high loading compared to two engines with low loading. Moreover, not only the fuel, emissions, and maintenance will be reduced, but the lifetime of each engine will increase due to fewer operating hours.

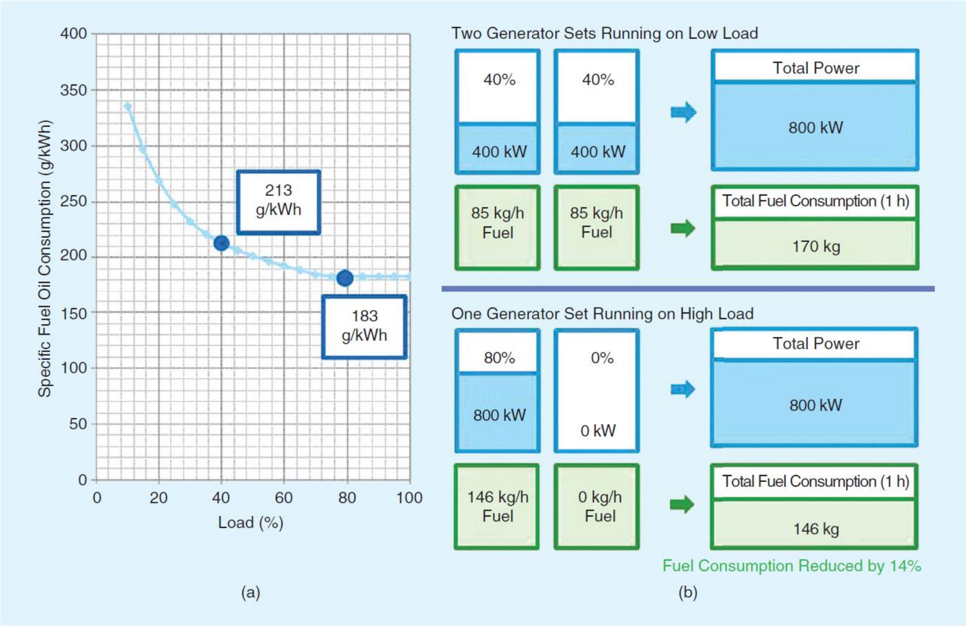


Figure 2. SFOC for two diesel engines at the different operating profiles (Alnes et al., 2017).

As a result, and due to the increased and growing demand for reducing the emissions and improving fuel efficiency of conventional propulsion systems, alternative energy sources shall be integrated into the power system such as fuel cells, solar, and wind (García-Olivares et al., 2018). However, the installations of solar and wind on shipboard are still debatable, as they do not have significant participation compared to the main conventional gensets, especially for large ships, where the propulsion motors loads are significant, so, the research and development in this area are growing to increase the sharing percentage of those alternative sources (Sciberras et al., 2017). On the other hand, the usage of fuel cells is considered one of the most promising alternative energy sources for ships in the future and upcoming projects (J. Han et al., 2014).

Moreover, besides the integration of these alternative energy sources to ship power systems to improve efficiency, the energy recovery technologies can also be included such as waste heat recovery systems, which produce electricity by utilizing exhaust fumes, that technology is capable of improving the engine effects by almost 5%, which can be translated to a reduction in fuel consumption and emissions (Andreasen et al., 2017).

Nevertheless, the integration of the aforementioned alternative energy sources in parallel with the conventional gensets is not enough due to several limitations such as slow and/or intermittency and are not capable of supplying plus loads such as radar, which in some cases exceeds the power generation capacity of the ship, which leads to unstable operation (T. van Vu et al., 2017). So, to avoid that challenge, the integration of energy storages technology becomes imperative such as an electrochemical battery to supply the high energy load with fast response and electrical supercapacitor energy storage to supply instant pulse loads (Crider & Sudhoff, 2010). Figure 3 shows the battery cost development in the automotive and maritime industry, as indicated, the prices are expected to decrease in the upcoming few years, moreover, the energy density and cycle life are expected to increase.

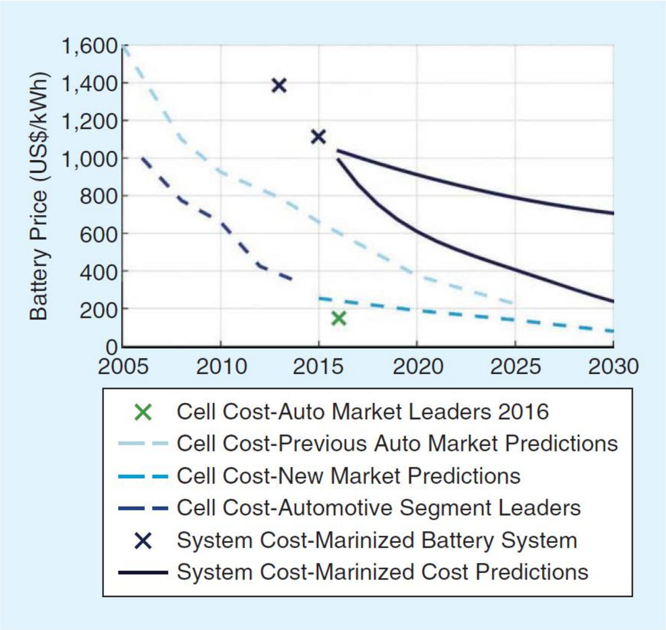


Figure 3. Automotive and maritime battery cost development (Alnes et al., 2017).

Alnes et al., (2017) stated that not only the low loading effect on the diesel engine's fuel consumption and emission but also any transient increase or decrease in engine loading causes transient variation in engine speed and/or load. Moreover, those transient events increase engine wear and consequent maintenance cost. So, as shown in Figure 4, the utilization of battery not only acts as a power reserve for the diesel engines, moreover, it enables the diesel engines to work within the high-efficiency area, moreover, it can be used in peak shaving of the loading profile.

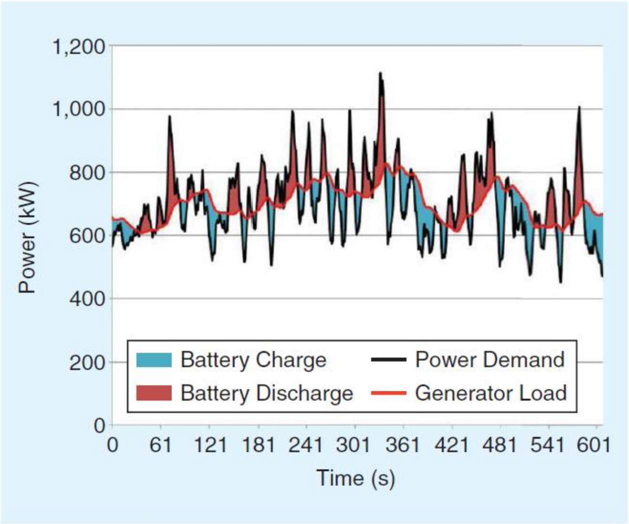


Figure 4. Peak loading shaving by batteries (Alnes et al., 2017).

The combination of gensets, alternative energy sources, energy recovery systems, and energy storage technologies can be represented as a typical islanded microgrid when the ship is in the sea, while the ship is at berth, it can be considered a grid-connected microgrid, there are some similarities to the conventional terrestrial microgrids (McCoy, 2015). However, in the terrestrial microgrid, the alternative energy sources have large participation in the total required energy compared to small or fractional in the case of ship microgrid, where, the main gensets are responsible for the major part of the total energy required, especially for large propulsion motors, beside the presence of pulsed loads, which is not the same for terrestrial microgrids (Elsayed et al., 2015).

Moreover, in ship microgrids, the major part of the energy is generally consumed by the propulsion motors, which are highly dynamic uncontrolled loads, and the presence of pulse loads as mentioned, these elements arose quality issues to ship microgrid operations (Jayasinghe et al., 2017). Currently, the usage of partially or fully electrified ships is increasing, for instance in Europe, Norway is a leader in this field, followed by Sweden and Finland are global leaders in manufacturing and launching electric ships (Chin et al., 2019). Table 1 introduces the current ships that are partially or totally electrified in different applications.

Table 1. Fully or partially electrified ships since 2013 (Chin et al., 2019).

Vessel	Delivered	Country	Purposes	Type of Battery	Capacity
M/S Viking Lady (partially electrified with fuel cell)	2013	Norway	Offshore activities	Lithium-ion	500 kWh
Ampere ferry (fully electrified)	2015	Norway	Cars and passengers	Lithium-ion	1 MWh
UT 776 CDG offshore vessel (partially electrified)	2016	Norway	Offshore activities	Lithium-ion	200 kWh / 600 kWh
MV Catriona ferry (after MV Hallaig and MV Lochinvar) (Partially electrified)	2016	UK	Passengers and vehicles	Lithium-ion	700 kWh
Bøkfjord offshore vessel (Partially electrified)	2017	Norway	Offshore activities	Lithium-ion	850 kWh
Tycho Brahe ferry (fully electrified)	2017	Sweden	Passengers and vehicles	Lithium-ion	640 kWh
Elektra hybrid-electric ferry (Partially electrified)	2017	Finland	Passengers and vehicles	Lithium-ion	1 MWh
Viking Princess OSV (Partially electrified)	2017	Norway	Offshore activities	Supercapacitors and lithium batteries	533 kWh
Guangzhou electric cargo ship (fully electrified)	2017	China	Transporting coals	Lithium-ion	2.4 MWh
Gloppefjord ferry (fully electrified)	2018	Norway	Passengers and vehicles	Lithium-ion	2 MWH
Aurora ferry (fully electrified)	2018	Sweden	Passengers and vehicles	Lithium-ion	4.16 MWh
Aranda maritime research vessel (partially electrified)	2018	Finland	Maritime research	Lithium-ion	2 MWh
SEACOR Maya OSV (Partially electrified)	2018	USA	Offshore activities	Lithium-ion	533 kWh

The main object of this thesis is to study and review the current work on the utilization of batteries in the momentary load variations of a cruise ship, the usage of batteries for the momentary load fluctuations, so the auxiliary engines are not needed to operate at uneconomical load range, focusing on both technical and economic aspects of the usage of batteries, study if usage of batteries can minimize the transformers losses, and finally calculating the payback period for the batteries with providing an estimation the size of batteries.

The thesis will be organized as follows, chapter two presents several types of propulsion systems; where the major concern will be the usage of electric propulsion with its different networks variants AC, DC, and hybrid AC/DC. Chapter three discusses the most common and feasible energy storage systems, where electrochemical-based batteries are introduced as a high energy source and supercapacitors as a high-power source. A literature review of different control strategies for different networks variants AC, DC, and hybrid AC/DC is covered in chapter four. A complete review will be presented of the feasibility of the usage of batteries and their effect in chapter five. Chapter six demonstrates different economic aspects of the usage of batteries in hybrid power supply networks. Finally, a conclusion and future work are considered in chapter seven.

2 Literature review about different propulsion systems for ships

This chapter presents different propulsion systems and technologies from conventional mechanical and electrical systems to up-to-date hybrid propulsion systems. In addition to that, different power supply systems are introduced including combustion-based diesel engines, electrochemical-based batteries, and hybrid power supplies. The advantages and disadvantages of each topology are provided including the challenges associated with each technology. In addition to that, different comparison criteria are provided with focusing on the major factors for performance criteria such as fuel consumption, emissions, radiated noise, propulsion availability, maneuverability, comfort due to minimal noise, vibrations, and smell, maintenance cost due to engine thermal and mechanical loading, and finally, purchase cost.

2.1 Mechanical propulsion

There are different propulsion systems used in the shipping industry nowadays such as mechanical, electrical, hybrid, electrical propulsion with hybrid power supply, hybrid propulsion with hybrid power supply, and electrical propulsion DC hybrid power supply. The choice of the used system depends on the required application. In this section, the focus will be on the mechanical propulsion system.

Curley, R. (2011) presents the complete history of ships and boats starting from sails and oars to the most upgraded nuclear-powered vessels. Before the 19th century, ships were running with sails and oars, till the industrial revolution and the presence of reciprocal steam engines and steam turbines. As a result, the mechanical propulsion system was presented as an efficient and reliable system compared to conventional available sails and oars.

A typical structure for the modern mechanical propulsion system is presented in Figure 5. As noticed, the propulsion part is separated from the electrical part. In that case, the only function of a prime mover is propulsion, it may be based on a gas turbine, diesel engine, or even nuclear power plant. While it is worth mentioning that the focus of this thesis will be on the diesel engine, as it is considered one of the most common uses in the shipping industry, moreover it presented the highest fuel efficiency. Geertsma et al., (2017) present a detailed description and comparison of different propulsion technology, which is out of scope for this thesis. As noticed, the electrical network part is separated from the propulsion part and supplied from separate generators and a separate AC netwrok. This network is responsible for supplying power for the thrusters or auxiliary motors, the hotel load (in the case of cruise ships,) and other auxiliary loads such as heating and ventilation.

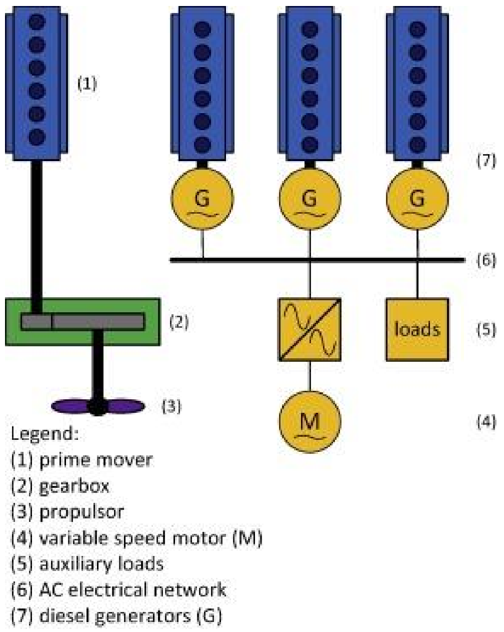


Figure 5. Mechanical propulsion system schematic diagram (Geertsma et al., 2017).

Geertsma et al., (2017) stated that the highest efficiency for mechanical propulsion can be achieved within the range of 80 and 100 % of top speed. In this range, the optimum operation for the system can be obtained. The mechanical propulsion system consists mainly of major three components which are: the engine, gearbox, and propeller. As a result, the conversation losses are low and the overall cost of the system is low. That's why the mechanical system is the most commonly used in the transport ship industry. The radiated noise is limited due to the separation between the engine and the propeller.

However, on the other hand, mechanical propulsion has a low availability due to the dependency on only one source, and in case of failure of any components, the whole system will collapse. Moreover, it exhibits a very poor fuel efficiency for the low speed, especially below 70% of top speed. In addition to that, the NOx emissions tend to increase during low speed as illustrated in Figure 6. An extensive review of proposed solutions and control strategies to maximize the efficiency of the mechanical propulsion system is provided by (Geertsma et al., 2017).

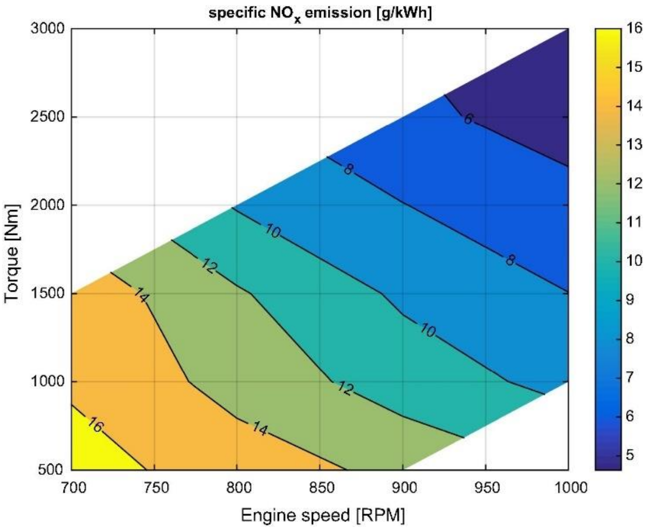


Figure 6. NOx measurement from the engine (Linden, Y. 2016).

2.2 Electrical propulsion

Sáiz, V. M. M., & López, A. P. (2007) introduced a brief historical introduction to the usage of electric propulsion in the ships industry. Nowadays, mostly, cruise ships use the electric propulsion system as it’s considered one of the most efficient and reliable systems compared to other systems (Kanerva & Hansen, 2009). Hansen & Wendt, (2015) stated that electric propulsion has been around since the 1900s, but it was not common and was very limited, due to the extensive development and upgrade that occurred in power electronics and converters from the 1990s till now, electric propulsion becomes very common and practical, electric motors have a high efficiency up to 95% within a wide range of power output between 5% and 100%, compared to combustion engines, which has its highest efficiency with a limited range between 85% and 90% of rated power, thus reduce the overall system flexibility and increase running cost indeed. Even though this high efficiency, the electrical system has about 5% to 15% losses accounted from power converters, transformers, generators, and electric motors, so a tradeoff shall be considered, and to overcome a hybrid power supply will be provided to maximize the benefits and reduce the operation costs (Geertsma et al., 2017).

Figure 7 depicts the schematic diagram for an electrical propulsion system. There are several diesel engines connected in parallel to a fixed frequency electrical bus. The propulsion motors, the thrusters or auxiliary motors, hotel loads (in the case of a cruise ship), and auxiliary loads are connected to that electrical bus. As illustrated, the electric propulsion motors have separate power electronic converters to control the motor drive and ship's speed. Compared to the mechanical system, electrical propulsion has one combined system rather than two separate systems, which increases the availability and reliability of the electrical system.

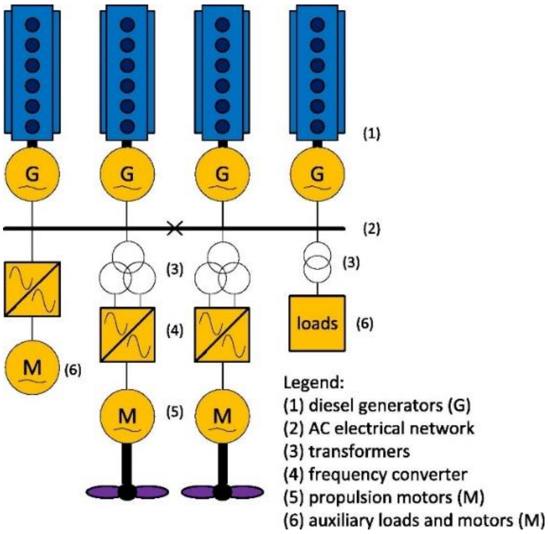


Figure 7. Electrical propulsion system schematic diagram (Geertsma et al., 2017).

As mentioned earlier, the choice of propulsion depends on the required application. Vie, R. (1998) stated that in case of the cruise ship applications, where the hotel loads are significantly larger than the power required for the propulsion system, and when the load profile is highly diversified and fluctuated, it will be more feasible to use the electrical propulsion system to achieve the optimum performance and fuel efficiency. So, an efficient Power Management System (PMS) is required to coordinate the operation of different generators to supply the power for both: hotel loads and propulsion motors.

Due to that, by coordinating the operation of the generator, NOx emissions were reduced significantly compared to the mechanical propulsion, the presence of PMS ensures that diesel engines operate within the optimum interval due to operating within the optimum speed. The availability of electrical propulsion is higher than mechanical propulsion, all diesel engines are connected to the same network in parallel, which increases the overall system availability in case of maintenance or failure of engines. In an electrical system the mechanical components are fewer, so that affects the radiated noise, which is less compared to a mechanical system. The radiated noise is a crucial factor in cruise ship applications to achieve resident satisfaction.

The above-mentioned merits for the electrical propulsions come at the cost of increased losses due to the presence of electrical components such as power converters, transformers, and electric motors. Also, all electrical loads are connected to the same main network, in case of voltage or frequency swing occurrence due to faults, thus might lead to the disconnection of other loads and this reduces the system availability and reliability. Sulligoi et al., (2016) analyzed this issue in brief and proposed two modeling strategies for mitigation.

2.3 Hybrid propulsion

McCoy, (2002) stated that when the auxiliary loads are fractional compared to the total loads, the hybrid propulsion system will be a better choice to achieve the highest fuel efficiency. In the case of the electrical propulsion system, there is plenty of different equipment and converters which increase the system losses and have a direct effect on reducing the fuel efficiency and has no function in this application. Also, Gemmell et al., (2014) demonstrate that the existence of electrical equipment will lead to more weight, size, and cost, which is not needed in such kinds of applications. So, according to Castles et al., (2009) and Sulligoi et al., (2012) the usage of a hybrid propulsion system is recommended to achieve the highest fuel efficiency and optimum operation in case of low-speed applications. Geertsma et al., (2017) provided an extensive review of different applications that vary between naval and towing vessels.

Figure 8 depicts the schematic diagram for the hybrid propulsion system. As illustrated, the propulsion system consists of both direct mechanical drive, which is responsible for providing the propulsion, when the high speed with high efficiency is required, besides that, an electric motor is decoupled to the same shaft in parallel with the mechanical drive, and responsible for the propulsion, when the low speed with high efficiency required. Moreover, this electric motor can be utilized to supply power to other auxiliary loads if needed instead of the diesel generators, to achieve fuel efficiency.

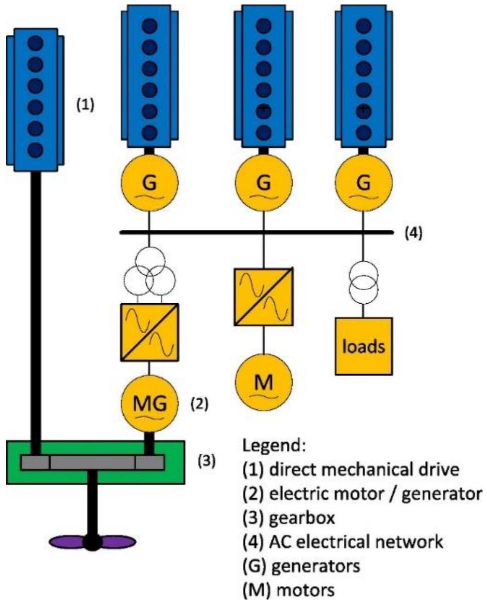


Figure 8. Hybrid propulsion system schematic diagram (Geertsma et al., 2017).

As discussed in the previous section, the mechanical propulsion system consists of many components and can utilize the both benefits of electrical and mechanical systems, taking into consideration the trade-off, which occurs when applying both systems. The main challenge here is that system requires a careful design with a sophisticated control system to manage the operation of all these components to achieve optimum performance. Geertsma et al., (2017) provided a brief discussion about different control strategies applied to the mechanical propulsion system.

2.4 Electrical propulsion with hybrid power supply

Electrical propulsion with a hybrid power supply utilizes two or more power sources to supply the necessarily required power for both the propulsion system and the auxiliary loads. Figure 9 presents the schematic diagram for the hybrid system. As illustrated, there are many conventional diesel engines connected in parallel with energy storage. Energy storage systems could be batteries, flywheels, or ultra-capacitors. Fuel cells are still limited in maritime applications, however, van Biert et al., (2016) provided a comprehensive review of the usage of fuel cells in maritime applications, which is out of our scope for this thesis.

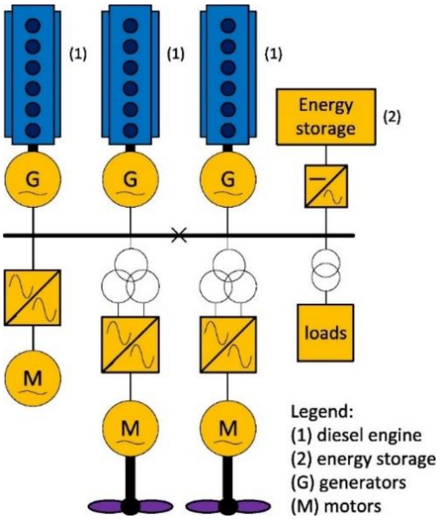


Figure 9. Electrical propulsion with hybrid power supply schematic diagram (Geertsma et al., 2017).

Recently, batteries have been used extensively in the automotive industry as a provider for all or part of the total power required. As a result, extensive research and development have been occurred to improve and increase the efficiency of different energy storage techniques, however, due to the limited range of energy storage and high demand for maritime applications, the usage of energy storage as its main source is still limited compared to the automotive industry. Roskilly et al., (2015) discussed different energy storage technologies in their review. In chapter three, the most common energy storage technologies will be discussed in brief focusing on electrochemical energy storage. Overall, the research on the usage of energy storage in maritime applications is limited and focuses mainly on the usage of batteries to supply a partial part of the total load.

Ovrum & Bergh, (2015) presented a model for lithium-ion batteries for crane application operation on the ship. Also, Dedes et al., (2012) provided an assessment to determine the potential of hybrid energy storage to reduce exhaust emissions in maritime applications and global shipping. While, Lan et al., (2015) introduced an optimal sizing for a hybrid system consisting of diesel engines, PV, and batteries to supply power to ship. In some special applications, such as naval and army applications, a high energy supply is required to provide sufficient power for pulsed loads and weapons. For instance, the power supply system is required to supply up to 10 GW during a microsecond. Lashway et al., (2016) proposed a hybrid power supply system consisting of both batteries to supply high energy density requirements and supercapacitors to supply high power density applications.

There are several merits to the usage of energy storage with the electrical propulsion system. One of these major advantages is flexibility. It can be connected to H.V or L.V bus bars via AC/DC converters or connected directly to the DC link of the motor converter. Zahedi et al., (2014) proposed an electric hybrid system with the usage of batteries as an energy storages source, which enables load leveling, thus eliminating power fluctuations and resulting in an almost constant load profile for diesel engines, which increases the overall efficiency by reducing fuel consumption as illustrated earlier in Figure 6.

Moreover, batteries can supply loads during peak periods, thus enabling peak load shaving for load profile, and can be charged during off-peak loading conditions. This can be done by coordinating the charging and discharging process for batteries to ensure the operation of diesel engines within the high-efficiency range. Völker, T. (2015) mentioned another advantage of the usage of batteries, they can be charged from the grid during stopping periods at berth, which is frequent for ferry and cruise ships. This will reduce the cost of operation and emissions produced from the operation of the ship. Fuel reduction can be increased by charging the batteries with a renewable energy source and also to avoid the trade-off, which happens when charging batteries from a conventional grid-based on fossil fuels.

Ovrum & Bergh, (2015) stated in their paper that batteries can be charged when electric motors brake, rather than the loss of that power in resistors. While it is worth mentioning that, braking generation for ship applications is not significant compared to automotive applications, frequent stopping for ships is not common. But it could be significant in other applications such as crane usage for container ships. Zahedi et al., (2014) introduced a DC hybrid power supply system to increase the system availability by utilizing batteries as an energy storage source to supply power for motors in case of failure of diesel ensigns. Geertsma et al., (2017) provided several examples in their review of the usage of batteries as an energy storage source for different current projects.

On the other hand, to achieve that system and those advantages, there are some challenges. The need for a very efficient and intelligent PMS to controls and coordinates the operation of all these components to ensure the operation of diesel engines within the high-efficiency range during most of the operation time. The cost of batteries and converters is considered as an added cost for the whole system, thus fuel saving during the overall life operation and diesel engine resizing shall be achieved to achieve cost optimization for the whole system.

2.5 Hybrid propulsion with hybrid power supply

As shown in Figure 10, the hybrid propulsion system consists of both mechanical and electrical propulsion, in addition to that, the electrical system network is based an on a hybrid power supply, which consists of both conventional one of egy storage sourcessourceresult, the system utilizes the benefits of all these components. The system can utilize maximum fuel efficiency by using the mechanical system for high-speed requirements and utilizing the energy storage for the hybrid electrical system for low-speed requirements or during maneuvering events close to harbors. High efficiency and flexibility will be achieved by utilizing an efficient control technique. Currently, the usage of this system is not common, Geertsma et al., (2017) stated that the system is only utilized for harbor tugs and yachts applications.

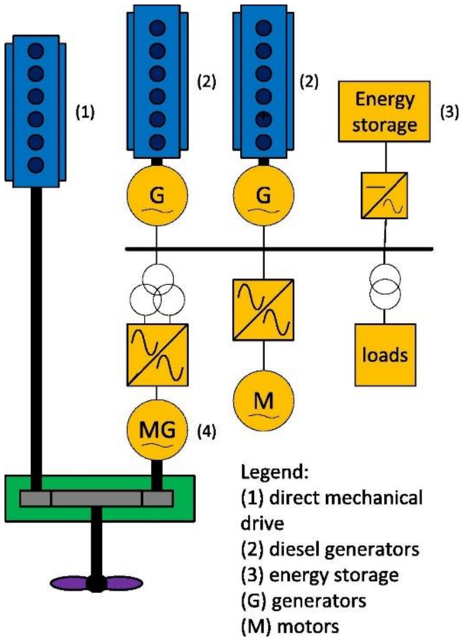


Figure 10. Hybrid propulsion with hybrid power supply schematic diagram (Geertsma et al., 2017).

2.6 Electrical propulsion with DC hybrid power supply

The schematic diagram for the electrical propulsion with the DC hybrid power supply is presented in Figure 11. As illustrated, the major components are similar to the electrical propulsion with an AC hybrid power supply, the major difference is utilizing the DC supply network to connect all these components rather than the conventional AC network. As mentioned earlier, the fuel consumption for fixed speed electrical propulsion is high compared to the variable speed electrical propulsion, so usually the variable speed concept is utilized for electrical propulsion to achieve maximum fuel efficiency, although fuel consumption is achieved, most consumers want to avoid the usage of variable frequency and prefer fixed frequency network.

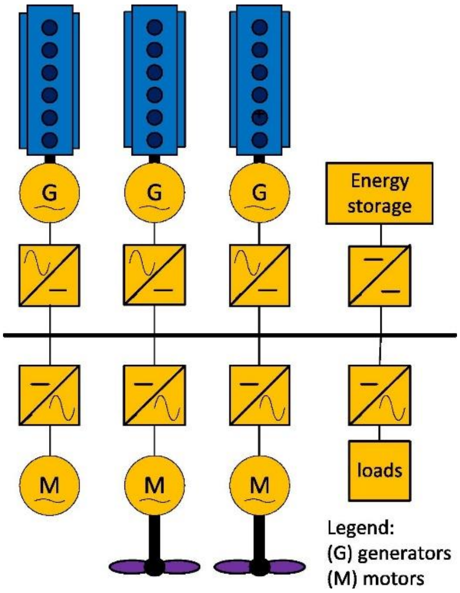


Figure 11. Electrical propulsion with DC hybrid power supply schematic diagram (Geertsma et al., 2017).

As a result, a DC network supply is proposed, it can also provide variable speed for engines to achieve fuel efficiency. However, currently, the usage of DC networks is limited only to submarines due to several challenges such as power stability and fault protection. In addition to that, a very efficient control system is required to manage the operation of all these components (Herrera et al., 2017). Currently, due to the continuous upgrade and development of power electronics (Zadeh et al., 2013), and the presence of more efficient fault detection equipment, this will provide more potential and feasibility for the usage of the DC network's power supply in the future (Butcher et al., 2009).

Although the presence of all these challenges, the DC supply-based system is capable of reducing fuel consumption by controlling the operation of the generator during part loads and reducing overall power losses, which occur in AC power converters (Zahedi et al., 2014). In addition to that, the DC network has instantaneous control over an electrical variable, thus enabling more resilience for the system against fault occurrence and protection (Geertsma et al., 2017). Also, the overall sizing for the DC system is less compared to AC, due to the reduced dimension of switchgear, as there is no need for sophisticated protection devices or power electronics compared to AC systems (Butcher et al., 2009).

2.7 Electrical Propulsion Overview (AC Power system architecture):

As mentioned earlier in this chapter, the electrical propulsion system is the most common and utilized in cruise and passenger ship applications. So, in this section, the ship AC power system architectures will be presented and described in brief mentioning the merits and demerits of each architecture.

Skjong et al., (2015) stated that the majority of ship AC power systems follow the same practice as shore such as 440V/60 Hz or 400V/50 Hz three-phase low voltage network, by utilizing that practice, it will be easier to use normal industrial equipment, which is more appropriate for working in the sea harch environment. All these auxiliary loads are considered fractional compared to the major load, which is the propulsion motors, it is not possible to supply the power required for the propulsion motors from the LV bus network, so, a separate medium voltage network is needed for that purpose. Generally, it can be 3.3, 6.6, or 11 kV network. Previously, all these components and networks are segregated from each other, but the current trend is to merge all these networks into Integrated Power Systems (IPSs).

Several passenger ships utilize the IPSs system such as Queen Elizabeth II, as shown in Figure 12, the schematic diagram of the power system, where all generators sets are connected to the main HV bus, and all other loads are connected to that bus, and all LV loads are connected via a step-down transformer (Jin et al., 2016).

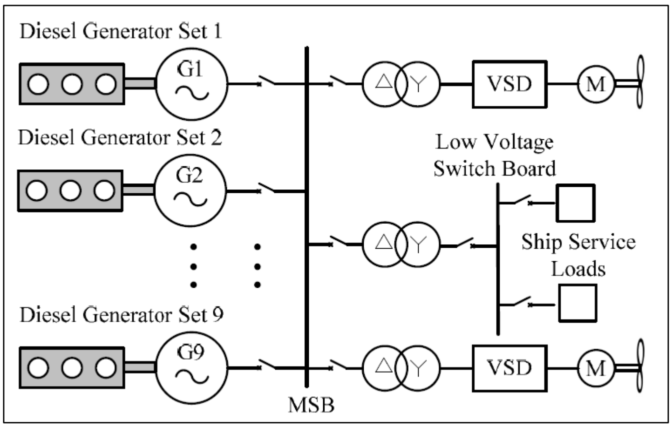


Figure 12. Queen Elizabeth II AC power network (Jin et al., 2016).

Even though all those components are connected to the same network, that architecture has a drawback and runs the risk of failure, as noticed, in case of fault occurrence on the HV side, all other loads connected to that network will be disconnected, and blackout will occur, so, to overcome that challenge a new proposed architecture was presented, which provides two HV/LV radial bus power system architecture, as depicted in Figure 13. In case of fault occurrence in HV bus, LV loads will not be affected, moreover, there is an emergency generator connected to the LV bus network, to provide the power required in case of failure in main generators sets. In addition to that, the integration of alternative energy sources such as fuel cells and energy storage will be possible (Huang et al., 2009).

Two HV/LV radial bus power system architecture showed a great performance with more merits than previous architecture, however, it has a major drawback, which is the risk of losing a major load in case of its associated bus failure, like the failure of HV bus, which responsible for supplying the propulsion motors or losing an essential load connected to LV bus network, so, currently, all modern electric ships are moving toward the usage of

Zonal Electrical Distribution System (ZEDS) architecture based on IPSs rather than the usage of radial architecture (Khushalani et al., 2008).

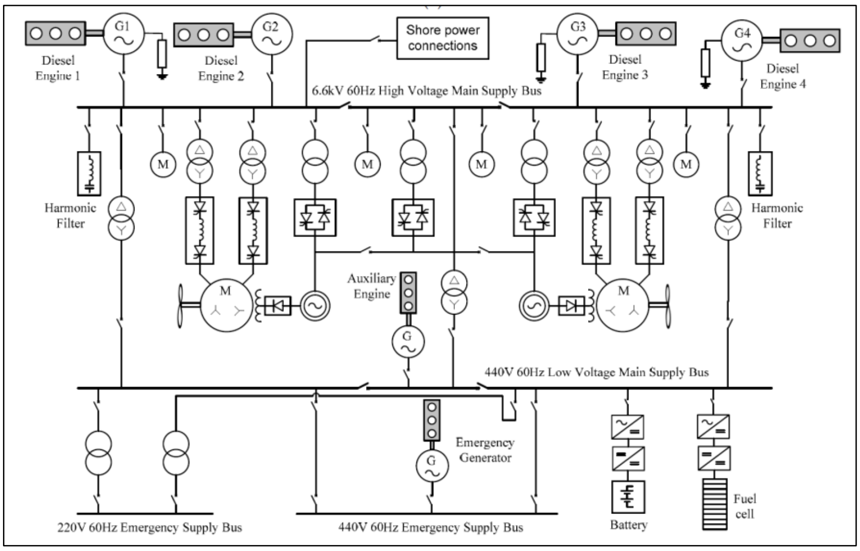


Figure 13. Two HV/LV radial bus power system architectures (Huang et al., 2009).

Figure 14 illustrates the schematic diagram of the ZEDS power system architecture, where the AC power network is splited into several sections or zones. All zones are connected via bus-tie switches and have their load center and generating source. All zones are connected with starboard and port bus, for increased reliability, one bus is located below sea level and the other above sea level to reduce the risk of damage for both buses.

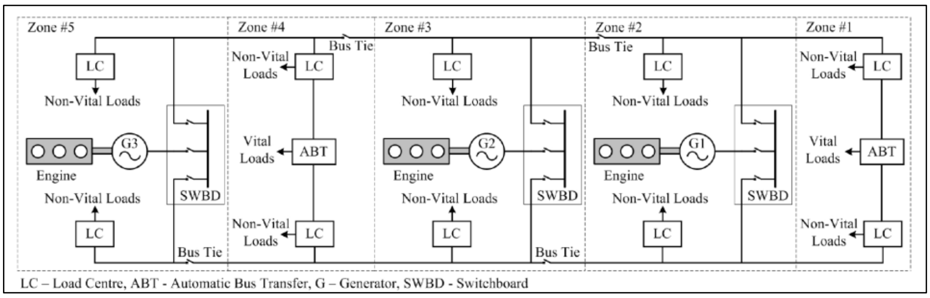


Figure 14. ZEDS power system architecture (Khushalani et al., 2008).

2.8 Conclusion

In this chapter, all commercially available propulsion systems for the shipping industry were presented in brief showing the merits and demerits and the application of each system, focusing on the electrical propulsion system, as it is considered one of the most commonly utilized systems for passengers and cruise ships applications. Several architectures for the AC power system were presented and described in brief. The latest described system was ZEDS, which is considered one of the most common architectures nowadays and can provide high reliability compared to other architectures. Table 2 introduces a comparison between different propulsion systems for ships, showing the advantages and disadvantages of each system. Moreover, Table 3 presents the current and future applications for each propulsion system, both summary tables were presented by (Geertsma et al., 2017).

Table 2. Propulsion systems comparison (Geertsma et al., 2017).

Technology	**Advantages**	**Disadvantages**
Mechnacical Proplosuion	• The low losses at design speed • Low CO2 and NOx emissions at design speed • Low conversion losses	• Poor part-load efficiency and emissions • High NOx at reduced speed • Low redundancy • path of Mechanical transmission • Noise • Engine loading
Electrical Proplusion	• Robustness • Matching load with generators • High availability • Reduced NOx emission at low speed • Potentially low noise	• Constant generator speed • Losses at design speed • Risk of constant power load • instability
Hybrid Propulsion	• The low losses at design speed • Robustness • Matching load & engines at low speed • Potentially low noise on electric drive	• Constant generator speed • System complexity
Electro-chemical PS	• Air independent • No harmful emissions • High efficiency and low noise	• Limited range • Safety • Complex with reforming
Store PS	• Air independent • No harmful emissions and noise	• Very limited range • Safety
Hybrid Power Supply	• Load leveling • Zero noise and emission mode • Storing regenerated energy • Efficient backup power • Enabling pulsed power • Reduced fuel consumption & emissions • No NOx increases during acceleration	• Constant generator speed • System Complexity • Safety due to battery • Battery cost
DC Power Supply	• Variable engine speed and load • Optimal engine loading • Reduced engine noise and vibrations • Reduced fuel consumption and CO2 • Enabling pulsed power	• System complexity • Cost & losses from power electronics • NOx increases due to variable speed

Table 3. Current and future applications for different propulsion systems (Geertsma et al., 2017).

Technology	**Current Applications**	**Future Applications**
Mechnacical Proplosuion	• Cargo vessels and crew suppliers • Naval vessels • Tugs and yachts	• Cargo vessels and crew suppliers • Naval vessels • Tugs and yachts
Electrical Proplusion	• Cruise ships • Capital naval vessels • Offshore vessels • Drilling vessels and crane vessels	• Cruise ships • Capital naval vessels
Hybrid Propulsion	• Warships and Patrol Vessels • Tugs • Long-range offshore vessels	• Warships and Patrol Vessels
Electrical prop. & electrochemical PS	• Submarines	• Submarines • Ferries
Electrical propulsion & hybrid power supply	• Tugs • Ferries	• Drilling vessels • Crane's vessels
Hybrid propulsion & hybrid power supply	• Tugs • Yachts	• Tugs • Yachts • Cargo ships
Electrical propulsion & DC hybrid power supply	• Yachts • Offshore vessels • Ferries • Naval Vessels	• Cruise ship • Naval vessels • Drilling vessels • Heavy crane vessels • Dredgers
Hybrid propulsion & DC hybrid power supply	• Yachts	• Warships • Patrol vessels • Tugs • Long-range offshore vessels

3 Literature review about energy storage systems

Why energy storage? Energy storage plays a significant role in the transition from the usage of centralized conventional power generation power plants, which needed to be dispatched regularly to match energy consumption and generation at all times, toward the usage of renewable energy sources. Currently, the extensive usage, integration, and increasing share of different renewable energy sources, thus force the need for storing excess energy off-peak and utilizing it during peak time, in addition to that it can provide load shaving. This provides great flexibility to the system to supply energy at different time scales ranging from seconds up to months depending on the type of energy storage technologies. Moreover, energy storage can act as a backup source during the failure or blackout of the main generation. Hansen & Wendt, (2015) provided a summary of major functions energy storage can be utilized for, which will be presented in Table 4.

Table 4. Energy storage functions (Hansen & Wendt, 2015).

Function	Description	Purpose
Spinning Reserve	In case of generator loss	Backup for running generators
Enhance Ride Through	Similar to spinning reserve but on a local level in sub-system	Higher power system availability
Peak Shaving	Absorb load variations	Improve running engines overall efficiency
Enhanced Dynamic Performance	Absorb sudden load changes	Support running engines
Strategic Loading	Optimize the optimum point of running engines	Optimize the operating point of the gensets
Zero Emissions Operation	Supply power – Turinning off the gensets	Harbour zero-emissions – Quiet engine room

Due to the above-mentioned merits of energy storage, its market grows exponentially. It added about 1.7 GWh in 2020 and is expected to add 3 GWh in 2021, with a total cumulative installation of 8.3 GWh in 2021 Europe only, in addition, that, it enables the achievement of a zero-emissions vision for power system generation in the EU countries by 2050 (EASE, 2022). Figure 15 shows the annual European energy storage market in

MWh from 2015 to 2021 across all sectors. Total cumulative installed energy storage increased from 0.6 GWh in 2015 up to 8.3 GWh in 2021, total installation almost doubled during 2021 only and is expected to increase shortly.

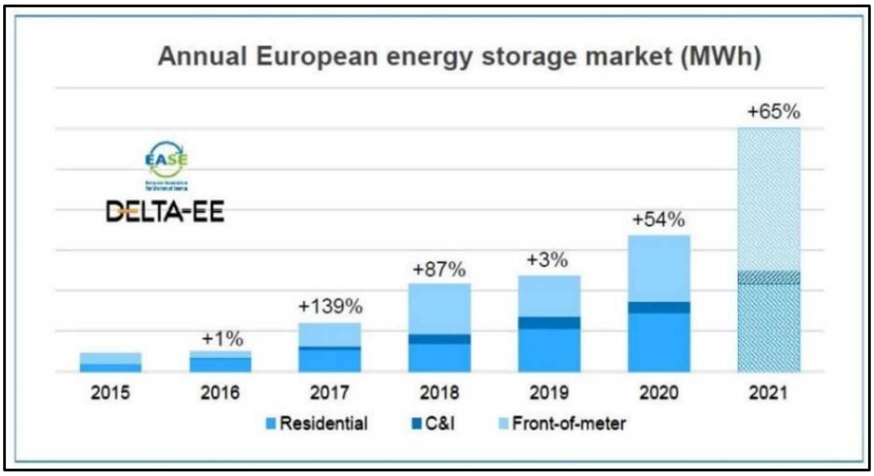


Figure 15. Annual European energy storage market (MWh) (EASE, 2022).

There are different energy storage technologies, which differ according to the operating mechanism. Figure 16 presents a summary of the most common available techniques, which are based on different mechanisms such as chemical, electrical, mechanical, and electrochemical. The usage and the selection of each technique are depending on the required application and natural limitations (like pumped storage), also the required level of flexibility and availability for the energy storage, which ranged from seconds up to months.

While it is worth mentioning that the main focus of this thesis and this chapter will be on the most common electrochemical based energy storage techniques such as lithium-ion batteries, lead-acid batteries, redox flow batteries, and sodium-sulfur batteries will be introduced as a high energy density source and one of the most common electrical-based energy storages techniques such as supercapacitors will be presented as a source of high-power density source. These types are considered the most commercially feasible and matured energy storage techniques and are utilized in most of the current projects and applications, which require energy storage.

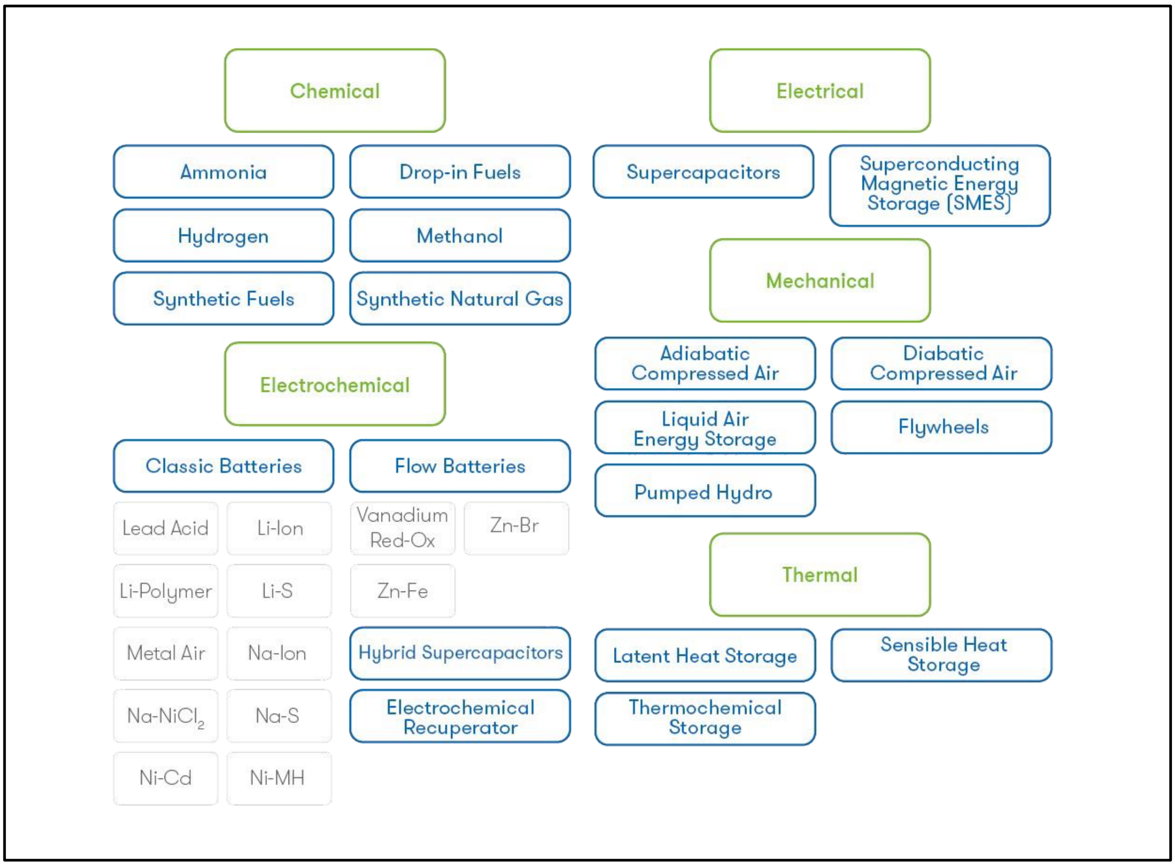


Figure 16. Energy storage techniques (EASE, 2022).

There are plenty of applications for the usage of energy storage, Figure 17 illustrates several examples. This list of applications is expected to grow in the upcoming few years due to the continuous research and development in the energy storage field. The main source for most of the data presented in this chapter will be the European Association for Storage of Energy reports (EASE, 2022).

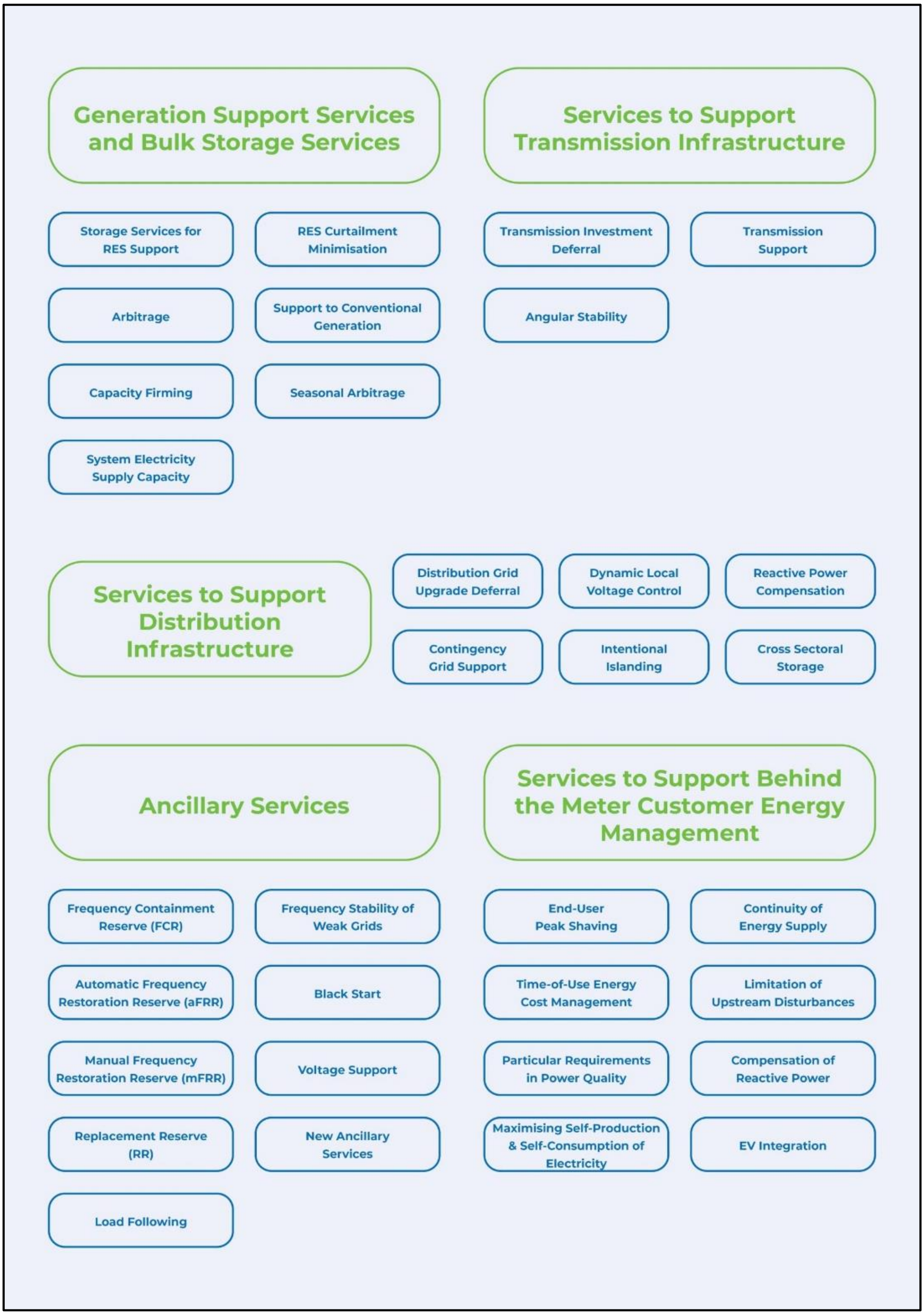


Figure 17. Energy storage applications (EASE, 2022).

3.1 Lithium-ion battery

The lithium-ion battery is considered one of the most commonly used batteries in the market nowadays due to several advantages such as high-power density, high energy density, long lifetime, and environmental friendliness (Lu et al., 2013). EASE, (2022) stated that Li-ion batteries have existed since the 1990s, and a few years later they controlled almost 50% of the mobile phones market. Schipper & Aurbach, (2016) discussed the full history of Li-ion batteries from the 70's up to date, moreover, the future technologies and promising applications are provided.

Even though, Li-ion batteries still facing some challenges such as large scale making, aging, fast charging, and extension of their calendar life, it is expected shortly these issues to be solved due to the continuous research, development, and investment that have been occurring and induced by energy storage and automotive market. Tomaszewska et al., (2019) presented a full review of fast charging issues for Li-ion batteries with an evaluation of new fast-charging techniques. Lu et al., (2013) discussed in their review, the key issues for Li-ion batteries in EV and Battery Management systems (BMS). Also, Barré et al., (2013) presented a review of the Li-ion battery aging mechanism and provided an estimation of battery life for EV applications. Moreover, Bandhauer et al., (2011) made a critical review of thermal issues associated with the operation of Li-ion batteries.

Since 2010, Li-ion batteries have been implemented in stationary applications significantly, total installed capacity was about 500 MW all over the world in 2015 with ranges varying from kW to MW. Moreover, it contributed to grid support with voltage up to 1 kV. Recently, Li-ion batteries reached more than 50% recycling efficiency, which is considered one of the main elements of battery chemistry selection due to its low effect on the environment. Zeng et al., (2014) presented a detailed critical review about the recycling of spent Li-ion batteries.

Europe is considered one of the leading continents in the usage of Li-ion batteries across different applications. Table 5 presents the key performance data for Li-ion batteries. As illustrated, the cost per energy and power is mentioned, but it varies a lot between wider limits, in chapter five, a more precise estimated cost will be presented according to real projects and data from different contractors, vendors, and suppliers.

Table 5. Lithium-ion key performance data (EASE, 2022).

Content categories	**Number**
Power Range	1kW up to 50 MW
Energy Range	Up to 10 MWh
Discharge Time	10 Min. Up to 4H
Cycle Life	2000 up to 10000 Cycles
Life Duration	15-20 Years
Reaction Time	Some miles.
Efficiency	90-98 %
Energy (Power) Density	120-180 Wh/kg
Energy Cost	700-1300 €/kWh
Power Cost	150-1000 €/kW

Figure 18 shows the charging principles of the Li-ion battery. Yoshio et al., (2009) presented a full historical development of Li-ion batteries with a brief explanation of different types and components. Electrochemical reactions occur during the charging and discharging process between the cathode (positive electrode), which consists of lithiated metal oxide, and the anode (negative electrode), which consists of carbon materials. There are different components rather than these such as $LiCO_2$, LiNCA, LiNMC, $LiFePO_4$, $LiMn_2O_4$, and LiT0. Porous polymeric materials act as a separation between electrodes, which permit the pass of electrons and ionic flow. These components are immersed in a lithium salts electrode. There are different shapes for cells, different electrode thicknesses, and different sizes. All these parameters depend on the required energy/power ratio for a certain application.

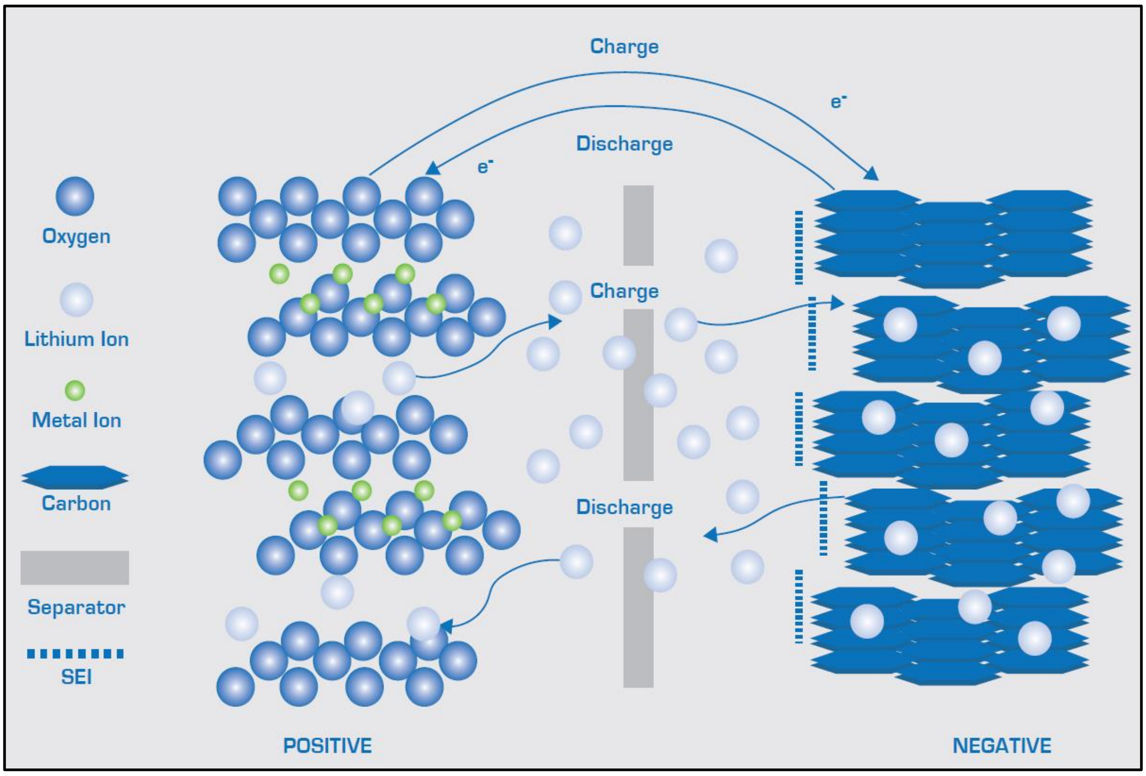


Figure 18. LI-ION battery charging principle (EASE, 2022).

3.2 Lead-acid battery

EASE, (2022) stated that lead-acid batteries have been around for almost a hundred year. It was utilized in almost all applications such as uninterrupted power supply, stationery standby batteries, which require high power at low temperature, and large Battery Energy Storage Systems (BESS), the only exceptions were for mobile and small portable applications devices. Moreover, it can be merged with other highly efficient energy storage systems to reduce the overall cost and maximize efficiency. Lead-acid battery manufacturing technology reached a high level of maturity, which leads to a great reduction in its cost compared to less mature technologies such as Li-ion and NiCd batteries, which are considered recent compared to lead-acid (Zeng et al., 2014). According to Ferg et al., (2019), lead-acid batteries have almost 50 % of the market share for the secondary battery market in 2015.

Table 6 shows the key performance data for lead-acid batteries. As presented, the cycle life is less compared to Li-ion batteries, but on the other hand, the total cost is significantly less than Li-ion, that's one of the major reasons, why it is common for large BESS. Also, it is worth mentioning that the values of energy (power) density per kg, is much less compared to Li-ion, this is a crucial element for battery selection for some applications, where there is limited space for batteries, this is the same situation for a cruise ship, as every square meter of space matter.

Table 6. Lead-acid key performance data (EASE, 2022)

Content categories	**Number**
Power Range	Up to MW
Energy Range	Up to 10 MWh
Discharge Time	Min. Up to 20 h
Cycle Life	500 up to 3000 Cycles
Life Duration	5-15 Years
Reaction Time	Some miles.
Efficiency	75-85 %
Energy (Power) Density	25-35 Wh/kg
Energy Cost	100-200 €/kWh
Power Cost	100-500 €/kW

Figure 19 depicts the charging principles of lead-acid batteries. It's based on an electrochemical reaction between positive and negative electrodes. Where the positive electrode consists of lead dioxide and the negative from spongy lead. Aqueous sulphuric acid acts as an electrolyte, where the electrodes are immersed inside. In a lead-acid battery, electrolyte takes part in the chemical reaction that happens during the charging and discharging process. There are two common subtypes of lead-acid batteries. The first one is flooded type (vented lead-acid, VLA), which requires regular maintenance, the other one is valve-regulated lead-acid (VRLA), which is considered maintenance-free. There are different variations and formations for the electrode's materials, the selection of these materials depends on the required application.

The lead-acid battery has a wide range of formats from 1 Ah up to 16000 Ah. It does not require a complicated management system, that's one of the reasons for having a lower cost per kWh compared to other types. As mentioned earlier, lead-acid battery exists in the markets for almost a century, even though it still has a potential for future upgrade and enhancement, which is motivated by the automotive and energy storage market, due to the emerging need for a low-cost energy storage battery. The current work focuses on increasing cycle life by executing enhancement for the design and reducing the resistance. Moreover, there is ongoing development for advanced lead-acid batteries such as: adding "supercapacitor-like" to improve power efficiency, also the usage of carbon to increase energy density (lead-carbon batteries), and the usage of advanced electrolytes to overcome issues related to acid stratification.

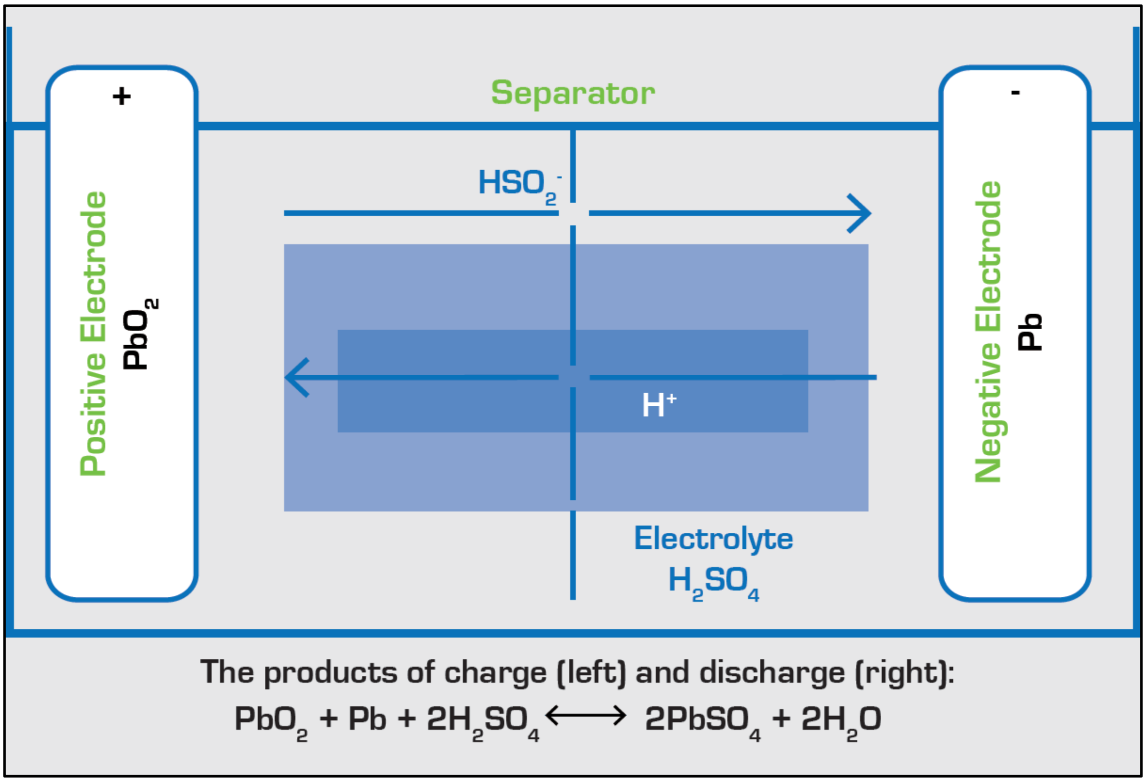


Figure 19. Lead-acid battery charging principle (EASE, 2022).

3.3 Flow battery

The flow battery concept has been presented and developed in the ’70s by Thaller, (1974). Later on, Thaller’s concept was developed by several groups, but the successful usage of flow batteries in large-scale energy storage applications was performed by the University of New South Wales, this prototype showed about 80% energy efficiency and long cycle life (Skyllas-Kazacos et al., 2011). In the meanwhile, NASA in the USA started searching and developing several types of flow types by utilizing different chemistries such as vanadium and iron chrome (EASE, 2022). The earlier developed models suffered from several issues and challenges, but later on, the presentation of vanadium flow batteries overcome these challenges by adopting new techniques and chemistries (Rahman & Skyllas-Kazacos, 2009). According to EASE, (2022) flow battery is considered one of the most flexible batteries, as its capacity can be increased by simply utilizing larger tanks, but on the other hand, that limits the area of its application as it requires special installation. It has been utilized in different applications such as peak shaving, energy time-shifting, and fixed (non-movable) energy storage systems, with different capacities ranging from 200 kW up to 800 kW (EASE, 2022).

Table 7 introduces the key performance data for flow batteries. As given, it has a long lifetime and cycle life compared to Li-ion or lead-acid batteries, but on the other hand energy (power) density is less than lead-acid, and much less than Li-ion. As mentioned earlier, in some applications, every kilogram of weight or square meter of space matters as in cruise ships, however, flow batteries may be a promising solution for the non-movable energy storage system, where the space and weight are not issues. The research and development for flow batteries are currently focusing on improving efficiency and increasing cycle life while reducing cost (EASE, 2022). Shi et al., (2019) presented novel methods for improving membrane efficiency for vanadium redox flow batteries, mentioning the current key challenges and presenting future research directions for improving flow batteries.

Table 7. Flow battery key performance data (EASE, 2022).

Content categories	**Number**
Power Range	kW up to MW
Energy Range	From 100 kWh up to MWh
Discharge Time	Some h
Cycle Life	More than 12000 Cycles
Life Duration	10-20 Years
Reaction Time	Some miles.
Efficiency	70-75 %
Energy (Power) Density	10-25 Wh/liter
Energy Cost	100-400 €/kWh
Power Cost	500-1300 €/kW

Figure 20 illustrates the charging principles of the flow battery. As shown, two liquid electrolytes act as energy carriers, one with a positive charge and the other with a negative charge. An ion-selective membrane is used as a separator between the two electrolytes. The selected ion can pass through the membrane during the discharging and charging process to complete the chemical reaction. Energy density is determined by electrolyte amount and size of the tank, while power density is determined by hydraulic pump control management and membrane-active surface. Its capacity can be increased simply by utilizing larger electrolytes tanks. There are two categories of flow batteries, true redox, and hybrid redox. All chemicals in true redox are dissolved in the solution at all times. But, for hybrid redox, at least one chemical is plated as a solid during the chemical process.

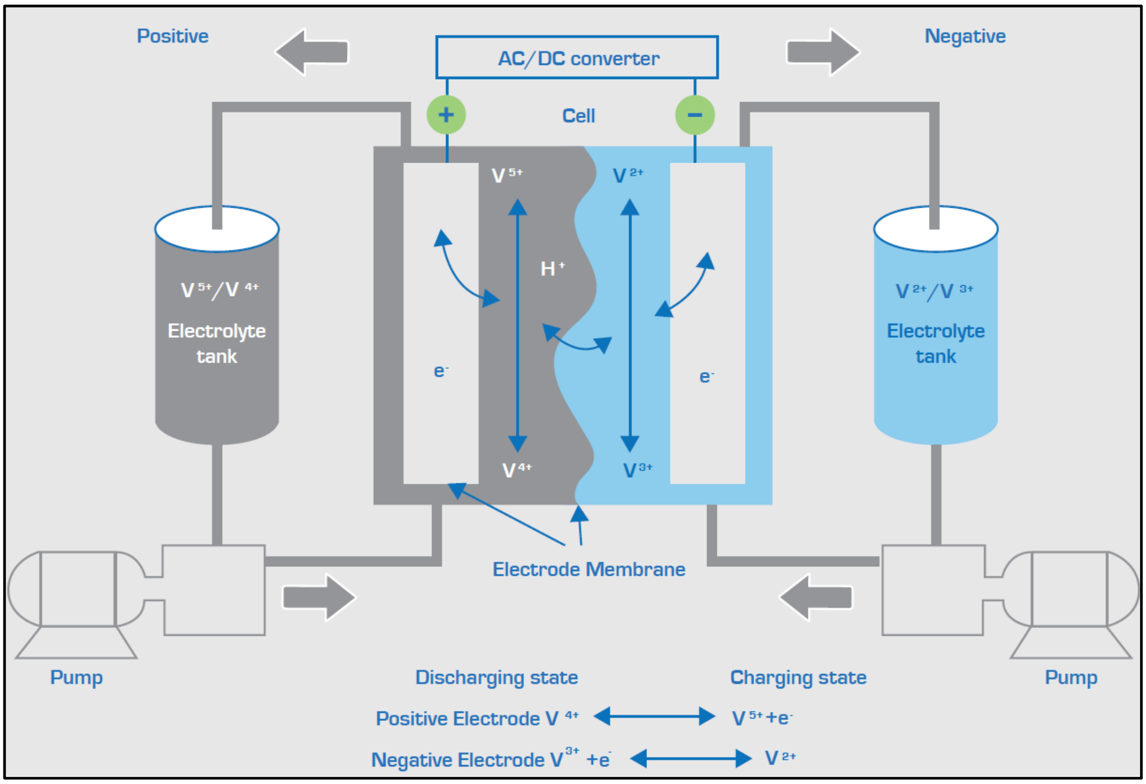


Figure 20. Flow battery charging principle (EASE, 2022).

3.4 Sodium sulfur battery

Sodium sulfur battery was presented in the ’60s due to its large volumetric energy density and is supposed to be used in EV (Sudworth & Tilley, 1986). Later on, during the ’90s, the sodium-sulfur battery was manufactured in Japan and utilized for peak shaving, currently, most of the installed batteries are in the USA and Japan (EASE, 2022). Sodium sulfur battery requires a high operating temperature, up to 300° C, also sodium polysulfides have a high corrosive nature, that’s why it’s currently suitable only for large scales (non-mobile) applications such as peak shaving, time-shifting, and stabilization of wind and solar farms (EASE, 2022). Sodium as a raw material is highly available compared to lithium, its content in the earth is 28,400 mg/kg and 1000 mg/L compared to 20 mg/kg and 0.18 mg/L for lithium, that’s one major reason why its cost is less compared to Li-ion battery, these reasons made sodium batteries the most studied type by scientists worldwide (Kumar et al., 2017).

As stated earlier, a normal sodium-sulfur battery requires a high operating temperature to work properly, that's increases safety concerns and limits its usage in many applications, and if the temperature goes down, it provides poor cycling performance and discharge properties. So, to overcome that challenge, the researchers currently focusing on developing a new sodium-sulfur battery that can operate normally and safely at room temperature without prior heating. Wang et al., (2017) provided an extensive literature review about the current research and development to introduce a sodium-sulfur battery capable of working at room temperature, to widen the area of applications of sodium batteries. Also, Xin et al., (2014) presented a new design for a high-energy sodium-sulfur battery that can work at room temperature. In addition to that, Xu et al., (2018) introduced a new sodium-sulfur battery model that can provide high capacity and stable cycling performance at normal room temperature.

Table 8 presents the key performance data for sodium-sulfur batteries. Sodium-sulfur batteries are commonly used in large applications ranging from 1.2 MW up to 400 MWh, as noticed, its energy (power) density is more than Li-ion batteries, in addition to that, the total energy cost is less compared to Li-ion batteries, that's one reason why it's presented as an alternative to Li-ion for large application related to the grid, but on other hand, the overall efficiency is less compared to Li-ion, due to the energy consumed to maintain the battery hot at 300° C.

Table 8. Sodium sulfur key performance data (EASE, 2022).

Content categories	**Number**
Power Range	200 kW up to 50 MW
Energy Range	From 1.2 MW up to 400 MWh
Discharge Time	6h at nominal power
Cycle Life	Minimum 4500 Cycles
Life Duration	10-20 Years
Reaction Time	Some miles (If hot).
Efficiency	70-80 %
Energy (Power) Density	206 Wh/kg
Energy Cost	300-450 €/kWh
Power Cost	2000-3000 €/kW

Figure 21 depicts the charging principles of sodium-sulfur batteries. As presented, the electrochemical reactions occur between molten sulfur, which acts as a positive electrode (cathode), and molten sodium, which acts as a negative electrode (anode). Sodium beta alumina acts as a separator between the cathode and anode, which permits only the pass of sodium ions. To keep the electrodes in a molten state, the temperature of the battery shall be maintained between 300° C and 360 C.

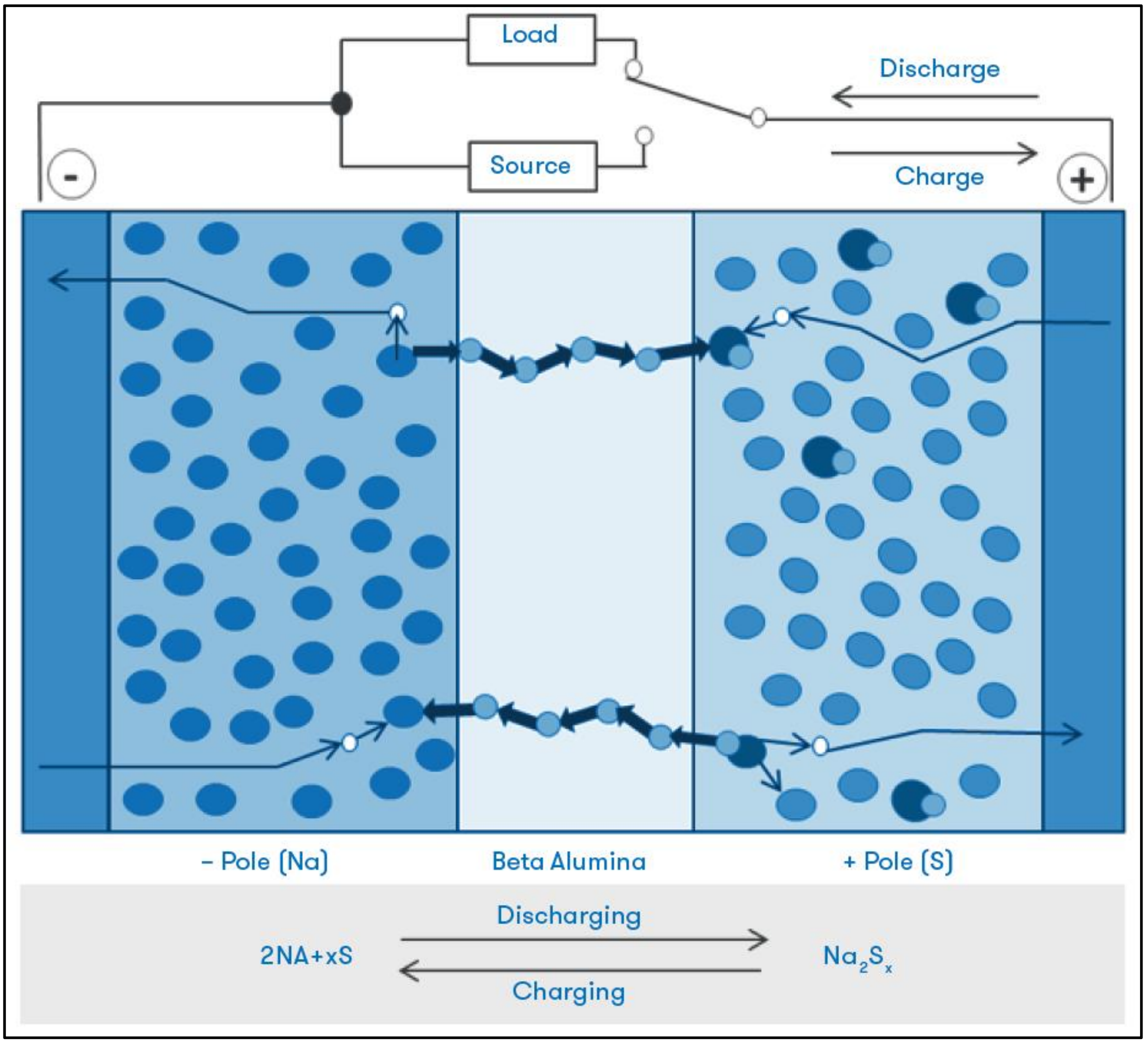


Figure 21. Sodium sulfur battery charging principle (EASE, 2022).

3.5 Electrochemical double-layer capacitor

As mentioned earlier, to maximize the benefits of utilizing energy storage, two energy storage technologies can be combined and work in parallel. The first system will be electrochemical-based energy storage to provide high energy density, the other will be based on capacitance such as Electrochemical Double Layer Capacitor (EDLC) to provide high power density. In this section, EDLC characteristics and key performance data will be presented in brief. Sharma & Bhatti, (2010) discussed different types of EDLC and construction, also a brief historical background is introduced in their review, in addition to several applications of EDLC are presented such as its usage in EV. EDLC is a very promising energy storage system with annual growth is 20% and its market value reached $2.18 billion in 2020 (Chang & Hu, 2019).

EASE, (2022) stated that EDLC has been available since the 1980s, in the beginning, it has been used in small applications as a backup source in electronic devices. Later on, during the 1990s, it has been used in large industrial applications. Currently, millions of EDLCs have been utilized in different environments including harsh ones like wind turbine pitch control. The Japanese dominated the EDLC market in its early days, but due to the increased need for high power density energy storages system, other Asian and European countries were encouraged to invest in developing and manufacturing EDLC, and the targeted overall cost is to reach 0.01 €/Farad.

EASE, (2022) presented several advantages of EDLC such as its long-life cycle, more than half million charge/recharge cycle, high power density, and high reliability, it is used in the car industry in many applications such as: start/stop systems, providing power boost for smooth engine starting, and due to its recuperating capability, it can regenerate energy back from braking. Also, it is utilized in Uninterruptable Power Supply (UPS) to cover peak power demand and as a backup source for short power failure. In addition to that, it is used to boost power and smoothing of voltage during sag occurrence in renewable energy plants. EDLC is considered a maintenance-free device, that’s why it’s used as a reliable backup source for safety electronics. Overall, due to the above-mentioned merits of EDLC, it can be utilized in parallel with another electrochemical energy storage system, the usage of this combination will maximize the benefits of the system in cruise ship applications, both can work efficiently with the conventional power generation plant to maximize the system efficiency and reliability. Jiya et al., (2018) introduced a review about the electrical modeling of EDLC and its usage in energy storage and power electronics applications.

Table 9 introduces the key performance data for EDLC. As presented, it can provide a high-power range, on the other hand, it’s limited for some kWh energy range, the main target here is to support the high-power density requirement, high energy density will be the function of the electrochemical energy storage. EDLC has a remarkable advantages such as long cycle life compared to other energy storage technologies, maintenance-free capability, fast response time, and high efficiency. EDLC power’s cost is not cheap, it is similar to Li-ion battery power’s cost.

Table 9. EDLC key performance data (EASE, 2022).

Content categories	**Number**
Power Range	Up to some MW
Energy Range	Some kWh
Discharge Time	Some sec. – Some Min.
Cycle Life	Up to 1,000,000 Cycles
Life Duration	10 Years
Reaction Time	5 milii Sec.
Efficiency	90 %
Energy (Power) Density	4 to 7 Wh/kg (5 to 8 kW/kg)
Energy Cost	10,000 to 20,000 €/kWh
Power Cost	100-500 €/kW

Figure 22 illustrates the basic design of EDLC. It is an energy storage system based on the electrostatic phenomena - in contrast to the battery - between two electrodes made of carbon with high specific areas per volume. A separator is used to separate between electrodes, both carbon electrodes are immersed in an electrolyte.

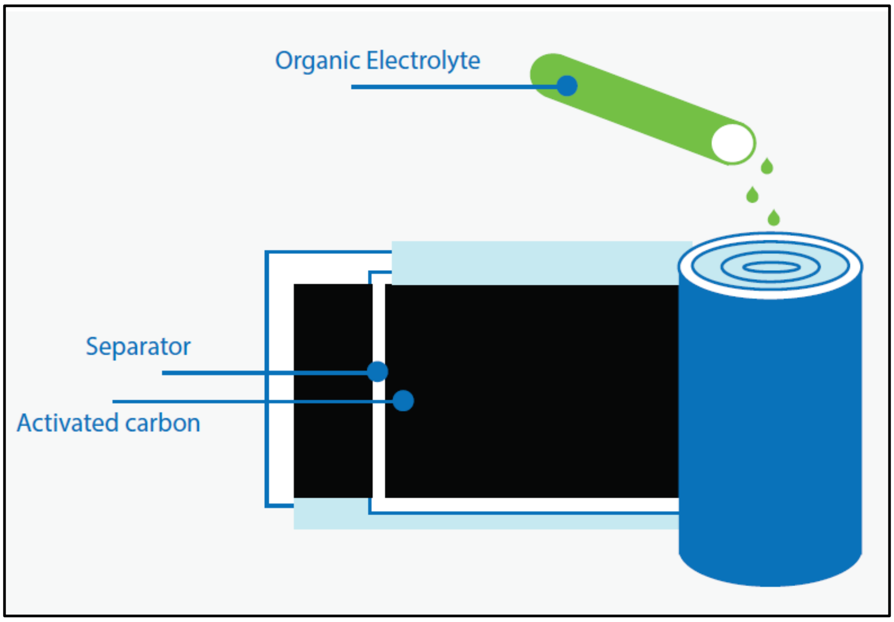


Figure 22. EDLC basic design (EASE, 2022).

Figure 23 shows EDLC charging principles, Helmholtz layers are formed due to the caption's accumulation between one side of electrolyte and solid negative electrodes, and another side of electrolyte with solid positive electrodes. EDLC is capable to work in a wide range of operating temperature ranging from -40° C up to 70 ° C, that wide range widens the application area for EDLC and increase its efficiency as no prior cooling or heating is required to operate functionally. The research and development of EDLC are continued to enhance its performance, Lin et al., (2017) presented a review about the recent development of EDLC by providing new techniques and electrolytes to double the capacitance. Chang & Hu, (2019) introduced a novel design of EDLC based on graphene electrodes, which are expected to achieve a commercial level mass due to its ultra-high capacitance without affecting volumetric capacitance.

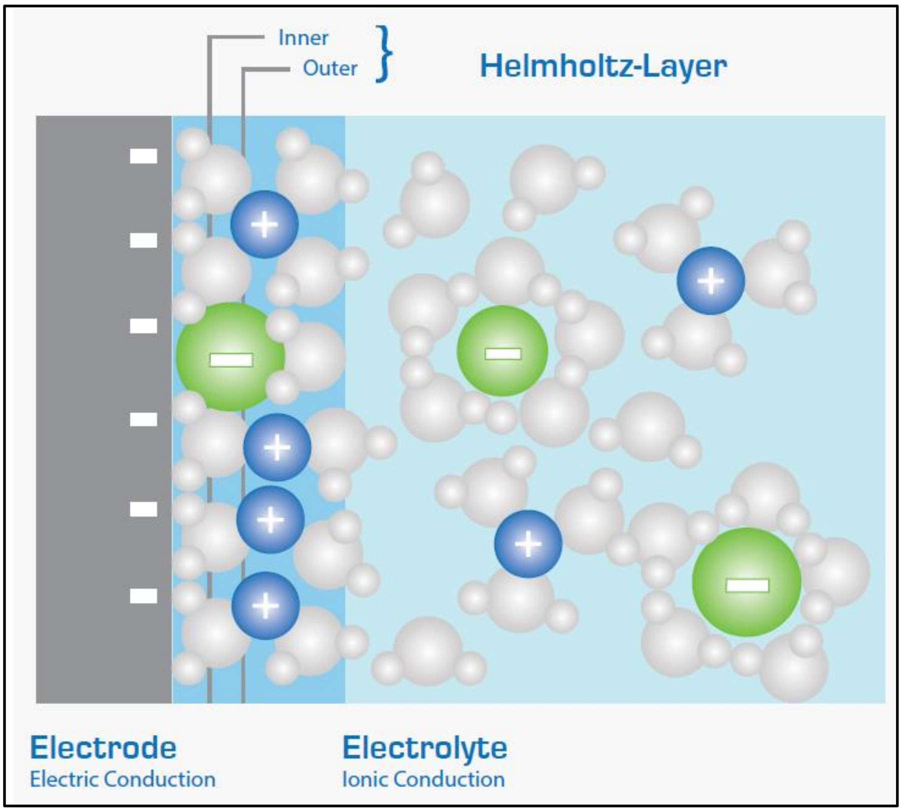


Figure 23. EDLC charging principles (EASE, 2022).

3.6 Conclusion

In this chapter, the most commercially feasible energy storage technologies have been presented showing the main characteristics and the operating mechanisms of each technology. Table 10 provides a summary and comparison between all aforementioned energy storage systems in this chapter.

Table 10. Comparison between different energy storage systems (EASE, 2022).

Content categories	**Li-ion**	**Lead-acid**	**Flow Battery**	**Sodium-Sulfur**	**EDLC**
Power Range	1kW up to 50 MW	Up to MW	kW up to MW	200 kW up to 50 MW	Up to some MW
Energy Range	Up to 10 MWh	Up to 10 MWh	From 100 kWh up to MWh	From 1.2 MW up to 400 MWh	Some kWh
Discharge Time	10 Min. Up to 4H	Min. Up to 20 h	Some h	6h at nominal power	Some sec. – Some Min.
Cycle Life	2000 up to 10000 Cycles	500 up to 3000 Cycles	More than 12000 Cycles	Minimum 4500 Cycles	Up to 1,000,000 Cycles
Life Duration	15-20 Years	5-15 Years	10-20 Years	10-20 Years	10 Years
Reaction Time	Some miles.	Some miles.	Some miles.	Some miles (If hot).	5 milii Sec.
Efficiency	90-98 %	75-85 %	70-75 %	70-80 %	90 %
Energy (Power) Density	120-180 Wh/kg	25-35 Wh/kg	10-25 Wh/liter	206 Wh/kg	4 to 7 Wh/kg (5 to 8 kW/kg)
Energy Cost	700-1300 €/kWh	100-200 €/kWh	100-400 €/kWh	300-450 €/kWh	10,000 to 20,000 €/kWh
Power Cost	150-1000 €/kW	100-500 €/kW	500-1300 €/kW	2000-3000 €/kW	100-500 €/kW

4 Literature review about control interface for energy storage systems

As mentioned earlier, in the case of a cruise ship, the load of the propulsion motors is fractional compared to the total electrical load, so the usage of an electric propulsion system will be more efficient than a mechanical propulsion system. Cruise ship operating profile is very diverse and contains many uncertainties, moreover, its electric propulsion motors have a large dynamic load, that’s why it requires several conditions shall be satisfied such as high reliability and durability to provide a comfortable trip at a safe speed. It can be considered as an islanded microgrid or floating city at sea, it contains a generation plant, transformers, electrical propulsion motors, power electronics devices, data center, general lighting, power..etc. (Frances-Roger et al., 2018). Also, it can be considered as a grid-connected microgrid while being at berth onshore during loading or off time, in that case, the ship can be powered from the grid, which is called ”cold ironing”. (Kanellos et al., 2015).

Chapter two presented the advantages and disadvantages of AC and DC networks utilized with the electrical propulsion systems, in this chapter different control techniques and PMS will be introduced and discussed for both networks, providing methods of integration for electrical motors for propulsion, renewable energy sources, energy storage systems, and general hotel loads with the main network, thus requires a very efficient and sophisticated PMS, to achieve optimum performance, which will result in fuel efficiency and reducing the operation cost and emissions.

4.1 Electrical propulsion control strategies for electrical network

In this section, different control strategies will be presented for controlling electrical networks when utilizing an electrical propulsion system. Figure 7 shows the schematic diagram of electrical propulsion, as illustrated, the major connected components to the AC electrical network are propulsion motors, auxiliary loads, and hotel load (as in cruise ship application). So, the main concerns are to provide a fixed frequency and reliable power supply for the connected loads, and robust control for propulsion motors to provide the required speed and direction precisely.

4.1.1 Electrical network control strategy

Figure 24 depicts the schematic diagram of the AC network control strategy for fixed frequency network, as presented it splits into two major elements, the primary and secondary control. Mahon, (1992) presented several techniques for providing fixed frequency AC networks. Generally, in the case of using multiple generators, governor droop speed control or electric isochronous can be used to share active power loading among running generators, in addition to that Automatic Voltage Regulator (AVR) is used to provide the required reactive power among sharing generators running in parallel to maintain the network voltage.

Those presented strategies act as a primary control level. While the secondary control level will be the function of PMS, its major functions are maintaining frequency and voltage during any uncertainties or dynamic load variation, controlling the generator's status of being on or off depending on the required need to ensure no overloading occurs for the running generators, ensuring that a spinning reserve is available, and it can protect the system during blackout occurrence by isolating the faulted area from the network and reconfigure the network back after fault clearance. According to Karim et al., (2002), all these control strategies utilized with PMS are considered rule-based, however, in some situations where high availability is needed, the operator may have the upper hand to reinitiate the system.

Currently, there are several advanced techniques proposed to improve PMS functions. Amgai & Abdelwahed, (2014) proposed a new approach, which uses power sources and loads sub-models to calculate the power source optimum frequency, however, that principle does not compare against the conventional one yet. Seenumani et al., (2012) proposed another principle based on multi time-scale to track the power with different dynamic responses supplied from two power sources, that principle showed efficient and fast power tracking, however, that proposed principle was simple and several engine constraints have not been applied.

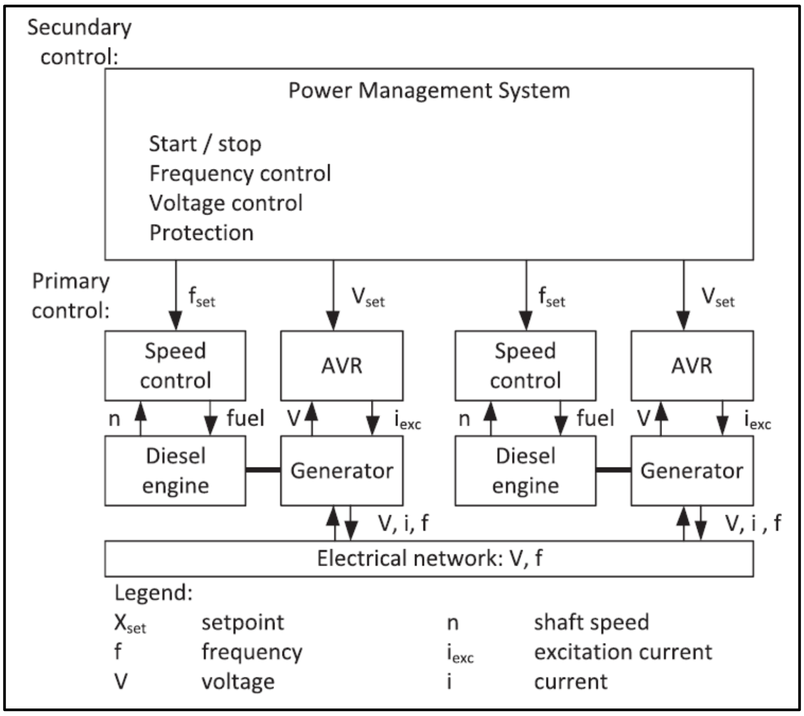


Figure 24. AC network control strategy for fixed frequency network (Geertsma et al., 2017).

Geertsma et al., (2017) stated that diesel engines used with a fixed frequency network always run at rated speed to achieve maximum fuel efficiency even when being partially loaded, Figure 25 presents the diesel engine’s Specific Fuel Consumption (SFC) while connected to the generator at different loading conditions. As shown, the diesel engine consumes more fuel while running on part load compared to full load or under-designed conditions, moreover, its centrifugal forces and wear are larger compared to a fully loaded one. These issues were considered a disadvantage for the usage of fixed frequency networks, so Simmonds, (2015) proposed a new system to utilize a variable frequency rather than a fixed frequency, that system showed good results with almost 5% fuel consumption reduction. However, electrical devices that can work with variable frequency are still limited, moreover, the system power losses increased due to the losses that occurred in the conversion process, so in the future, DC-based electrical network work will be utilized, it will be presented in section three in this chapter.

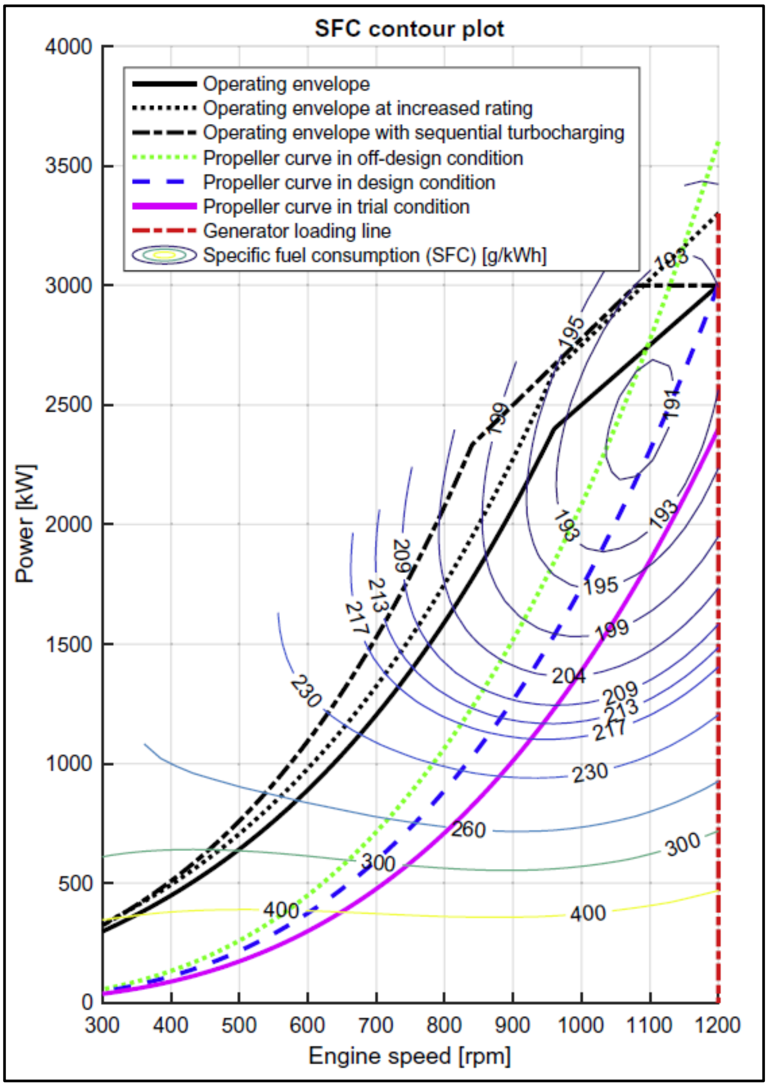


Figure 25. Diesel engine operating profile with operating generator with typical SCF. (Geertsma et al., 2017).

4.1.2 Propulsion system control strategy

The purpose of this system is to control the propulsion motors to provide the required speed precisely. PWM converter is used to control the flux and torque of propulsion motors (Geertsma et al., 2017). Figure 26 illustrates the schematic diagram of the control strategy. Trzynadlowski, (2000) presented several torque control strategies for induction motors such as; direct self-control, field orientation, or direct self-control, the selection of control method depends on the accuracy level required, so by utilizing one of these techniques, the torque control can almost be instantaneous.

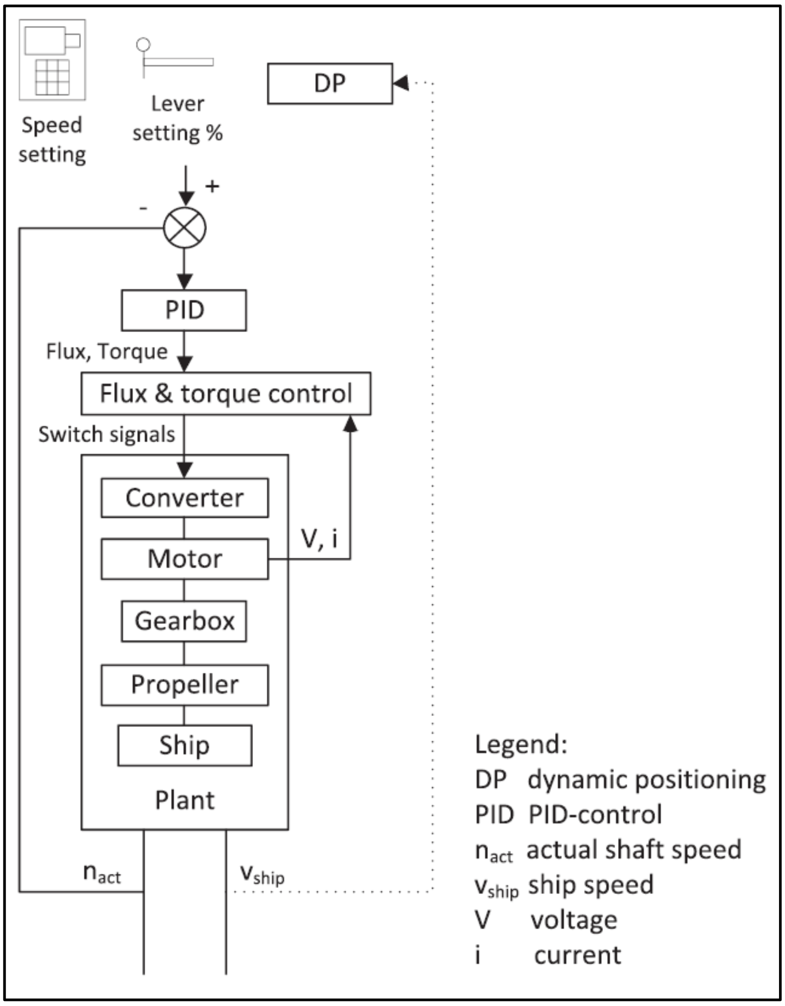


Figure 26. Schematic Diagram for propulsion motor control system. (Geertsma et al., 2017).

4.2 Electrical propulsion control strategies for an electrical network with a hybrid power supply

This section discusses different control strategies for controlling the electrical network when utilizing a hybrid power supply. The schematic diagram for the electrical propulsion with a hybrid power supply is provided in Figure 8. As mentioned earlier, the hybrid power supply may consist of two or more sources, the main source will be conventional sources such as diesel engines or gas turbines, the auxiliary source will be renewable sources such as fuel cells or solar cells, in addition to that, an energy storage system can be utilized such as battery or supercapacitor depends on the application. That system has many similarities with microgrid in the terrestrial grid, so the same control techniques and classification will be adopted and utilized in a ship in case of the usage of a hybrid power supply, few modifications are required due to the nature of ship operation. Guerrero et al., (2011) classified the control strategy for hybrid power supply microgrid into primary, secondary, and tertiary control, all these strategies will be described in brief in the next sections.

The primary control objective is to provide the network with stable frequency and voltage, it is splited into two parts, the first part is grid following, which is utilized when the ship is at berth, the second part is grid forming, which is utilized when the ship at sea (Unamuno & Barrena, 2015). However, it's worth mentioning that generators in the microgrid are connected to the grid via a frequency converter, but for the ship microgrid, it's connected directly to the grid (H. Han et al., 2016). So, droop control will be the best option for providing primary control (Olivares et al., 2014). Guerrero et al., (2011) stated that scalable hierarchical control can be provided by utilizing droop control, which can provide a multizone grid. Multizone grid structure provides a robust, reliable, and high available system against any failure that occurs within the system compared to the conventional structure (Hebner et al., 2016).

The secondary control system function is to correct any deviation that occurs in frequency and voltage, moreover, it provides a balance between supply and demand (Guerrero et al., 2011). Unamuno & Barrena, (2015) classified microgrid secondary systems as centralized and non-centralized. But, due to the ship grid's limited size compared to the microgrid size, the centralized paradigm is usually used, however for some applications such as navy ship, which requires high power continuity, a non-centralized (distributed) paradigm can be utilized (Geertsma et al., 2009). More details about secondary control were presented in section 4.1.

The tertiary control system objective is to control the flow of active and reactive power when the microgrid is connected to the main grid, by changing the settings of the global frequency and voltage of the microgrid (Guerrero et al., 2011). Usually, that control strategy is used while the ship is at berth and connected to the main grid, while one of its generators running at the same time in parallel. Currently, this is not common practice and new measures have been used such as heuristic control, Equivalent Consumption Minimization Strategy (ECMS), power management through operating load estimation, and load leveling, these measures will be described in the next sections.

4.2.1 Heuristic control strategies

Geertsma et al., (2017) stated that the plant operating mode and battery charging and discharging can be determined by using logical rules, when utilizing a heuristic control strategy, for instance, when engines are switched off or in case of the need to work silently or without any emissions, batteries can be utilized to provide the required power, overall, rule-based techniques can provide fuel saving, especially when the operating mode is discrete and distinct. Sciberras & Norman, (2012) provided an example for the usage of a rule-based control strategy by utilizing a battery to supply the power for propulsion at low speed, and assist in supplying power in parallel with the engine at high speed, the total fuel saving is determined by the size of the used battery and overall system weight and cost, however, it’s worth to mention that there is no comparison between that model and the base model without battery.

4.2.2 Equivalent consumption minimization strategy

ECMS uses optimal control problem formulation to calculate optimum power management setpoints by minimizing fuel consumed by the engine and power generated for the battery during charging, power supplies share the loads to minimize the cost (Geertsma et al., 2017). ECMS provided the lowest fuel consumption among other control strategies when applied for hybrid vehicle applications for unknown operating profiles Sciarretta et al., (2014). Figure 27 depicts the schematic diagram for the overall control strategy utilizing Energy Management System (EMS), which is based on ECMS for controlling a hybrid power supply network, this system provided about 10% fuel savings during operational trials (Breijs & Amam, 2016).

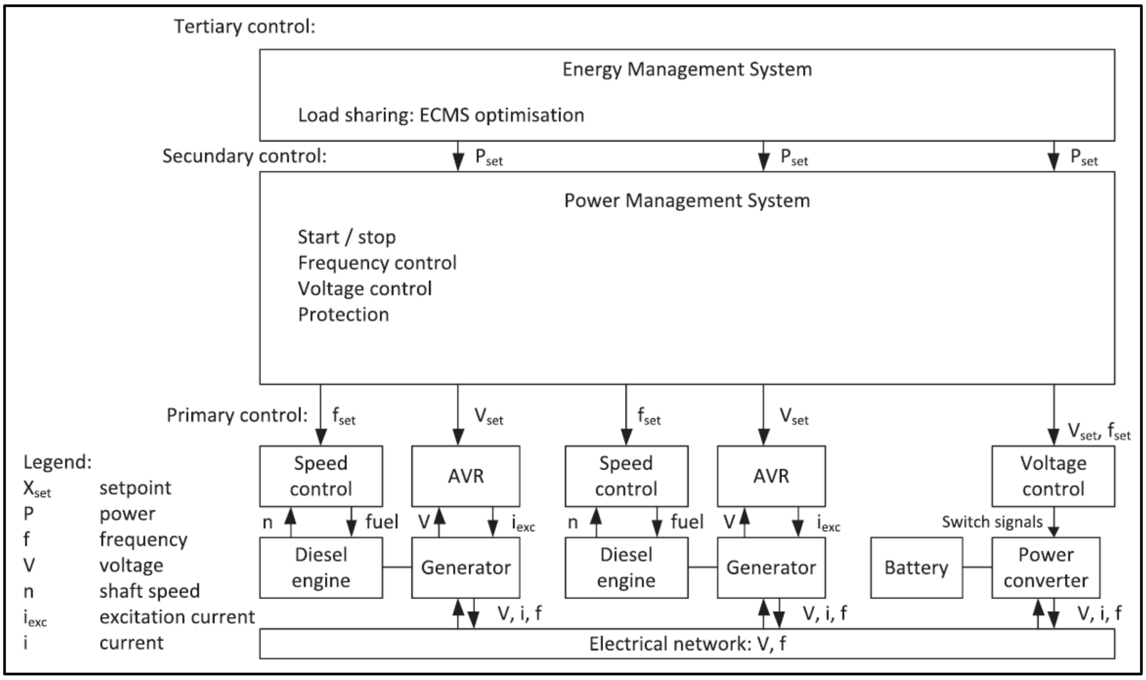


Figure 27. Control strategy for hybrid power supply network (Geertsma et al., 2017).

4.2.3 Power management through operating load estimation

Vu et al., (2015) presented a power management strategy for determining optimal power required based on available future operating profiles, that strategy utilizes non-linear optimization to minimize the combined cost of fuel consumption and battery life, moreover, it can predict the future required power based on historical information, if the future operating profile is not available, also, it's capable of controlling discrete events in case of multiple generators switching on or off, this strategy achieved 9% improvement in the combined cost function capered to the rule-based heuristic control strategy.

4.2.4 Load leveling

Geertsma et al., (2017) cruise ships loading profile is diverse due to load fluctuations and other disturbances, as a result, the engines can’t operate within the optimum operation range, thus increasing fuel consumption and emissions, moreover, these variations increase dynamic loading and engine wear, thus limit engine lifetime and increased maintenance, so by utilizing battery to supply the required power for transient and fluctuations loads, thus enabling the engine to work within the operating limit by providing average power based on historical loading profile, this reduces fuel consumption and engine wear. This strategy showed a very good performance in the case of transient applications like the usage of cranes. Ovrum & Bergh, (2015) presented a model for hybrid ship crane operation with the usage of the lithium-ion battery, which showed almost 30% in fuel consumption.

4.3 Electrical propulsion control strategies for an electrical network with DC power supply

Different electrical-based propulsion systems have been discussed in chapter two mentioning the advantages and disadvantages of each system, as mentioned earlier, a fixed frequency AC network has some drawbacks, especially in the case of cruise ship application, when the loading profile is very diverse and unpredictable, later on, a suggestion for a variable frequency AC network was presented, but it was not feasible to due to the limitation of different equipment able to work with variable frequency and increased power losses, also clients require a fixed frequency AC network.

Currently, due to the continuous upgrade and development of power electronics, the DC network is presented as an alternative option for the AC network to reduce fuel consumption and power losses, however, it’s a complex system due to power converters’ nonlinear properties and semiconductors switching behavior, it requires an effective PMS. The generic schematic diagram for electrical propulsion with a DC hybrid power supply is shown in Figure 9. Zahedi & Norum, (2013) presented in Figure 28, a detailed single line diagram for ship DC network distribution. As depicted, there are major components that need to be connected to the main network, which are diesel engines, clean energy sources like fuel cells or PV (if exist), energy storage like batteries or supercapacitors, hotel (for a cruise ship), and auxiliary loads, and finally propulsion motors. In this section, different control strategies and different converters required for the connection of these components with the main network will be discussed.

Zahedi & Norum, (2013) stated that the majority of generated and supplied power to the electrical network in the ship have been originated from the synchronous generators, which coupled with the diesel engine or gas turbine, generally, three-phase rectifiers are used to supply the generated power to the DC distribution network. In the case of the usage of wound rotor generators type, the generator excitation system will regulate the voltage so, an uncontrolled three-phase diode rectifier can be utilized during normal operation time, but during a fault condition, control functionality can be utilized. While in the case of the usage of permanent magnet synchronous generators, a three-phase controlled bridge converter will be utilized, in that case, the converter will regulate the voltage or control the current according to the system requirement. Another scheme is presented by Bash et al., (2009) when a thyristor-based rectifier is utilized with wound rotor generators that supply power to the DC distribution network.

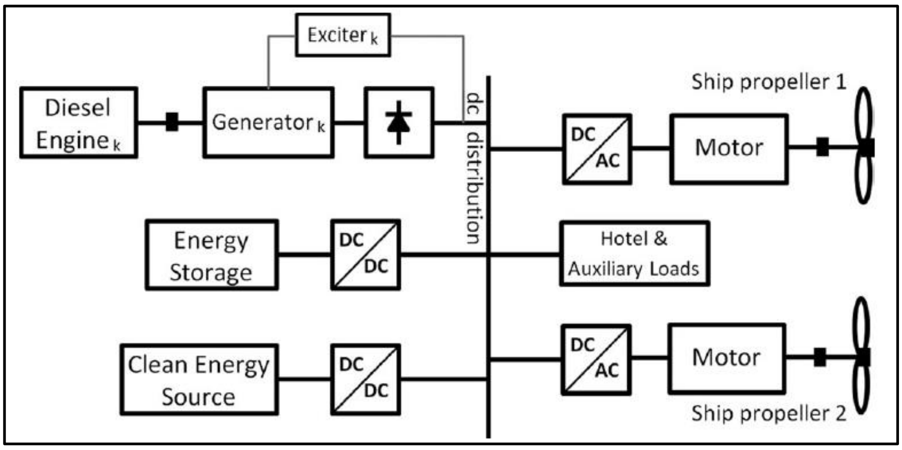


Figure 28. Typical DC distribution network for ships (Zahedi & Norum, 2013).

DC/DC converters are the most common for EMS in hybrid ship power networks, it’s common to connect energy storage to electric power networks with bidirectional converters (Zahedi & Norum, 2013). Also, DC voltage can be shifted by DC/DC converters along with the DC network (Chan et al., 2008). Boost type bidirectional converter is the best option for connecting a low voltage energy storage or auxiliary energy sources such as fuel cells, to a high DC voltage network, for increase the system reliability, it’s better to utilize a lower number of series batteries (Lai & Nelson, 2007). Generally, the majority of generated power will be consumed by the electric motors for propulsion, for controlling and supplying the motors, a three-phase bridge rectifier can be utilized (Hansen et al., 2011). Several control strategies such as prime mover frequency control, load sharing, and optimum load-leveling strategy, will be presented in the next section.

4.3.1 Prime mover frequency control

Geertsma et al., (2017) stated one major advantage of a DC-based distribution power system is that AC voltage is rectified, thus enabling the selection of required frequency for each generator separately from other generators, so the speed governing control loop is not required for providing load sharing among running generators as in AC power system, that advantage enables the possibility for different optimization procedure to the whole system such as; reducing fuel consumption, emissions, noise, or achieving optimal engine loading. Zahedi et al., (2014) presented a controlling scheme for the DC system, and compared with the conventional AC system, the proposed system achieved almost 8% fuel reduction.

4.3.2 Load sharing

Frequency droop control is utilized for achieving load sharing among running generators in an AC system, however, voltage droop control is utilized in a DC system (Zahedi & Norum, 2013). For the DC case, the system has different power sources, the power ripple can be unevenly distributed among them by setting different values for voltage droop control, that’s why in case there is a hybrid power supply, it’s possible to share and control the dynamic among power sources (Geertsma et al., 2017).

4.3.3 Optimum load-leveling strategy

Zahedi et al., (2014) suggested an online optimization control strategy that utilizes a battery to perform two major tasks by applying to charge and discharging, first enable the running generators to operate at the optimum loading level, second, provide the required power for transient or ripple load. By utilizing that strategy for several running generators, the overall efficiency working point will be shifted to a higher efficient point. However, the average required power and power ripple, which depend on future data and operating mode, need to be determined to achieve that strategy. A simulated model utilized that strategy provided almost 7% fuel reduction compared to a conventional control strategy.

4.4 Conclusion

In this chapter several control and EMSs were presented for both AC and DC-based electrical networks, showing the operating principle for each method. Geertsma et al., (2017) provided a summary table for different applied control strategies with different propulsion systems showing the benefits of each system, this summary is provided in Table 11.

Table 11. Control strategies summary (Geertsma et al., 2017).

Control strategy	Applicable architecture	Benefits
Speed control	• Mechanical, electrical and hybrid propulsion	• Minimum speed fluctuation • Prevent over-speed • Robust control strategy • Intuitive relation with ship speed
Torque and power control	• Mechanical, electrical and hybrid	• Reduced fuel consumption • Improved thermal loading
Frequency droop and isochronous control	• AC power supply	• Effective load sharing • Splitting load dynamics
Heuristic control strategies	• AC & DC hybrid power supply	• Different operating modes • Zero-emission mode
ECMS strategy	• AC & DC hybrid power supply	• Reduced fuel consumption and emissions • Optimization of other criteria
Voltage droop load sharing	• DC hybrid power supply	• Splitting load dynamics • Reduced engine loading
Optimum load leveling	• DC hybrid power supply	• Reduced fuel consumption • Engine Loading • Emissions • Noise and vibrations

5 Literature review about economic aspects of energy storage

Recently, the energy storages industry expanded significantly, and the research and development continue due to the increased penetration of different renewable sources, which have intermittency characteristics, the increased usage of EVs, the need for batteries in different grid applications, and the need to reduce environmental effect while improving the fuel consumption efficiency for ship industry by utilizing batteries to enable the optimum performance of ships propulsion systems. As a result, the batteries cost decreased and the efficiency increased thus enabling new opportunities and more usage in new applications.

In this chapter, the economic evaluation for the most common and mature battery electrochemical-based energy storage will be presented and discussed. The focus will be on four types which are Li-ion, Lead-acid, Flow battery, and Sodium-sulfur battery. These four types have been introduced and discussed in brief in chapter three of this thesis. In addition to that, the economic evaluation for utltracpaicotor presented as one of the most mature electrical energy storage will be presented.

Mongird et al., (2020) presented a detailed review of the cost and performance characteristics for different energy storage systems in the united states for executed and ongoing projects, the prices are presented in US dollars for projects in 2018, also 2025’s forecasted prices are presented based on ongoing projects and taking into account the escalation rates and the reduction of different batteries prices due to the maturity of its technologies and expansion in the production and development. Most of the data in this chapter will be based on that review.

To provide a complete economic aspect for the usage of batteries and ultracapacitors, not only the cost information will be presented, but also the performance evaluations for each type will be introduced. So, (Mongird et al., 2020) review focused on cost information and performance evaluation for each type of energy storage. The cost information consists of four major elements, which are, capital cost for the battery packs in \$/kWh, power conversion system (PCS) in \$/kW, the balance of plant (BOP) in \$/kW, construction and commissioning (C&C) in \$/kWh, fixed operation and maintenance (O&M) in \$/kW-yr, and finally variable operation and maintenance (O&M) in cents/kWh-yr. While the performance metrics consist of seven major elements, which are, round-trip efficiency (RTE), annual RTE degradation factor, response time, cycle life, calendar life, manufacturing readiness level (MRL), and finally technology readiness level (TRL).

5.1 Technology cost

As mentioned earlier, the cost of each technology will be broken down into four major elements and will be presented in brief in this section, to provide a full picture of the technology, which are capital costs, PCS costs, BOP, C&C., and Fixed and variable O&M.

5.1.1 Capital cost (\$/kWh)

According to Mongird et al., (2020) review, the total capital cost of battery back is usually presented in dollars per kilowatt-hour (\$/kWh), but in the case of ultracapacitors, it can be presented in either \$/kW or \$/kWh depending on the application, overall, the capital cost of utiltracapictors will be presented in \$/kW in this chapter due to its high-power density. The capital cost for batteries and ultracapacitors means the procurement of the energy storage itself (DC) units only, other costs such as PCS, BOP, or C&C will be presented separately. That’s a matter as in this thesis, the application is intended to be on a cruise ship, which might be different from the regular applications and projects.

5.1.2 Power conversion system (PCS) (\$/kW)

PCS costs represent the costs of the inverter, inverter control, packing, and container. Its common for batteries and ultracapacitors and its effect on them is similar. Several elements affect the system design, such as the voltage-related cost. Mongird et al., (2020) stated that the DC voltages for different types of batteries are increased, and the current values for the same power will be reduced, as a result, the PCS costs are expected to decrease. Li-ion DC voltage is almost 1.6 times that compared to other technologies, so its PCS’s cost is expected to be less by 82 percent. By 2025, It is expected that the nominal DC voltage difference between different technologies will not exist. Moreover, the increase in manufacturing scale, scalability, and the presence of different standardization is expected to reduce PCS costs in the future. For instance, the Li-ion PCS costs are expected to reduce by 25 percent in 2025. Table 12 provides the current nominal DC voltage for different battery technologies obtained from different manufacturers and current projects. Also, the presence of new technology such as Silicon carbide (SiC) - based inverters, which showed a great performance in different applications such as EV, charging infrastructure, PV, power supplies, motor drives, and UPS, will affect reducing the PCS costs in the future (Murray Slovick, 2018). Currently, there are wafer supply limitations, that might affect the prices of PCS, however, this will not be taken into consideration in this thesis.

Table 12. The nominal DC voltage for different battery technologies.

Technology	Nominal DC voltage (V)	Source
Li-ion	1221	(Samsung SDI, 2018)
Lead-acid	756	(May et al., 2018b)
Sodium-sulfur	640	(Kishinevsky et al., 2005)

5.1.3 Balance of plant (BOP) ($/kW)

Kleinberg, M, (2016) stated that the BOP for energy storages systems is measured in ($/kW) and represents the costs of site wiring, interconnecting transformers, and other additional ancillary equipment, it’s mainly associated with electrical wiring and connections. Also, for large systems, which consist of several modules, the interconnections between modules are added to BOP. Mongird et al., (2020) presented several examples of BOP obtained from different projects and references, however, the average BOP for all battery technologies was assumed to be $100/kW. It is worth mentioning that BOP has no major improvements in the future, so, only a 5 percent reduction in BOP is expected in 2025 due to the increase in scale.

5.1.4 Construction and Commissioning (C&C) ($/kWh)

Kleinberg. M, (2016) stated that the C&C costs are related to site design, equipment transportation, procurement, the installation of parts, and the cost of labor, usually called EPC (engineering, procurement, and construction). C&C costs are not related to technology, it's considered a mature cost and not expected to decrease greatly in the future. Mainly, it's calculated based on the system weight and footprint for grid integration applications, with some consideration like a factory or onsite assembly and the architecture of the system (open racks or containerized systems) (Mongird et al., 2020).

In the Mongird et al., (2020) evaluation report, the system footprint, or the weight and volume of the system is used for determining C&C costs. It's worth mentioning that, this is a significant factor in selecting the type of BESS, especially when the space or available volume for the system is limited, like in cruise ship applications, where every square meter of space or additional kilogram of weight matter. Table 13 presents the estimated capacity in Wh per volume in a liter of different battery technologies from different suppliers and vendors collected by Mongird et al., (2020), as noticed, Li-ion Wh/L is significant compared to other technologies. Table 14 introduces the average C&C costs for each technology taking into account a 5% reduction in cost in 2025, as indicated, the C&C cost of Li-ion is considered the less among other technology. The aforementioned factors are considered to be very important for the selection of BESS, especially in limited space applications.

Table 13. The estimated volume weight for different battery technologies.

Technology	**Wh/L**	**Source**
Li-ion	90:130	(RESEARCH INTERFACES, 2018)
Lead-acid	22.5	(ITP Renewables, 2022)
Redox flow	12.5	(UET, 2022)
Sodium-sulfur	40	(Gotschall & Eguchi, 2009)

Table 14. C&C costs in 2018 and 2025, for different battery technologies (Mongird et al., 2020).

Technology	C&C Cost in 2018 ($/kWh)	C&C Cost in 2025 ($/kWh)
Li-ion	101	96
Lead-acid	176	167
Redox flow	190	180
Sodium-sulfur	133	127

5.1.5 Fixed Operations and Maintenance (O&M) ($/kW-yr.)

Mongird et al., 2020, presents the fixed O&M costs as the necessary cost required to keep the system functional and operational throughout its economic life and do not change based on energy usage. It ranged between $6–14/kW-yr, for Li-ion batteries fixed O&M costs may be higher than other technologies due to safety concerns and costs related to its BMS. For larger size BESS, fixed O&M costs are expected to increase, due to increased costs related to safety. Mongird et al., 2020, assumed a fixed O&M cost of $10/kW-yr. for different battery technologies in his evaluation report and this will be the case in this thesis.

5.1.6 Variable Operations and Maintenance (O&M) (cents/kWh-yr.)

Mongird et al., 2020, stated that variable O&M costs are the necessary costs for the operation of BESS through its economic life and are normalized based on the annual discharge energy and expressed in cents/kWh. Mongird et al., 2020, assumed a variable O&M cost of 0.3 cents/kWh-yr for different battery technologies.

5.2 performance metrics

Technology costs are presented and broken down in the previous section, however, to provide a full evaluation of BESS, it’s essential to provide a full picture of its performance besides its costs. So, in this section, the performance metrics will be presented and it consists of seven major elements, which are round-trip efficiency (RTE), annual RTE degradation factor, response time, cycle life, calendar life, manufacturing readiness level (MRL), and finally technology readiness level (TRL).

5.2.1 Round-trip efficiency (RTE)

According to the US Department of Energy, (2010), RTE is the net discharged energy (without the auxiliary load) to the net charged energy to the battery (with the auxiliary load). Mongird et al., (2020) stated several categories of losses for BESS such as loss of AH capacity, which can be significant for the whole battery life, but can be neglected for each cycle, other losses occur due to internal resistance which is responsible for increasing charge voltage while reducing discharge voltage, finally losses due to the connected auxiliary loads like HVAC (heating, ventilation, and air-conditioning), BMS, PCS control and pumps load in case of a flow battery. RTE value for each technology is not available, but 0.96 RTE for PCS is used to obtain the overall RTE for each technology (Newbery, 2016)

5.2.2 Response Time (Ramp rate)

Mongird et al., (2020) stated that the response time is the time required for the system to change its output power from the rest to the rated value, it’s usually in seconds or minutes. Lower response times or faster ramp rates are required. Usually, it’s determined and affected by the selected inverter, PCS limitations, and overall system design. It is assumed to range from 1-to 13 seconds based on an extensive literature review made in Mongrid ‘s evaluation report.

5.2.3 Cycle Life

The battery cycle life is a function related to its depth of discharge (DoD), it’s for conventional batteries and not applicable for redox batteries. (Mongird et al., 2020).

5.2.4 Calendar Life

Calendar life for the battery is the maximum life without being operated, it’s highly dependent on the operating condition, for batteries and ultracapacitors, it decreases with temperature increase. In the case of the system being operated, the system life will depend on degradation occurring per cycle. (Mongird et al., 2020).

5.2.5 Manufacturing Readiness Level (MRL)

MRL is a method for measuring the level of maturity for each product or technology, it usually ranged from 1 to 10, while 1 is the basic manufacturing level, and 10 is the highest and most matured level with efficient production practices. (US Department of Defense, 2022).

5.2.6 Technology Readiness Level (TRL)

TRL is a method for measuring the development phase of each technology. It represents the maturity of each technology and usually ranged from 1 to 9. Whole 1 is the basic principle and 9 means that the system is used in project operations successfully. (U.S. Department of Energy, 2009).

5.3 Assumptions

Mongird et al., (2020), evaluation report made several assumptions for energy, power, and energy to power (E/P) ratios for each technology as introduced in Table 15. The battery cost will be in \$/kWh and ultra-capacitor costs will be in both \$/kW and \$/kWh.

Table 15. Energy, power, and E/P for each technology (Mongird et al., 2020).

Technology	MW	MWh	E/P
BESS	1	4	4
Ultra-Capacitor	1	0.0125	0.0125

5.3.1 Forecast Methodology

Mongird et al., (2020) presented cost estimates predictions for 2025 by utilizing performance improvements forecasts, which enable the extraction of more energy per unit, and scale of economics. Batteries' power density is expected to increase as the performance will be enhanced, which enables few stacks to provide the same power, thus will decrease the overall cost. Moreover, for larger and more extensive energy applications, which utilize redox flow battery systems, a larger DoD or state of charge (SoC) expected value for the same power density will be estimated, and as a result, the unit cost will drop.

According to Michael Kleinberg, (2016), Li-ion batteries prices are expected to decrease by 67%, Sodium-Sulfur by 9 %, redox flow by 18 %, and vanadium redox by 18 %. However, in Mongird et al., (2020) evaluation report, an assumption is made that Li-ion batteries prices will decrease by only 31 % instead of 67 %, as the economic scale is expected to be balanced due to the increasing demand for lithium, cobalt, and nickel, moreover, the reduction for vanadium redox battery will be assumed to be 29 % percent rather than 18 %, as it's expected that the demand will increase, hence the membrane and electrodes prices are expected to decrease, that will reduce the overall price.

Also, currently, the development of sodium-sulfur battery systems is mainly in Japan, in addition to that, more safety concerns are presented, so a 24 % reduction in prices is expected rather than 9 %, as this technology is expected to increase globally, thus will drop the prices. A 15 % cost reduction is expected for lead-acid batteries as it's considered a mature technology compared to other systems, and used extensively in automobiles applications, especially for starting lighting ignition and gains usage in the energy storage space. Table 16 summarizes the expected cost reduction per each technology, which will be applied in this thesis.

Table 16. Battery technology expected cost reduction (2018 to 2025) (Mongird et al., 2020).

Technology	Cost reduction (2018 to 2025)
Li-ion	31 %
Lead-acid	15 %
Redox flow	29 %
Sodium-sulfur	24 %

5.3.2 Degradation-Related RTE Reduction Methodology

Kindermann et al., (2017) stated that battery degradation occurs due to the loss of Ah capacity, which occurs due to the increase of the resistance of battery cells. This is an important element for calculating the annual degradation of RTE. Mongird et al., (2020) assume that RTE depends on the average charge and discharge voltage. There are several methods for calculating the battery's RTE degradation, Table 17 presents the annual RTE loss, the ratio of final to initial RTE, and the calendar life for each battery depending on its chemistry type, The calendar life estimation will be described in more detail in each technology-specific finding.

The loss of active material cause battery degradation and as a result change transfer resistance increase, for instance, the Li-ion battery's loss of capacity occurs due to the loss of lithium and as a result, the internal resistance builds up. Overall, the battery's end of life occurs when it reaches 80% of its total Ah capacity. Generally, the resistance may change by 1.3:2x depending on the mode of degradation and chemistry of the battery. Mongird et al., (2020) evaluation report assumes that each battery's internal resistance will increase by 50% at the end of its useful life. Ultracapacitors' voltage decreases linearly with discharge time due to voltage drop associated with internal resistance (Mongird et al., 2020). Asher et al., (2010) provided an estimation method for calculating the ultracapacitor RTE, that method is similar to RTE estimation for batteries. Tecate, (2018) stated that 75 % of ultracapacitor energy content can be with demand when it's cycled between maximum and half maximum voltage

Table 17. RTE and calendar life for each battery technology (Mongird et al., 2020).

Technology	Final RTE/Initial RTE	Annual RTE Loss	Calendar Life (Years)
Li-ion	0.959	0.50 %	10
Lead-acid	0.898	5.40 %	3
Redox flow	0.847	0.40 %	15
Sodium-sulfur	0.956	0.34 %	13.5
Ultracapacitor	0.979	0.14 %	16

5.4 Technology-Specific Findings

In this section, several specific findings for each technology will be presented and discussed in briefs such as capital cost, fixed and variable O&M costs and performance metrics, cycles, lifespan, efficiency, and technology and manufacturing readiness levels (TRL & MRL).

5.4.1 Lithium-Ion Batteries Specific Findings

Li-ion battery operation and key performance data were presented in brief in chapter three. However, in this section, the focus will be on specific findings related to the technology itself and its usage in real applications. Mongird et al., (2020) collected those findings from manufacturers, suppliers, vendors, and contractors from ongoing current projects.

5.4.1.1 Capital costs

Li-ion battery primary components have a module, which assembles cells, including electrolytes, electrodes, and separators, a multitude of modules represent the battery system as well as BMS and PCS (Mongird et al., 2020). According to EASE, (2022), an 80 % reduction in Li-ion battery prices occurred between 2011 and 2017 reaching around $200/kWh and is predicted to reach $96/kWh within the next eight years.

In Mongird et al., (2020) evaluation report, the average collected prices for executed projects utilizing Li-ion battery was ranging from $300:700/kWh for grid-scale battery energy storage systems, the variation of prices was affected by several factors such as project scale and the selection of the used chemical like lithium-ion NMC, li-phosphate (LFP), or lithium-titrate (LTO). Generally, that price includes grid integration, PCS, tax, equipment, fees, and General & Administrative (G&A). While the average collected prices for battery packs used in EV was ranging between $200:300/kWh, it was less than the grid-scale storage costs by 10 % on average. For the assumed 4-hour case in this thesis and as on Mongird et al., (2020) evaluation report, the estimated DC battery cost was 60 % of the total installed cost.

It is worth mentioning that most of the available costs for executing projects provide the total cost and are not broken down to the costs of each component, in addition to that, the economic scale of each project represents a major factor in determining the average price, as the size of project increase, the overall average cost will decrease. Overall, the used estimated price in this thesis for a Li-ion battery was $469/kWh including PCS, BOP, and C&C costs.

5.4.1.2 Fixed and Variable O&M Costs and Performance Metrics

According to the collected data by Mongird et al., (2020), the average costs for fixed O&M for Li-ion batteries ranged between $6–$14/kW-yr, and variable O&M costs were approximately $0.0003/kWh. The typical usable life of Li-ion batteries is approximately 10 years, and to remain operational, major maintenance is required every 5 to 8 years (Balducci et al., 2017). The average estimated cost for major maintenance ranged between $150–$400/kW (Lahiri, 2017). Overall, the used estimated price in this thesis for a Li-ion battery fixed O&M and variable O&M cost will be assumed to be $10/kW-yr and $0.0003/kWh, respectively for all battery technologies. It is predicted that the fixed O&M costs will decrease to $8/kW-yr by 2025 (Mongird et al., 2020).

5.4.1.3 Cycles, Lifespan, and Efficiency

The lithium-ion battery is considered one of the most mature battery storage technologies, however, the improvement and development continue to increase the calendar life, the number of operational cycles, and energy density. According to the collected data by Mongird et al., (2020), the average life span ranged from 10 to 20 years, but this requires performing major maintenance and replacement of batteries to keep the system operational during its life. The number of cycles ranged from 400 to 5475 cycles, however, Mongird et al., (2020), summarize that the estimated life cycle will be 3500 at 80% DoD. Moreover, an assumption of 10 years life span was estimated with 86% RTE for the system. Overall, PCS RTE will be assumed to be 96% for all battery technologies.

5.4.1.4 Technology and Manufacturing Readiness Levels

As mentioned earlier, Li-ion batteries have been commercialized in the early 1990s in different sizes and different applications. The technology has been through many tests and deployed in different environments with different scales, so both TRL and MRL reached a higher scale. So, the Li-ion battery has a TRL of 8 and MRL of 9, those numbers are expected to reach 9 and 10, respectively (Mongird et al., 2020).

5.4.2 Lead-acid Batteries Specific Findings

Lead-acid battery operation and key performance data were presented in brief in chapter three. However, in this section, the focus will be on specific findings related to the technology itself and its usage in real applications. Mongird et al., (2020) collected those findings from manufacturers, suppliers, vendors, and contractors from ongoing current projects.

Lead-acid batteries are very common across a wide variety of applications such as large and non-portable systems. As mentioned earlier, there are two main types of lead-acid batteries, VLA (flooded) and VRLA. Geoff James, (2014) stated that lead-acid battery has several advantages such as a high cycle life in partial SoC cycling at various rates, high cumulative energy, faster charging due to good charge acceptance, and finally uniform cell to cell behavior. The lead-acid battery offers a low cost with efficient performance and is expected to spread over the coming few years by performing upgrades (EASE, 2022).

According to the collected data from lead-acid battery manufacturers by Mongird et al., (2020), Lead-acid batteries showed cost-effectiveness for load following and time-shifting applications, and on the other hand, they showed poor performance for frequency regulation applications due to highly volatile signals characteristics. Moreover, the recycling rate of the lead-acid battery reaches almost 99%, which represents a huge advantage and incentive compared to other technologies.

5.4.2.1 Capital costs

The positive electrode of the lead-acid battery consists of a grid plate and the negative electrode consists of a copper or lead grid. A large battery system can be formed by interconnecting battery cells. It requires a PCS system similar to the Li-ion battery, as its one of the most important components for the operation of the battery system. According to the presented data collected by (Aquino et al., 2017b), the average capital cost ranged between \$200–\$500/kWh, however, in Mongird et al., (2020) evaluation report \$260/kWh assumption was estimated for the capital cost.

5.4.2.2 Fixed and Variable O&M Costs and Performance Metrics

As mentioned earlier, one major advantage of the lead-acid (VRLA) type, is the lack of maintenance requirements. However, Aquino et al., (2017a), provided an estimated cost for fixed O&M to be \$7–\$15/kW-yr and variable O&M to be \$0.0003/kWh, but the system was accompanied by an asymmetric supercapacitor. So, as mentioned earlier, in Li-ion batteries, fixed and variable O&M will be assumed to be the same for all technologies.

5.4.2.3 Cycles, Lifespan, and Efficiency

As presented earlier in chapter three, a lead-acid battery has a shorter lifetime compared to a Li-ion battery (EASE, 2022). Due to that reason, it was utilized in special applications such as capacity or resource adequacy (Aquino, Zuelch, et al., 2017a). According to the collected data by Mongird et al., (2020), lead-acid batteries’ average cycle life ranged between 600 to 1250 at 80% DoD. Also, its lifetime was assumed to be 2.6 years and 75% DC-DC RTE. So, due to its lower initial capital cost, compared to other technologies, its full life cycle is comparable to Li-ion.

5.4.2.4 Technology and Manufacturing Readiness Levels

As mentioned earlier, lead-acid batteries are considered one of the most mature available electrochemical battery technologies, however, there are several upgrades and improvements to increase its energy density and increase its lifetime to enhance its performance, but on the other hand, this will be on the cost of less mature systems. It has a low cycle and calendar life, especially at high DoD, is less productive, and lower energy density compared to Li-ion batteries. Overall, Mongird et al., (2020), provided levels 8 and 9 for TRL and MRL, respectively, similar to the Li-ion battery.

5.4.3 Flow Batteries Specific Findings (Redox Type)

Flow battery operation and key performance data were presented in brief in chapter three. However, in this section, the focus will be on specific findings related to the technology itself and its usage in real applications. Mongird et al., (2020) collected those findings from manufacturers, suppliers, vendors, and contractors from ongoing current projects.

Redox flow battery technology is very different compared to other presented technologies, as presented earlier, it consists of two tanks of electrolyte solutions one acts as an anode and the other as a cathode. Storing and generating energy are done by passing the electrolyte across a membrane. Flow battery technology is still in its early phases of commercialization compared to other mature battery technologies such as lead-acid or Li-ion, however, its early models offer several competitive advantages, especially easy salability, low operation temperature range, and long-life cycles (Mongird et al., 2020).

5.4.3.1 Capital costs

Flow battery consists of electrolyte solutions, membrane, and hydraulic pump, these components represent the capital cost. By composing different design variants and stacking them together a battery system with larger capacities can be formed. According to several data collected by Mongird et al., (2020), the average cost was ranging between $542–$952/kWh for a vanadium redox flow battery system. However, the final estimated cost was found to be $555/kWh in 2018 and is expected to reach $393/kWh by 2025, with an almost 30 % reduction expected due to the expected maturity level of the technology.

5.4.3.2 Fixed and Variable O&M Costs and Performance Metrics

Vanadium redox flow battery system fixed O&M and variable O&M cost was estimated to be $7–$16/kW-yr and $0.0003/kWh, respectively by Aquino, Roling, et al., (2017a). So, as mentioned earlier, in previous battery technology, fixed and variable O&M will be assumed to be the same for all technologies as the information for O&M costs is lacking. Moreover, newly emerged battery technology has a growing pain, as a result, O&M costs are high as other technologies.

5.4.3.3 Cycles, Lifespan, and Efficiency

As mentioned earlier, a redox flow battery has a special construction compared to other technologies, thus limiting its sensitivity to ambient temperature, moreover, the main transfer reactions occur in the solution, non-degradable electrolyte if used properly, the electrodes just provide a path for electron transport, that’s why the stress happened to electrodes during cycling on other technologies is avoided (Mongird et al., 2020). All these mentioned merits of redox flow battery technology have a great effect on increasing its lifetime and have a typically longer life span compared to other electrochemical battery technologies.

Aquino, Roling, et al., (2017a) provided an estimated life of redox flow battery to be up to 15 years and RTE to be ranged between 65:78 %. May et al., (2018a) provided an estimated life cycle for Vanadium redox flow batteries to be up to 10,000 cycles. But, Aquino, Roling, et al., (2017a) provided an estimated life cycle for Vanadium redox flow batteries to be up to 5,000 cycles, less conservative compared to May's estimations. Overall, in the Mongird et al., (2020), evaluation report, an assumption of Vanadium redox flow batteries to be 10,000 cycles at 80% DoD, with a calendar life of up to 15 years. The system RTS is assumed to be 67.5 % and 70 % in 2018 and 2025, respectively.

5.4.3.4 Technology and Manufacturing Readiness Levels

Although the development of redox flow batteries started in the 1970s, the only recent important innovations made it more popular. Also, due to its long cycle life and flexible characteristics, it has gained high prominence. Overall, Mongird et al., (2020), provided levels 7 and 8 for TRL and MRL, respectively, according to the state of commercialization.

5.4.4 Sodium-sulfur Specific Findings

Sodium-sulfur battery operation and key performance data were presented in brief in chapter three. However, in this section, the focus will be on specific findings related to the technology itself and its usage in real applications. Mongird et al., (2020) collected those findings from manufacturers, suppliers, vendors, and contractors from ongoing current projects.

Sodium-sulfur batteries were introduced by a Japanese vendor called NGK Insulators, and the total installed capacity of this technology is 450 MW worldwide and considered one of the mature electrochemical energy storage systems with high energy densities

(Aquino, Zuelch, et al., 2017a). The currently available models of sodium-sulfur one battery consist of twenty 50 kW and 100 kWh modules, thus allowing for reaching several megawatts, the largest installation for wind stabilization was 34 MW/245 MWh in Japan (NGK INSULATORS, 2022). As mentioned earlier, a sodium-sulfur battery requires a high operating temperature between 300 °C and 350 °C to stay in the molten state, this high operating temperature requires more safety precautions, thus limiting the usage of this technology in movable or mobile applications (EASE, 2022).

5.4.4.1 Capital costs

The basic components of a sodium-sulfur battery system are a large combination of modules, PCS, and a control system. According to several data collected by Mongird et al., (2020), the average cost was ranging between \$500–\$1000/kWh just for the battery cost, and the average cost of PCS was ranging between \$580/kW and \$870/kW. Overall, the final estimated cost was found to be \$661/kWh in 2018 and is expected to reach \$465/kWh by 2025, assuming an almost 30 % reduction expected due to the expected maturity level of the technology., and the average price for PCS to be in the range of \$230–\$470/kW.

5.4.4.2 Fixed and Variable O&M Costs and Performance Metrics

According to Mongird et al., (2020), there are not enough resources for providing the estimate of O&M costs for sodium-sulfur batteries, however, Aquino, T, et al., (2017a), provided an estimate of fixed O&M costs to be \$7–15/kW-year, without providing an estimate for the variable O&M costs.

5.4.4.3 Cycles, Lifespan, and Efficiency

Sodium-sulfur battery system lifespan is estimated to be up to 15 years, more than Li-ion and less than redox flow battery (Aquino T, et al., 2017). The cycle life was estimated to be ranging between 4000 to 4500 cycles according to EASE, (2022). However, Mongird et al., (2020), estimated the cycle life to be 4000 cycles at 80 % DoD. Mongird et al., (2020), provided several findings for RTE ranging between 77 and 85 %, but the final used assumption was 75% for AC-AC.

5.4.4.4 Technology and Manufacturing Readiness Levels

Sodium-sulfur battery has been around since the ’90s and has been utilized in almost 450 MW projects, in different applications such as wind farm stabilization, peak shaving, and other applications (EASE, 2022). As a result, due to the multiple years of research and development, Mongird et al., (2020), provided levels 8 and 9 for TRL and MRL, respectively, in 2018, and are expected to reach 9 and 10, respectively, in 2025.

5.4.5 Ultra-capacitors Specific Findings

Ultra-capacitors operation and key performance data were presented in brief in chapter three. However, in this section, the focus will be on specific findings related to the technology itself and its usage in real applications. Mongird et al., (2020) collected those findings from manufacturers, suppliers, vendors, and contractors from ongoing current projects. Typically, ultra-capacitors have extremely fast ramp rates and are used with battery systems to provide high power density and absorb pulse power. The usage of a hybrid system of ultra-capacitor and battery can be utilized in several applications such as time-shifting of energy, peak shaving, photovoltaic smoothing, and load-following (Maxwell, 2022).

5.4.5.1 Capital costs

Similar to Li-ion batteries, ultra-capacitors can be consisting of multiple cells and modules and can be scaled up to achieve the desired range of the project. Ultra-capacitor is used to achieve high power density and it is not competitive on a $/kWh basis like a battery system, but on a $/kW basis, it will be competitive. According to several data collected by Mongird et al., (2020), the average cost was ranging between $160–$401/kW and $32,365/kWh to $32,565/kWh, depending on the size of the system, however, the used estimated average capital cost at E/P ratio of 0.0124 will be $401/kW or

$32,500/kWh, assuming that the maximum power density is 360 W/kg, and maximum energy of 4.5 Wh/kg, for 45-s storage.

5.4.5.2 Fixed and Variable O&M Costs and Performance Metrics

One major advantage of ultra-capacitor is less need for maintenance compared to other energy storage systems to stay operational during their usable life, so O&M costs can be considered negligible or very small (Mongird et al., 2020). So, Mongird et al., (2020), assumed a nominal $1/kW-yr fixed O&M, and $0.0003/kWh variable O&M similar to other battery system technologies.

5.4.5.3 Cycles, Lifespan, and Efficiency

Capacitors have a long-life span ranging from 20 to 40 years, which is only exceeded by some pumped hydro storage plants, and that's considered an attractive quality compared to other energy storage technologies (Naoi et al., 2013). Three different types of capacitors have been presented and compared by Atmaja & Amin, (2015), showing their capability of reaching a 40 years life span and 95 RTE or higher. According to ultra-capacitors supplier Maxwell, (2022), their product is capable to reach almost 1,000,000 cycles. Overall, on Mongird et al., (2020) evaluation report, the capacitor's life span was estimated to be 16 years with 1,000,000 cycles and 945 RTE.

5.4.5.4 Technology and Manufacturing Readiness Levels

As mentioned earlier, capacitors have been utilized in several projects and reached a good mature level compared to other energy storage technology, and showed a longer life span, that's why Mongird et al., (2020) assumed an 8 and 9 TRL and MRL, respectively in 2018, with the expectation that no change will occur in 2025.

5.5 Specific finding summary in 2018 and 2025

In this section, a summary table will be presented showing all collected data for each energy storage technology. Table 18 presents each technology capital cost – energy capacity ($/kWh), PCS ($/kW), BoP ($/kW), C&C ($/kWh), O&M Fixed ($/kW-yr) and an estimation for the project cost in ($/kW) and ($/kWh) in 2018 and (2025), the assumed project data is provided in section three of this chapter. While, Table 19 illustrates each technology's technical data such as RTE, annual RTE (degradation factor), response time, and No. of cycles at 80% DOD, life-span, MRL, and TRL.

Table 18. Energy storage capital costs summary (Mongird et al., 2020).

Energy Storage Technology	**Lithium-Ion**	**Lead Acid**	**Redox Flow**	**Sodium - Sulfur**	**Ultraca-pacitor**
Year	**2018 2025**	**2018 2025**	**2018 2025**	**2018 2025**	**2018 2025**
Capital cost ($/kWh)	271 (189)	260 (220)	555 (393)	661 (465)	400
PCS ($/kW)	288 (211)	350 (211)	350 (211)	350 (211)	350 (255)
BoP ($/kW)	100 (95)	100 (95)	100 (95)	100 (95)	100 (95)
C&C ($/kWh)	101 (96)	176 (167)	190 (180)	133 (127)	80
O&M Fixed ($/kW-yr)	10 (8)	10 (8)	10 (8)	10 (8)	1
Total Project Cost ($/kW)	1876 (1446)	2194 (1854)	3430 (2598)	3626 (2674)	930 (835)
Total Project Cost ($/kWh)	469 (362)	549 (464)	858 (650)	907 (669)	74,480 (66,640)

Table 19. Energy storage technical data (Mongird et al., 2020)

Energy Storage Technology	**Lithium-Ion**	**Lead Acid**	**Redox Flow**	**Sodium - Sulfur**	**Ultraca-pacitor**
Year	**2018 2025**	**2018 2025**	**2018 2025**	**2018 2025**	**2018 2025**
System RTE	0.86	0.72	0.675 (0.7)	0.75	0.95
Annual RTE	0.50%	5.40%	0.40%	0.34 %	0.14%
Response time	1 s	1 s	1 s	1 s	0.016 s
No. of Cycles	3500	900	10,000	4000	1 Milion
Life-span	10	2.6 (3)	15	13.5	16
MRL	9 (10)	9 (10)	8 (9)	9 (10)	9
TRL	8 (9)	8 (9)	7 (8)	8 (9)	8

5.6 Conclusions

In this chapter several energy storage technologies have been presented. Four types of electrochemical-based energy storage such as Li-ion, lead-acid, redox-floe, and sodium-sulfur, have been presented to provide an example of a high energy density source, and one electrical-based energy storage, ultra-capacitors has been presented as an example of high-power density source. Each technology-specific finding has been presented in brief. All these data-based preliminary on Mongird et al., (2020), evaluation report, which was collected from several suppliers, vendors, and academic papers. An assumption of a 4-hour battery energy storage system is provided to calculate the associated cost of the project.

Overall, by comparing all findings, Li-ion showed a very good performance in terms of costs, life-span, and practicality compared to other electrochemical technologies, which can be utilized in cruise ship application in a hybrid system in conjunction with ultra-capacitors, to provide both high energy and power density requirements for loads. The lead-acid battery showed a mature performance but has fewer capabilities compared to Li-ion batteries. Redox flow battery showed a good performance and scalability, but it is expected to not be practical in movable applications like cruise ships. Also, sodium-sulfur batteries showed a good performance, but it’s not recommended in movable applications like cruise ships due to safety concerns related to high-temperature operation requirements.

6 In-depth review for load leveling losses and case study

In this chapter three main topics will be presented, first, an overview about the effect of load leveling and how to mitigate its associated losses by utilizing batteries in distribution power system. Second, the effect of load changes to shipping power system and the usage of BESS as a potential solution. Finally, a techno-economic case study will be presented and discussed showing the benefits behind utilizing the batteries to reduce the operation of auxiliary diesel engines during low loading conditions.

6.1 Overview of the effect and losses that occur due to load leveling in the power system

In this section, the effect of load-leveling on the power distribution system will be discussed in brief for the normal distribution grid, while showing the advantage of the usage of batteries as an energy storage system (ESS) to reduce losses and increase the system efficiency and its lifetime.

Ibrahim, (2000) stated that most of the losses in the power system occur at the distribution level due to several technical and non-technical reasons, the losses associated with technical reasons occur due to the passage of active and reactive energy through the distribution level, while non-technical losses occur due to error in metering or energy theft, which is not the focus in cruise ship application. The losses of power not only have an economic effect, but those losses produce extra heat, which increases the temperature of the system components, thus might lead to the failure or break down or at least reduce its lifetime and reliability (Kashem et al., 2000). However, several techniques and measures can be utilized to minimize those losses, such as demand-side management, optimal planning and design of the distribution system, and automating the distribution configuration (Ibrahim, 2000). Besides those techniques, the load-leveling technique is considered one of the most effective methods to shave the peak load and fill the load valley, since the losses are a function of the square of the current or the load, so by reducing the peak load, the losses will be reduced, moreover, the system resistance will decrease due to the decrease of the distribution system components temperature, thus have direct relation to reduce the cost and increase the power system components life-time (Malinowski & Kaderly, 2004).

As mentioned earlier, due to the continued progress and development in power electronics and ESS and reaching a sufficient level of maturity, it can provide a promising solution for slaving the load-leveling issues and reducing the system losses (Oudalov et al., 2007). So, Saboori & Abdi, (2013) presented a case study, where an ESS was utilized to shave the peak loading by discharging and fill the load valley by charging, to reduce the losses in the distribution system. Figure 29 shows the single line diagram for the studied system, Saboori & Abdi, (2013) applied an ESS on the MV and LV sides of a 1600 kVA transformer, which has a total yearly demand of 8.5878 GWh.

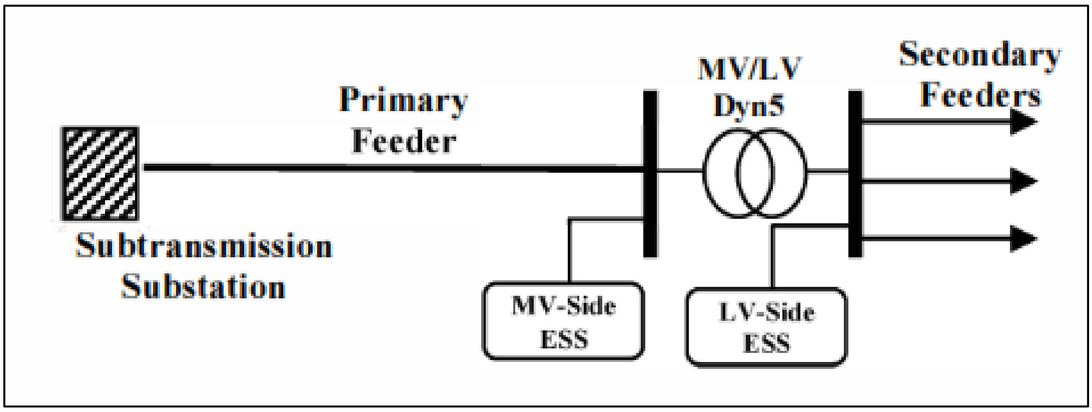


Figure 29. The studied network single line diagram (Saboori & Abdi, 2013).

Table 20 presents the total yearly losses of the system in MWH and in percent before and after applying ESS on the MV and LV sides of the transformer. Table 21 indicates the MWh yearly saved energy and percent of that losses after applying the ESS on MV and LV sides, as noticed its more beneficial to install the ESS in LV if reducing the system losses is the main concern. While Table 22 gives the total ESS required to be installed on MV or LV sides in kW. The usage of ESS not only helps to reduce the system losses but is capable of reducing the network capacity as indicated in Table 23.

Table 20. yearly losses in MWh and percent (Saboori & Abdi, 2013).

			Line	**Transformer**	**Line & Transformer**
Before ESS		**MWH**	346.58	144.41	**490.99**
		Percent	4.0357	1.6815	5.7172
After ESS	**MV-Side ESS**	**MWH**	335.98	144.41	**480.39**
		Percent	3.9122	1.6815	5.5937
	LV-Side ESS	**MWH**	335.98	139.99	**475.97**
		Percent	3.9122	1.6301	5.5423

Table 21. Yearly saved energy in MWh (Saboori & Abdi, 2013).

	Line	**Transformer**	**Line & Transformer**
MV-Side ESS	10.6	0	10.6
LV-Side ESS	10.6	4.4	15.02

Table 22. The required ESS is to be installed for both sides in kW (Saboori & Abdi, 2013).

Charge			**Discharge**		
Min	Average	Max	Min	Average	Max
0	77.5	387.74	0	77.4984	272.10

Table 23. Expected release for network capacity (Saboori & Abdi, 2013).

	Min	**Average**	**Max**
Net (kVA)	195.622	284.837	384.724
Percent	12.226	17.802	24.04

So, the aforementioned study was presented to indicate the importance of the usage of EES to reduce the transformer losses and the overall system losses by shaving the peak by discharging or filling the valley by charging for the loading curve. The same concept can be applied to the cruise ship power system, as its loading curve is highly dynamic with many associated uncertainties, in the next section, the operating conditions and minimum requirement for the power system operation will be presented in brief, later on in this chapter, a case study will be presented showing the economic aspects and benefits for the usage of batteries to support with the fluctuation occur in the loading profile.

6.2 Load changes affect the ship power system and the usage of ESS as a potential solution

In this section, the effect on the ship power system due to severe load transient and various operating conditions will be discussed. As known, the large and sudden variations in power demand cause fluctuations in voltage and frequency of ship power system. Radan et al., (2008) stated several solutions to reduce the power load fluctuations on the ship by utilizing power redistribution control, however, there are not enough studies studying the effect of load fluctuations for a hybrid propulsion-based power system. In a hybrid propulsion-based power system, the presence of different mechanical and electrical components including ESS represents a complicated system to be controlled, however, with the utilization of an effective control system, ESS will have the potential to reduce the effect of load variations to a large extent (Hou et al., 2014).

As presented earlier, the ship's operating environment is highly dynamic and can change very quickly while affected by several elements such as wind, wave, and current in harsh sea environment, for instance, variations can reach up to 40% of the nominal power in less than 10 seconds, moreover, the frequency can change up to 70% in 5 seconds, which is not acceptable for the operation of sensitive loads (Tetra Tech. Inc., 2007). That sudden or transient change of load is affected by the time required for engines to start up for the propeller and the ship, usually, it ranges between 60 to 500 seconds for the ship and between 1 to 60 seconds for the propeller, usually electric machines' dynamic time constant varies between 1 ms to 1 second, which might affect their ability to cope with the sudden change in loading during transient conditions (Shagar et al., 2017). As shown in Figure 30, how the frequency profile acts during load addition or removal, as noticed, there is an overshooting occurs after the control measures have been applied to reduce these fluctuations.

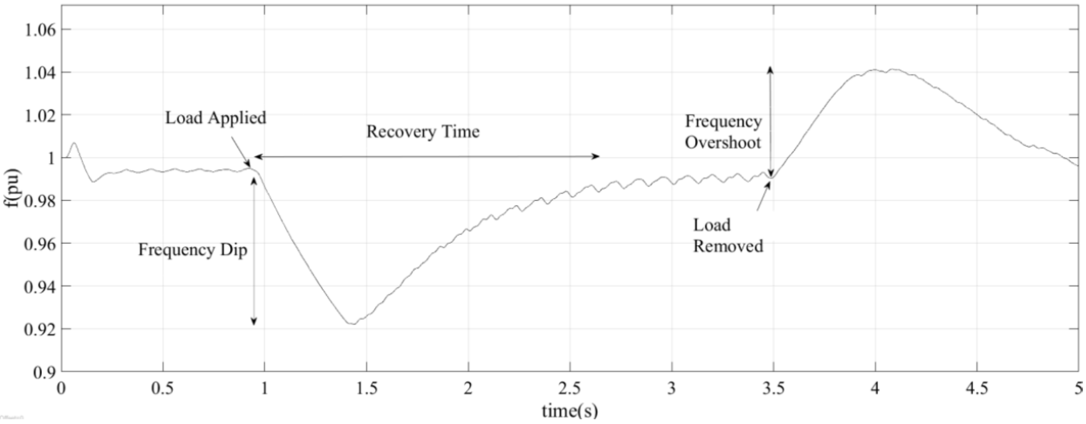


Figure 30. Frequency profile during load fluctuations (Shagar et al., 2017).

The occurrence of long and short frequency and voltage deviation due to load changes have severe and negative effects such as energy losses, equipment malfunction, and overheating, which will reduce the equipment's lifetime (Bent Ørndrup Nielsen, 2009). So, to regulate and overcome this issue, IEC-defined specific limits shall be followed for the variations of voltage and frequency during the normal and transient states as presented in Table 24 (Tetra Tech. Inc., 2007).

Table 24. Voltage and frequency limits for AC power supply (Tetra Tech. Inc., 2007).

Quantity of Operation	Permanent Variation	Temporary Variation
Frequency	(+/-) 5%	(+/-) 10% (5 s)
Voltage	+6% to -10%	(+/-) 20% (1.5 s)

That fluctuations can be reduced by the utilization of ESS, which can supply active and reactive power simultaneously in a controlled manner, moreover, due to the additional capacity in ESS, it can provide an additional capacity to reduce the generation sources reserve margins (Shagar et al., 2017). Hou et al., (2014) utilized effectively Li-ion battery and supercapacitor as an ESS to mitigate the fluctuations in electric ship power system due to load demands variation. The presence of ESS not only helps mitigate the fluctuations that occur due to the load variations but it can be considered as an emergency power supply, which is recommended practice by IEEE for shipboard electrical installation (IEEE, 2017).

6.3 Case study for the utilization of batteries to mitigate the load fluctuations in a cruise ship

In this section, a fully detailed study made by Ritari et al., (2020) about the utilization of batteries for mitigating load fluctuations occurs due to variation of thruster loads, which are supplied by the auxiliary engines focusing on both technical and economic aspects. As presented earlier in chapter five, energy storage density and efficiency increased and its cost continued to decrease due to the continued development in the industry associated with EV expansion, so, as a result, it becomes more feasible to be utilized in the hybrid power systems in ships.

Generally, the total output of the ship's diesel engines shall meet the demanded load all the time, and as discussed earlier, during some operation conditions with low demand, the diesel engines run at low speed, thus increasing fuel consumption and emissions, moreover, the number of operating hours for the engines increased, thus can be translated to less lifetime and higher cost of maintenance. So, by utilizing batteries as an ESS, peak or valley loading profile can be mitigated and the number of operating hours for the engines can be reduced while reducing fuel consumption and emissions, however, this requires complicated control techniques to determine the most optimum time for the discharging and charging of the batteries to mitigate that fluctuation on the loading profile.

According to Ritari et al., (2020), the batteries can be utilized in five different mechanisms to increase fuel efficiency and reduce harmful emissions which are: shifting the operating point to the peak efficiency for the diesel engines. In case of the absence of shore connection, batteries can supply electricity, thus eliminating the emissions while being at berth. Sub-optimally operated diesel engines can act as an emergency or reserve power supply. Providing the required power for thruster motors during their demand peaks instead of running additional diesel engines. Finally, the number of installed engines in new build ships can be minimized. Ritari et al., (2020) stated that “Substituting a sub-optimally operated generator set as a reserve power source” is the most common and feasible for the ships that operate in coastal or archipelagos and visit ports frequently, normally, those ships utilize an auxiliary diesel engine at low loads to guarantee the power availability in case of rapid up or peak demand is needed for thruster electric motors.

So, what is the auxiliary engine?! Generally, it’s a diesel engine used to supply the required power for the auxiliary system and thrust motors, it can be two or more synchronized engines and connected to the ship power grid, in parallel operation, the engine loads can be divided equally to ensure that any change of speed of engines to be the same during any transient events (Ritari et al., 2020). It was found that the most of time, the loading of auxiliary engines for cruise ships is less than 50% (Baldi et al., 2018). So, as discussed earlier, the diesel engine’s highest efficiency occurs at 85% of its loading capacity, and that efficiency is reduced dramatically at 50% or less loading. Based on MAN, (2018) report, the diesel engine fuel consumption at 25% loading is 14.4% higher compared to 85% loading, so it is crucial to run the diesel engines close enough to their peak efficiency point. So, there is a good opportunity to utilize ESS to enable the auxiliary diesel engines to operate in the high-efficiency loading area, moreover, the transformer losses will decrease by reducing the peak loading events that occurred by thrust motors.

6.3.1 Data acquisition and case ship

Ritari et al., (2020) used data for the RoPax ship, which has a 48-hour cycle in the Baltic Sea and has a deadweight of 3779 tons with 203 meters long, and was built in 1990. Figure 31 shows its operating path and Figure 32 indicates its average speed during its operating cycle.

Figure 31. RoPax ship operating path (Ritari et al., 2020).

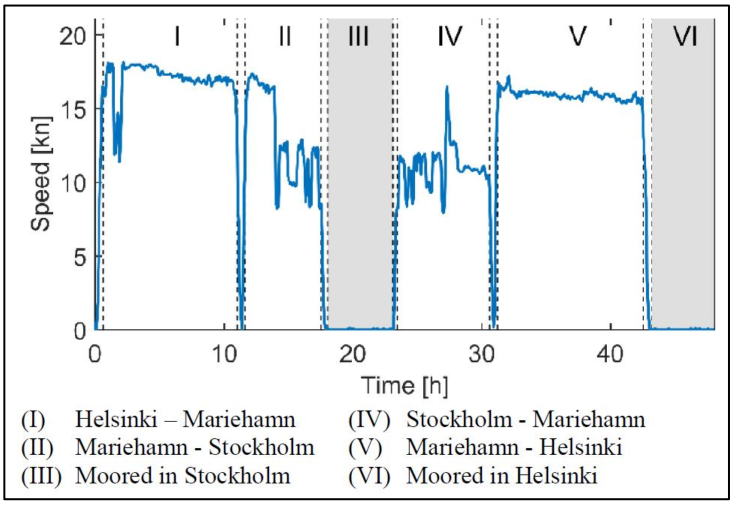


Figure 32. RoPax ship average speed during its operating cycle (Ritari et al., 2020).

Figure 33 illustrates the single line diagram for the propulsion and power system for the ship including the battery packs. As noticed, the main propulsion network is separated from the auxiliary network, which consists of four 8145 kW diesel engines responsible for the operation of the main two propellers. While the auxiliary network is supplied via two 3200 kW and two 2400 kW diesel engines responsible for proving the required power for three thrusters' motors and the hotel loads.

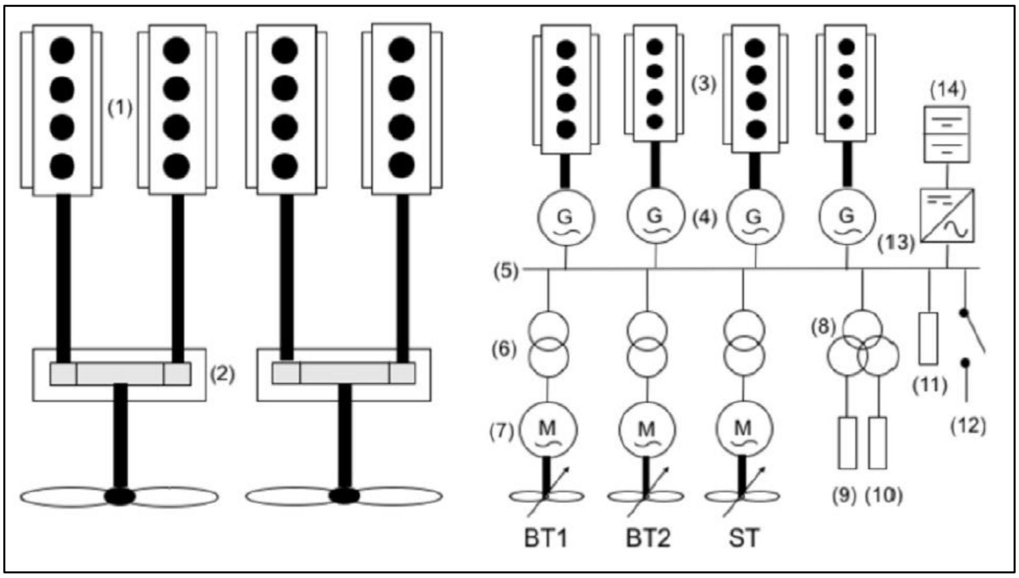


Figure 33. RoPax ship single line diagram (Ritari et al., 2020).

Improving the efficiency of the auxiliary network diesel engines is the main concern, as it contains more fluctuations, so, the loading profile for the auxiliary network is presented in Figure 34, as noticed, the average consumed power for the hotel was ranging from 2000 kW to 3000 k, except during some periods while the ship maneuvering in a harbor and thrusters motors consume more power

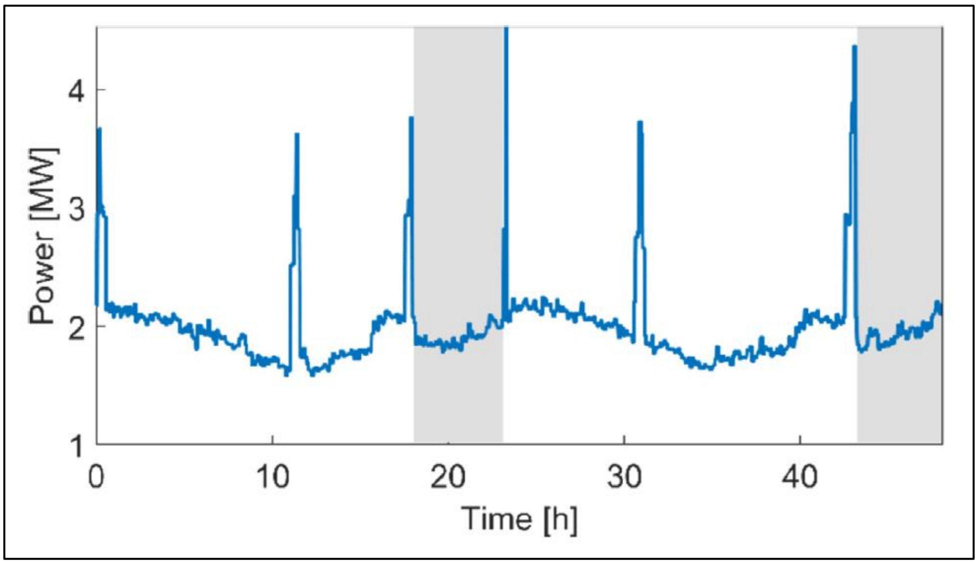


Figure 34. RoPax ship auxiliary network loading profile (Ritari et al., 2020).

6.3.2 Battery chemistry selection and sizing

Earlier in chapter three several technologies of electrochemical batteries were discussed and presented and in chapter five an evaluation was made based on economical and performance data for each technology, and the final selection was for Li-ion batteries due to their high density and long cycle life. In this section, a discussion will be presented on the selection of the chemistry of Li-ion material made by Ritari et al., (2020), which will be the best selection to be used for the cruise ship application.

Li-ion is considered one of the most mature commercial battery technologies with different chemistries such as $LiNiMnCoO_2$ (NMC), $LiFePO_4$ (LFP), and $LiMn_2O_4$ (LMO), $LiNiCoAlO_2$ (NCA), and Li_2TiO_3 (LTO) (The Boston Consulting Group, 2020). The selection of chemistry depends on several dimensions such as specific energy and power, life span, cost, thermal performance, and safety. For instance, NCA provides overall good performance but for the cost of the thermal runway, similarly, safety concerns associated with LMP. On the other hand, the safety concerns of the thermal runway are less for LFP and LTO but they are expensive and have low specific energy. So, it’s very important to balance all these selection criteria for a highly reliable application such as ships, where the safety concerns came first, then high specific energy and power, cost, and the required space. All the above-mentioned criteria exist in NMC chemistry, so, Ritari et al., (2020) selected NMC with a C-rate of four as its capable of providing high energy and power density and its output power can meet the thruster motors induced peaks. The characteristics of Li-ion batteries are determined by main four key elements which are open-circuit voltage, temperature effect, rate-dependent capacity, and aging effect (Zhang et al., 2014).

The auxiliary diesel engines were designed to supply the power for the auxiliary loads which was ranging from 2 to 3 MW, as presented earlier when the ship is close to the harbor, thrusters motors run, and that requires the operation of extra auxiliary engines and that considered a sub-optimal operating point with a minimum efficiency. So, the accurate sizing for the utilized battery can provide the required power for those transients loads. Now, for our case study, the smallest auxiliary engine power is 2400 kW and the C-rate for the selected NMC battery was four, so at least 600 kWh battery packs are required to provide the required power. To achieve a high life cycle of batteries, the SOC was determined to vary between 95% and 20%. It’s also possible to size the battery to provide the required energy for the thruster’s motors during maneuvering in harbors.

Based on the collected data by Ritari et al., (2020), the minimum consumed energy by thrusters’ motors was 300 kWh and the maximum was 850 kWh with 11% occurrence. So, to satisfy all maneuvering events, the battery pack size shall be 1130 kWh. As presented earlier, the ESS consists of battery cells, modules, and a converter. So, it requires enough space for maintenance, ventilation, thermal management, air temperature regulation, and thermal management (DNV-GL, 2014). According to Corvus Energy, (2016), the specification for a 123.4 kWh NMC battery pack is presented in Table 25, to satisfy the required power, eight packs are needed to provide the required 940 kWh, which requires almost 9 m^2 of space. For providing four C-rate from the battery pack, a 3.76 MW inverter is needed, so, Ritari et al., (2020) used four 680 kW modular inverter systems, which required a total area of about 10 m2. So, the total area required for the 940-kWh system is approximately 20 m^2. Now, for the RoPax ship case study, the vehicle cargo space is about 2700 m2, based on that, the required space for the 940-kWh system is almost 0.7% of the total space, and for the maximum 3280 kWh option, the required space will not exceed 3% of the total available space.

Table 25. NMC 1234. kWh battery pack (Corvus Energy, 2016).

Attribute	Value	Unit
Capacity	123.4	kWh
Height	2.24	m
Width	0.87	m
Depth	0.74	m
Weight	1620	kg

6.3.3 Results and discussion

In Ritari et al., (2020) study, the battery system cost was assumed to vary between 150 to 450 €/kWh, and the fuel cost varies between 0.35 to 0.9 €/kg. The average prices for shore energy were 0.08246 €/Wh, RoPax ship consumes about 4.34 GWh annually during stopping at harbors. Ritari et al., (2020) selected four sizes of battery packs which are 940, 1720, 2500, and 3280 kWh with a C-rate of four to be applied in the model. Figure 35.a shows the loading profile for the conventional operation scenario with six peaks loading of thruster’s motors operation for maneuvering in harbors and the loading ranging between 30 to 40% for the two auxiliary engines, which act as reserve power. Figure 35. b, illustrates the hybrid operation scenario with a maximum battery option of 3280 kWh, as presented, all six thrusters’ peaks were covered with the batteries, thus enabling the shutdown of two of the auxiliary engines. While in Figure 35. c, the SOC for the batteries is depicted for the 48-hour cycle showing the charging and discharging cycles. As noticed, during the mooring event, batteries can be recharged from a shore connection, and the cost of electricity is 82.5 €/MWh, which is considered less for generating power on board with average costs ranging from 77 to 198 €/MWh.

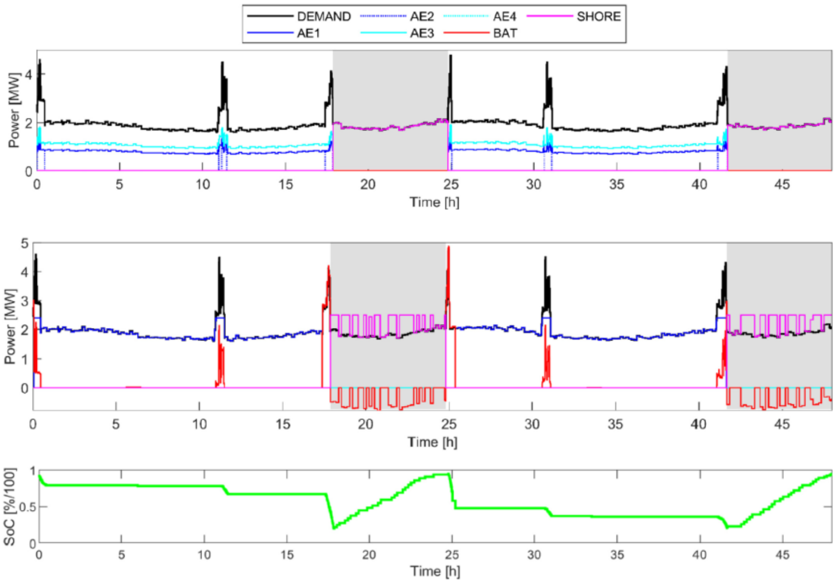


Figure 35. (a) Conventional scenario. (b) Hybrid scenario. (c) SOC for batteries (Gray: Mooring at harbors) (Ritari et al., 2020).

Figure 36 presents the loading percentage of the auxiliary engines during the conventional and hybrid scenario, as indicated, during a hybrid operation mode, the loading is mostly more than 70% and almost close to the peak efficiency operation area for the engines. Moreover, the total number of operating hours for the auxiliary engines in the case of the 940 kWh scenario was reduced by 41.9% from 15627 to 9072 hours in the absence of shore connection, while it was reduced by 49.2% from 12957 to 6582 hours in the presence of shore connection. That not only increases the operational life of the auxiliary engines but, the maintenance outage time and cost will be reduced.

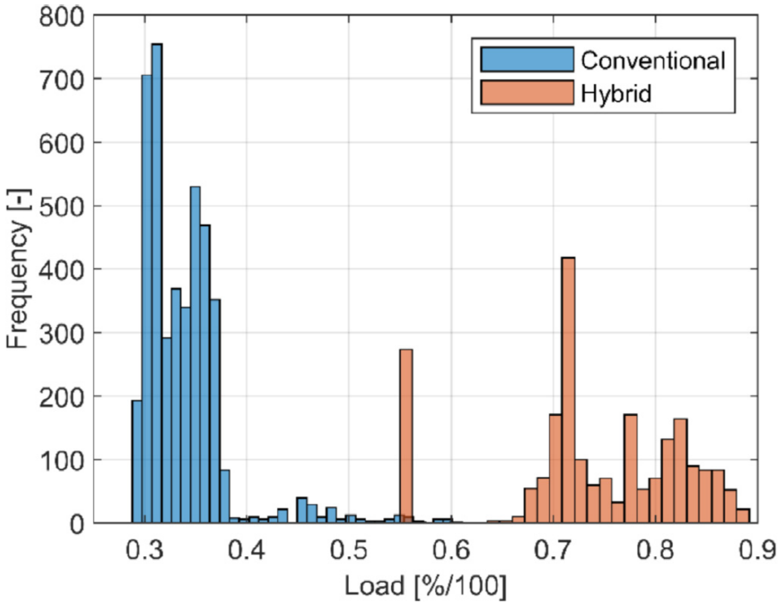
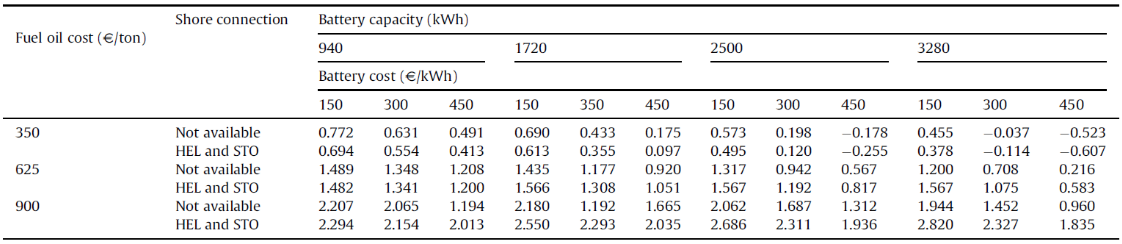


Figure 36. The loading percentage of the auxiliary engines during hybrid and conventional scenarios (Ritari et al., 2020).

There are main factors that affect the operating costs such as fuel costs, shore electricity cost, and batteries cost. Based on the Ritari et al., (2020) model, the operation cost ranges from €13.8 to €35.6 million affected by the aforementioned factors. Table 26 presents the cost advantages of the proposed hybrid model with different operation scenarios, sizes of batteries, and fuel oil prices while indicating if the shore connection is available or not. As noticed, the maximum profit advantages occur when 3280 kWh battery packs scenario with almost €2.8 million saving, that's happened when the battery prices are the lowest and the fuel cost is the highest. So, maximizing the benefits occur by adding the price of canceled auxiliary engines, while using the lowest cost of batteries in the presence of the highest cost of fuel.

Table 26. Cost advantages for the proposed model by Ritari et al., (2020).



Fuel oil cost (€/ton)	Shore connection	Battery capacity (kWh)											
		940			1720			2500			3280		
		Battery cost (€/kWh)											
		150	300	450	150	350	450	150	300	450	150	300	450
350	Not available	0.772	0.631	0.491	0.690	0.433	0.175	0.573	0.198	−0.178	0.455	−0.037	−0.523
	HEL and STO	0.694	0.554	0.413	0.613	0.355	0.097	0.495	0.120	−0.255	0.378	−0.114	−0.607
625	Not available	1.489	1.348	1.208	1.435	1.177	0.920	1.317	0.942	0.567	1.200	0.708	0.216
	HEL and STO	1.482	1.341	1.200	1.566	1.308	1.051	1.567	1.192	0.817	1.567	1.075	0.583
900	Not available	2.207	2.065	1.194	2.180	1.192	1.665	2.062	1.687	1.312	1.944	1.452	0.960
	HEL and STO	2.294	2.154	2.013	2.550	2.293	2.035	2.686	2.311	1.936	2.820	2.327	1.835

It is worth mentioning that there is a debate about the amount of CO2 emissions produced from the production of batteries, so, Ritari et al., (2020) made a comparison between the total reduction in CO_2 emissions by utilizing the batteries. According to the results, almost 250 tons of fuel can be saved annually or 2500 tons during the 10 years lifetime of batteries, which corresponds to about 6800 tons of CO_2 emissions. On the other hand, the production of a 940-kWh battery produces about 188 tons of CO_2, that's less than 3% compared to emissions produced from burning the fuel.

As noticed, it's obvious that utilizing the batteries will have a direct effect on reducing emissions. Now, the economic feasibility of using the batteries shall be calculated by knowing the average payback period of using the batteries with different prices options for fuel and battery. Table 27 presents the total saving of not purchasing 2,500 tons of fuel over the lifetime of the batteries with different prices options, for the 3280 kWh scenario. Also, the average overall price for purchasing the batteries with different ranges. As indicated, the minimum payback period was 2.18 (Year), which occurs when the fuel price is 900 (€/ton) and battery price is 150 (€/kWh), the maximum payback period was 16.86 (Year), which occurs when the fuel price is 350 (€/ton) and battery price is 450 (€/kWh).

Table 27. Calculating the payback with different fuel and battery prices options.

Saved Fuel total cost / 10 Years		3280 kWh price / 10 Years lifetime		Payback Period
350 (€/ton)	875,000 (€)	150 (€/kWh)	492,000 (€)	5.64 (Year)
625 (€/ton)	1,562,500 (€)	150 (€/kWh)	492,000 (€)	3.14 (Year)
900 (€/ton)	2,250,000 (€)	150 (€/kWh)	492,000 (€)	2.18 (Year)
350 (€/ton)	875,000 (€)	300 (€/kWh)	984,000 (€)	11.24 (Year)
625 (€/ton)	1,562,500 (€)	300 (€/kWh)	984,000 (€)	6.29 (Year)
900 (€/ton)	2,250,000 (€)	300 (€/kWh)	984,000 (€)	4.37 (Year)
350 (€/ton)	875,000 (€)	450 (€/kWh)	1,476,000 (€)	16.86 (Year)
625 (€/ton)	1,562,500 (€)	450 (€/kWh)	1,476,000 (€)	9.44 (Year)
900 (€/ton)	2,250,000 (€)	450 (€/kWh)	1,476,000 (€)	6.56 (Year)

While it is worth mentioning, by utilizing the maximum size of battery which is 3280, the auxiliary diesel engines are supposed to be canceled in the new builds, and their price shall be included in calculating the pay period, which is not considered in the presented case study. That will have a direct effect on increasing the feasibility of utilizing the batteries. Moreover, for this option, if the auxiliary engines still exist, as presented earlier in the case study, the total number of operating hours for two of the auxiliary engines in the case of the 940 kWh scenario was reduced by 41.9% from 15627 to 9072 hours in the absence of shore connection, while it was reduced by 49.2% from 12957 to 6582 hours in the presence of shore connection. That number shall be reduced to zero for two auxiliary engines when using the 3280 kWh, this means less maintenance cost and a longer lifetime, which is not calculated and studying the presented case study. The usage of batteries in this option is not expected to reduce the transformer losses, as the peak events in the loading profile still exist, the only difference is that being supplied from the batteries rather than the auxiliary diesel engines. In conclusion, if the environmental effects and reducing the emission are not the main concern, it’s obvious that the usage of batteries will be more economically feasible only when the fuel prices are high, prices of batteries are lower, and by canceling two the auxiliary engines in new builds.

7 Future Work and Conclusion

The increasing demand for reducing emissions and improving fuel efficiency for the shipping and maritime industry becoming imperative due to the new applied regulations and measures from IMO. As mentioned earlier in the introduction, the utilization of only gensets, which are based on diesel or gas engines is not enough to meet the new requirements, especially for low speed or variable speed operating conditions, where the emissions are the maximum and the efficiency is the least.

So, the integration of alternative energy sources such as fuel cells, wind, or PV is essential to supply the excess power required to maintain the fixed speed condition for the gensets, however, in some situations, both the gensets and alternative sources, may not be enough to supply the pulsed loads, which in some situations exceed the power system capability. As a result, the integration of energy storages technologies is important to provide the stability for the system and provide the required power for pulsed loads. Also, there is excess energy in the exhaust fumes, and it can be recovered by one energy recovery technology, that not only increases the overall efficiency of the system but limits the emissions. Overall, all future electrical ship power systems will consist of four major elements, the conventional gensets, one or two alternative energy sources technology, one or two energy storages technology, and finally energy recovery technology.

Several AC power system architectures were presented such as radial and ZEDS showing the advantages and disadvantages of each architecture. However, all future power systems in the ship will utilize ZEDS architecture as it provides high reliability in case of failure of any section and prevents blackout occurrence. Recently, the power converter industry and technologies received a high advancement, thus enabling the integration of alternative energy sources to the AC power system of ships without compromising the stability of the system, moreover, different energy storage technologies can be connected to the system for supplying high pulsed load or help in smoothening severe load transients, thus provide more stability and security for the ship power system.

In addition to that, according to Castellan et al., (2018) review, the continuous development of power electronics technologies increases the usage of DC distribution systems in the shipping industry. Generally, the voltage ranges for MVDC power system for ships ranges between 1 to 35 kV (IEEE, 2010). The usage of DC over AC has several advantages as mentioned earlier such as enabling the usage of prime mover speed optimization, thus enabling fuel consumption reduction and emissions as well, the integration of alternative sources and energy sources will be more flexible, and finally, getting rid of harmonics and reactive power issues. So, more future work will focus on applying DC over AC power systems for the shipping industry.

Several control interface techniques were presented for controlling all these connected components to the AC power network of the ship. As mentioned earlier, the AC power system suffers from frequency and voltage deviations and the presence of harmonic and its associated effect on the voltage regulation, so, the usage of droop control will be effective to handle these issues besides the existence of HV distribution systems and synchronous generators in ships. The presence of alternative energy sources, energy storage, or waste energy recovery is growing for ship microgrids; however, their power level is relatively small compared to the main gensets and can be connected to the ship microgrid via interfacing converters, which act as grid feeding inverters. In the presence of all these inverters in the ship microgrid, especially the grid feeding inverters, the control system becomes very complex, that’s why the utilization of hierarchical control can be used and adapted to overcome that challenge.

The presence of all the above-mentioned components in the ship power system requires an efficient power or energy management system, to optimize fuel consumption and reduce emissions, so several energy management systems were presented in brief, however, the one based on meta-heuristic optimization, which utilizes PSO or GA showed promising results than classical methods, due to their capacity to solve a multi-objective optimization problem with the presence of several constraints. Hybrid power supply and the instantaneous load sharing among all these components will require a more complex and efficient energy management system, as shown in Figure 37, Geertsma et al., (2017) presented a future integrated control strategy that enables hybrid power supply. Another important element is needed, which is fast and reliable communication, the same as for terrestrial microgrid, the need for safe and reliable communication is highly needed to manage all these elements.

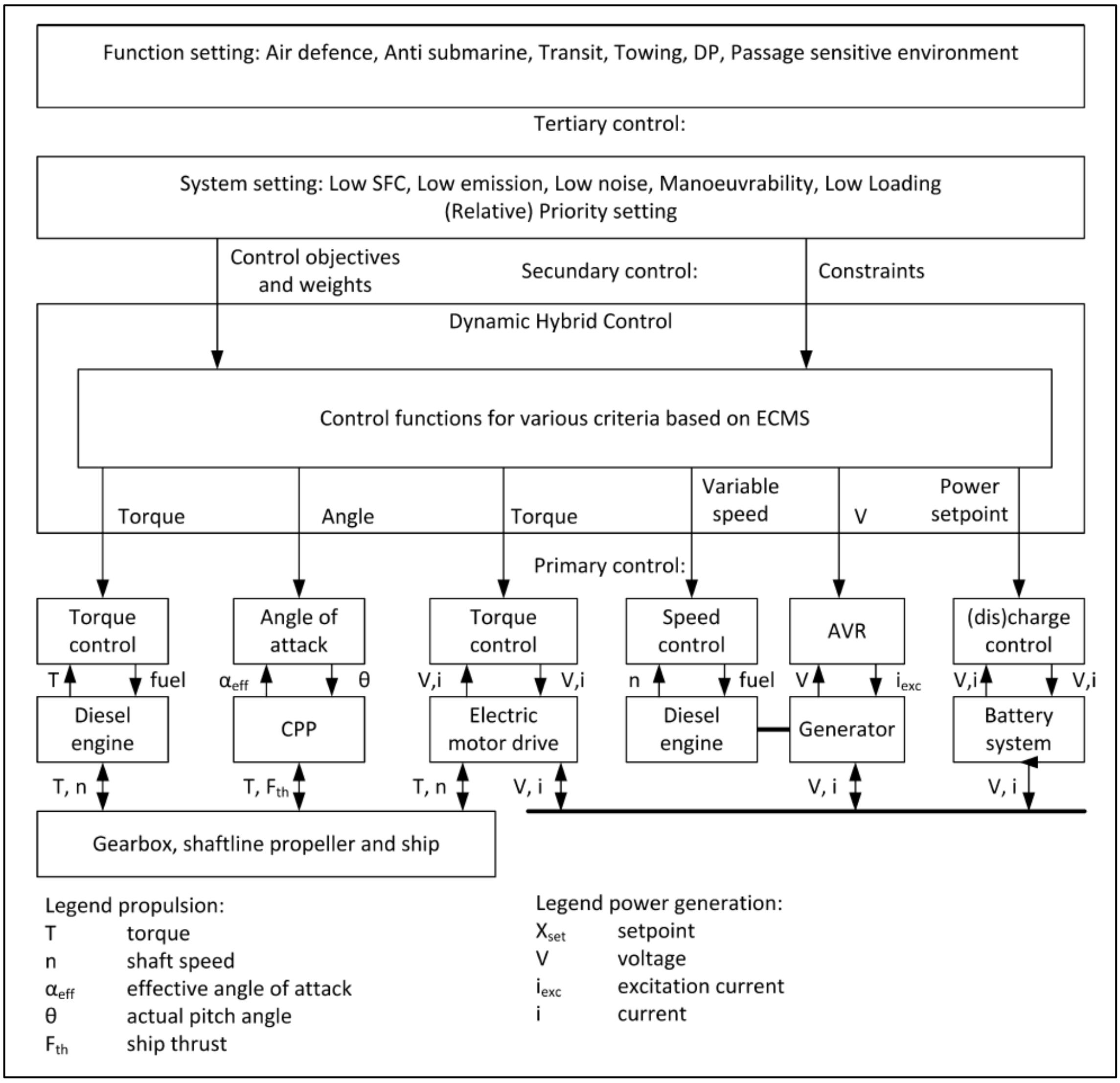


Figure 37. Future integrated control strategy (Geertsma et al., 2017).

In this thesis, a brief introduction about the shipping industry focusing on cruise and passenger ships, showing the importance of the maritime and shipping industry as it’s considered one of the cheapest means of transportation for cargo and humans. The cruise industry is expanding and the presence of new regulations and measures by IMO forces the shipping industry to utilize new technologies and apply new measures to meet those new regulations. Several techniques and technologies have been applied to the shipping industry to reduce fuel consumption and emissions, but in this thesis, the main focus was on utilizing energy storage in conjunction with the main gensets. Two main energy storage technologies were presented, the first is electrochemical energy storage, which will act as a high energy source, and supercapacitors as a high-power source for supplying pulse loads.

In chapter two, all commercially available propulsion systems and technologies were presented in brief showing the advantages and disadvantages of each system and its main applications, focusing on electrical propulsion, as it’s considered the main used propulsion technology for current and future cruise ships applications, with its different variants. The current electrical system utilizes ZEDS AC power system architecture, but due to the advancement that occurred in the power electronics industry, DC power system architecture is expected to be dominated in the future due to its aforementioned merits.

Chapter three summarizes the most common energy storage technologies based on electrochemical such as Li-ion, lead-acid, flow battery, and sodium-sulfur battery technology, and one of the most feasible electrical storages is super or ultracapacitors. A brief comparison between the technical and common applications of each technology shows if it’s feasible or not to be utilized for cruise ship applications. Li-ion battery was considered the most technical and economically feasible in terms of electrochemical based energy storage, as it can provide high energy and power density with small volume compared to other technologies, for instance, sodium-sulfur provide a high energy and power density but that came with several limitations and temperature issues, which is not recommended for movable applications such as cruise ships, where safety and reliability are considered the main priority.

As mentioned earlier, the presence of all these hybrid power supply components in the ship power system makes it considered a floating city or like terrestrial microgrid, so in chapter four the most common control interface technologies and energy management system were introduced in brief, which has been utilized to control all hybrid power supply and optimize the fuel consumption while reducing the emissions. The main object of the thesis is to present an economic study for the utilization of batteries in cruise ships, so, in chapter five, a literature review was given comparing energy storage technologies performance metrics, associated costs, and several specific findings, providing an overview about each technology and its current and expected prices in the future.

Finally, in chapter six, three main parts were presented and discussed, firstly, the utilization of batteries to reduce the transformer losses by shaving the peak or valley in the loading profile in a general distribution network was presented, not enough data is studying the effect of using the batteries in a cruise ship to reduce the transformer losses, however, in the presented study, the peak loading is not canceled out, it just supplied from batteries rather than the auxiliary diesel engines, so the transformer loading profile is still the same, and the losses are higher during peak events due to the higher current components. Secondly, the effect of load variations on the ship power system was introduced. Finally, a complete technical and economic study made by Ritari et al., (2020) about the feasibility of batteries utilization in a cruise ship with different sized options was reviewed and studied showing the selection procedure of the chemistry of batteries and the main criteria for the selection, moreover, the payback period purchasing the batteries was calculated based on three expected fuel prices, showing the most feasible options.

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