Choosing a sustainable, economical energy supply system, considering all operational variables of an autonomous submarine dredger

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A study as part of the development of the ALERD, which will serve as sustainable coastal maintenance in the service for The Netherlands.

Figure 1 Conventional dredger operating at the surface with the ALERD operating underwater [78]

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Choosing a sustainable, economical energy supply system, considering all operational variables of an autonomous submarine dredger

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Abstract

The Autonomous Low Energy Replenishment Dredger (ALERD) strives to revolutionize the dredging world. The ALERD operates autonomously underwater, which saves energy during the dredging process and transit. Autonomous underwater operation drives the need of alternative energy facilities. However, due to the energy savings of dredging, alternative energy supplies are possible. A wish of C-Job is that the ALERD operates with zero emissions, and therefore the system should comply with it as well. This introduces the research goal: Devising a sustainable electrical energy supply for ALERD. An additional challenge to the research goal is that the dimensions are not yet established and are still an open question in the research.

The simulation model uses the calculated electric load balance of the Autonomous Underwater Maintenance Dredger (AUMD) and scaling to determine the power balance of the ALERD over various hopper volumes. Furthermore, the operational area has been studied to determine charging/bunker locations and distances. The project requires an annual sedimentation of 12 million m³, including foreshore and coastal replenishment.

To determine the best system, a literature review was done towards the systems. Two key systems came out as the best systems for autonomous and sustainable operation: The Li-ion battery and the Proton Exchange Membrane Fuel Cell (PEMFC). The systems have very different characteristics. Typically, batteries have high costs for the energy storage and fuel cells costs are determined by the nominal power output.

The abovementioned systems were both used in a simulated operational profile of the ALERD. Results from the simulation, suggests that the battery has the optimal performance at 2-3 times dredging per energy cycle, where 4-9 times are the optima for the Hybrid solution. When both systems have charging/bunker stations near the operational area, a dredging cost of per m³ can be achieved for both systems. However, when the ship is charging/bunkering in the port, the costs per m³ increase with for the hybrid and for the battery powered ALERD. This results in a maximal investment of million for a local charging/bunker station, to be economically feasible. By making these stations accessible for other purposes, profit can be taken to recoup the investment. It is however expected, that these local stations will not be feasible for the first generation of ALERDs.

When cost development is taken into account, the Total Cost of Ownership (TCO) prefers the hybrid system. Which is a result from the sharply decreasing hydrogen and fuel cell costs. The system also achieves a lower TCO than a conventional dredger, in a manageable time.

A (near) future orientated system has also been considered, the direct-fed ammonia Solid Oxide Fuel Cell (SOFC). It has comparable costs per cubic metre for port bunkering as the other systems, when they are locally charging/bunkering. Furthermore, there are a lot of practical advantages by the use of ammonia instead of hydrogen as fuel. This consists of better fuel handling and easier storage.

Together with the benefits of taking more energy inside the ALERD, it is believed that the hybrid types of ALERD have the best characteristics for coastal maintenance. It depends on the developments of the ammonia SOFC, if it is ready to supply energy to the ALERD, or that the hydrogen PEMFC is the best solution in a hybrid design. Furthermore, the decision depends on the results of the weight and stability study, which is still ongoing. The results could eliminate a systems by its volume or weight. Due to the reserved space and freedom in the ship design, this is however not expected.

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Nomenclature

Abbreviations

AIP	Air Independent Propulsion
ALERD	Autonomous Low Energy Replenishment Dredger
AUMD	Autonomous Underwater Maintenance Dredger
C	Resistance Coefficient
CAPEX	CAPital EXpenditure
CoG	Centre of Gravity
CO_x	Carbon oxides
COP	Coefficient Of Performance
DBFC	Direct Borohydride Fuel Cell
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
E	Energy [J] or [Wh]
ECI	Environmental Cost Indicator [€]
EGR	Exhaust Gas Recirculation
H_2	Hydrogen
kt	Knots
LC	Local Charging (bunkering)
MARIN	MAritime Research Institute Netherlands
MCFC	Molten Carbonate Fuel Cell
MESMA	Module d'Energie Sous-Marine Autonome (Autonomous Submarine Energy Module)
n	Number of dredging cycles per energy cycle
N_2	Nitrogen
NH_3	Ammonia
NO_x	Nitric Oxides
OPEX	OPerational Expenditures
P	Power [W]
PC	Port Charging (bunkering)
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cells
$\dot{Q}$	Heat transfer [W]
Q	Flow [m³/s]
$r_{scaling}$	Scaling ratio WRT volume unit
R	Resistance [N]
SCR	Specific Catalytic Reduction
SOC	State of Charge [%]
SO_x	Sulphur Oxides
SOFC	Solid Oxide Fuel Cell
t	time [s]
T	Temperature [°K] or [°C]
TCO	Total Cost of Ownership [€]
TEG	Thermo Electric Generator
THSD	Trailer Hopper Suction Dredger
v	Speed [kt]
V	Volume Hopper [m³]

Greek symbols

η	Efficiency
ρ	Density [t/m³]
Δ	Displacement [t]
∇	Displacement volume [m³]
μ	Viscosity [mPa*s]
υ	Kinematic viscosity [m2/s]

1 Introduction

Introduction and background of the research

1.1 Background

1.1.1 Dredging in general

Dredging includes all activities that are necessary for the removal of sand, silt, and other layers from the seabed, as well as land reclamation and cleaning of surface water. The word dredging comes from the dredge, which is sludge that is created by plant residues, waste, and bottom material settling on the bottom of waterways. In the long run, this can hinder shipping traffic or the capacity to discharge water. Therefore regularly dredging is important. Often the dredge is contaminated, making disposal more complicated (and more expensive). The Netherlands and Belgium are known for their many dredging companies that do this work in many places around the world.

1.1.2 Dredging purposes

Dredging can be applicable for several reasons. There are three main traditional reasons:

1. Capital dredging: For example the construction of new docks or fairways or preparation of the seabed for offshore installations.
2. Land reclamation: The construction of artificial islands
3. Maintenance dredging: Maintaining waterways and ports

The goals of dredging work are diverse, but usually, it is one, or a combination of the following goals:

1. Removing material from below the surface of the water to create greater depth
2. Filling a void, on land or underwater, with material that is extracted underwater
3. The extraction of building materials such as sand
4. The extraction of precious ores and minerals
5. Improving the environment by removing or covering (capping) contaminated sludge.
6. Land reclamation by the use of dredged sand

1.1.3 The Autonomous Low Energy Replenishment Dredger

The Autonomous Low Energy Replenishment Dredger (ALERD) has been invented by C-Job and is a dredger that can be fully submerged and operates near the seabed. The main purpose will be maintenance on coastlines of the Netherlands. Due to current and waves, sand from the dikes and sandbanks near the coast are removed. The goal of the ALERD is to replenish the sand for the safety of the coastal regions of the Netherlands against the North Sea in a sustainable way.

The ALERD will be a future-oriented, energy-saving solution for the dredging industry. The developed system can also be valuable or be an inspiration for other purposes in the maritime sector. The development status of the ALERD is in the initial state, with its main characteristics based on the Autonomous Underwater Maintenance Dredger (AUMD). A short description of the AUMD is given in the following section. A render of the concept design has been given in figure 1.

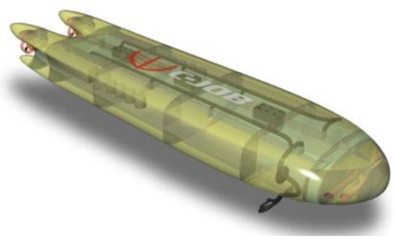


Figure 2 Concept design ALERD [1]

1.1.4 The Autonomous Underwater Maintenance Dredger

The AUMD is designed for maintenance in the port and waterways. More specifically, the operational area of the AUMD will be the port of Rotterdam. Research have been carried out on the AUMD by C-Job and the MARIN, including studies to the hydromechanics and energetic data. The AUMD is further in the development and the main characteristics such as the size and equipment have already been determined. Because the dredger operates near the coast, an electrical connection to the shore is possible for the power supply of the system. The research in this report is about the ALERD, where the above has not yet been established and a best solution has yet to be determined. In addition, there is a difference in density in the material to be pumped, with differences in power and energy demand expected.

When the results from the research are promising, it is possible that the ALERD will be applied for the purposes of the AUMD. If this is the case, the AUMD will not be further developed.

1.1.5 Why the ALERD (and the AUMD) has been invented

The ALERD has been invented to significantly reduce the power requirement. This has been done by making it autonomous and by bringing the surface dredger to the seabed. By taking the dredger towards the seabed, the pumping height and thereby the resistive and potential losses is reduced. This results in a reduction of the pump power. When the dredger is submerged, the wave-making resistance will be eliminated as well and consequently, the propulsion power is reduced. By making the dredger autonomous, there will be no need for hotel power and accommodation. Without the accommodation, the dredge displacement and hull shape will be improved, thereby further reducing the drag of the ALERD. According to C-Job, the dredger has a promising transit and dredging power reduction of respectively 55% and 80%. [1]

1.2 Research and outline

1.2.1 Research description

To date, no research has been done into the electrical energy supply of the ALERD and there is no system off the shelf available. The electrical energy supply system is a crucial part of the design, with specific requirements. That is why C-Job wants, through this report, to have this research carried out.

1.2.2 Research Objective

The objective of the research is to devise the best electrical energy supply system for the ALERD.

The objective includes the data for the development of the ALERD. This consists of the energetic data, such as the nominal and average power, energy storage, cooling requirement and other data that are specific for the ALERD. Additional data, such as the schematic drawings of the systems are not included in the scope of the research. This has been chosen, because these will be made by the manufacturers of the systems. It is expected that sufficient research has already been done by them, and this will only be necessary for new systems, of which this will be applied to the ALERD for the first time. If this is the case and there is no literature for this yet, this will be within the scope of the research.

The research objective has been accomplished, when the best system that meet the requirements has been found and the design data of this system has been elaborated.

1.2.3 Design requirements and wishes

The project requires a yearly dredging capacity of 12 million m^3, including foreshore and coastal replenishment. Ideally, the whole project will be done by the ALERD fleet in the future.

The design requirements for the ALERD differs from a traditional dredger, because it has to be designed in a submarine environment. This means that the supply of oxygen is more complicated. The design of an electrical energy supply system in a submarine has some additional challenges to be met. One should think about challenges such as keeping the submarine neutral buoyant and preserve sufficient hopper and energy capacity. A dredger is subject to high power requirements, and therefore the solution should be able to deliver this for a prolonged time.

The ALERD will be developed for commercial purposes, therefore the financial feasibility should be considered as well. However, this is not the main scope of this research.

Redundancy is of major concern for the ALERD. Therefore all systems, such as the propulsion, navigation and dredging systems are redundant designed. The same should hold for the energy supply system. There should be an emergency backup in the case of failure or calamities. This is especially important, because the ALERD will be autonomous and will not have a crew on board. This means that maintenance and the usual inspections can only be carried out in the port. Together, this calls for a system that is maintenance-free and reliable.

Furthermore, C-Job has the wish that the dredger may not emit harmful emissions. The wish has been created for the growing demand for sustainability and the upcoming energy transition for the maritime sector. In addition, with the design, C-Job aims to become the leading standard in terms of sustainability in the dredging industry.

There is a wish to charge the ALERD nearby the dredging locations, because sailing from and to the port is seen as a loss of energy. In addition, this takes time and therefore less dredging can be done.

As it stands today, the prototype of the ALERD has to set sail in 2024. This is a very short time for such a large and new project. Because the ALERD is so complex in itself, the application of a less complex system is important to facilitate the development process. Furthermore, the systems itself should be commercially available when the prototype/first ship will be build.

1.2.4 Report outline

The report consists of the literature review and the research.

Chapter 2 and 3 are the literature review of the research. In chapter 2, the challenges of the specific design requirements are covered. In chapter 3, various systems are given that could supply the ALERD with electrical energy. Where possible, the literature review is divided in conventional and state-of-the-art solutions. At the end of each chapter, a research gap is given, which has yet to be fulfilled. The literature found and described in these chapters forms the basis of the research, which will be carried out after this report.

In chapter 4, the research plan is covered. In this chapter, the research questions and the research outline is covered. Furthermore, the methodology is discussed in this chapter.

Chapters 5 until 10 is the research part of this research. In chapter 5, the simulation model is acquired and used on the data of the Autonomous Underwater Maintenance Dredger. In this chapter the mathematical model that is created for the research is explained, together with the used assumptions and data. Chapter 6 consists of the optimization of the model, together with the adaptation to the ALERD and the implementation of a suggested hybrid system using fuel cells. Chapter 7 covers the varying input data of the situation, to verify the static results of the model. Chapter 8 gives the results/design data of systems from the research. The report is closed with the discussion in chapter 9 and a conclusion in chapter 10. This is followed by the recommendation and a validation chapter of the research.

The report focusses on answering the main research question:

Which sustainable system has the best capabilities to supply the ALERD with electrical energy, and what are the design data?

2 Problem analysis

Literature review of challenging factors and solutions in the development of a sustainable electrical energy supply in an autonomous submarine environment.

2.1 Introduction

In this chapter the challenges of the design of a sustainable electric energy system in the ALERD is discussed. The challenges discussed, together with classical and state-of-the-art solutions are the endurance, oxygen, cooling, sustainability and autonomous requirements of the project.

2.2 Challenges of the submarine environment

In a submarine environment, oxygen is not easily available. In the enclosed environment, cooling is an issue. The system has to be designed bearing in mind that the submarine has to be neutrally buoyant and stable at all times.

2.2.1 Endurance limitations

The endurance of the submarine is completely dependent on the stored energy. It must be taken into account that this is available in the submarine environment. Much research has been done to increase the underwater endurance of submarines. Many different techniques have come into consideration for this.

Conventional systems

Conventionally, the diesel-electric submarine charges a battery while it sails near the water surface. When the submarine dives, (lead-acid) batteries supply the energy. Consequently, the underwater autonomy is poor in comparison with state-of-the-art, Air Independent Propulsion (AIP) systems. Nuclear submarines do not belong to this designation, but they do meet the requirements. Classically, they even have the best underwater performance. Experimental submarines were equipped with closed cycled diesel, where exhaust gasses are regained. However, these submarines were never considered a success. In the 2000s, submarines were produced or retrofit with Stirling Engines or the MESMA system. The MESMA system works the same as nuclear propulsion, but with non-nuclear components. The basic principle is the same: Generate steam to drive a turbine that runs a generator. The MESMA engines are highly efficient and are better than the closed cycled diesel with regards to emission handling. Because they work at high pressure, they can overcome the high back pressure dependent on the diving depth. [2]

State-of-the-art systems

Currently, most new-build submarines use AIP systems for the energy supply. These submarines can sail significantly further underwater, than conventional diesel-electric propulsion. Currently, fuel cells are taking over the industry and recent innovations in Li-ion batteries improve underwater autonomy considerably. Because the ALERD is designed to decrease the energy requirement, there may be other out-of-the box methods of supplying energy for a sufficient submerged autonomy.

2.2.2 Oxygen supply limitation

Many energy conversion methods depend on the reaction of oxygen with a fuel. This can be for example in an internal combustion engine or a fuel cell. It may therefore be clear that the availability of oxygen, depending on the system, is necessary. The energy for all tools (from heating to the propeller) onboard a diesel-electric submarine comes from a large battery. After a while, the battery needs to be recharged by the diesel engines. This is possible while sailing at the water surface, because there is sufficient oxygen and the exhaust gases can be removed.

Conventional oxygen supply

For the supply of oxygen, 2 methods are used in classical systems. Snorkels are used to “sniff” oxygen from the air. Secondly, oxygen was generated by the decomposition of stored hydrogen peroxide (H_2O_2) by steam. The snorkel system is used underwater, operating just below the surface. In this way, air can be introduced into the diesel engine and the exhaust gas can disappear, while the ship is still underwater to reduce resistance and operate stealthily.

In recent applications of AIP systems, liquid oxygen is stored in cryogenic vessels which can then be used by the system. When hydrogen is used as fuel, 8 kg of oxygen per kg of hydrogen is required according to the stoichiometric ratio. This means further that when both elements are stored as a liquid, a storage volume of 0,5 m³ of oxygen per 1m³ of hydrogen is required. In a conclusion, the possibility to use air via a snorkel could be beneficial in terms of total system sizing. [3] [4] [2]

2.2.3 Cooling limitation

A submarine is an enclosed environment, in which heat is added by the energy losses. Heat is added, but the dissipation of this is difficult because of the enclosed environment. Because the ALERD operates near the seabed, a lot of seawater contamination is expected, which decreases the ability to use seawater as cooling agent.

Conventional solutions.

Conventionally, two systems are commonly used for cooling. These are air cooling and internal (sea)water cooling.

Air cooling can commonly be found in road transport and diesel generators. The volume flow is a function of cooling capacity and the difference between the system temperature, air temperature and specific heat of the involved materials, air and fluids. [5]

Generally, in the internal (sea)water cooling system, surrounding water is pumped through heat exchangers to cool the machinery. These types of systems are frequently used in the maritime sector, because it has a very large cooling capacity. Due to water contaminations, these systems need maintenance and inspections. Depending on the sailing area and seasonal influences, it may be necessary to clean the strainers daily. Moreover, the seawater system is strongly subject to erosion through sand and salt. [6] [7]

State-of-the-art cooling

External (sea)water cooling or keel cooling has been applied for many years in private yachts and recreative sailing. These systems use an internal cooling system with heat exchanging at the hull. They are not applied in large ships, because they have typically a low cooling capacity. Due to developments in keel cooler heat exchangers, together by applying a highly efficient energy supply system, larger purposes such as merchant shipping become feasible. Keel cooling systems have two advantages over the conventional seawater cooling system. These are higher efficiencies by the elimination of seawater pumps and higher redundancy. A counter-argument for using these systems is that the low cooling capacity makes the heat exchangers bulkier. Furthermore, because the heat exchange takes place along the skin, the entire system is also much larger. [6] [7]

2.2.4 Size limitations

A submarine has to be neutrally buoyant so as not to sink or float. Submerged stability is critical, because there is no reserve buoyance and thus no restoring moment. The weight, volume, and placement of equipment and machinery inside the submarine is an iteration process, for which there are endless possibilities, but only a few ideal solutions. [8]

Volume and weight

For the electric energy supply system, a mass of approximately 125 tons has been reserved. Furthermore, a volume of 130 m³ is available. However, these values are dependent on the size of the ALERD, which has yet to be determined. Aside from the main powerplant, all subsystems and stored energy has to comply with the calculated size, range and speed of the ALERD. The reserved weight and size is scalable according to the actual dimensions of the ALERD, which is part of the research in the optimization of the parameters. [1]

Centre of mass

From the stability study of the AUMD, the following data is retrieved. The vertical centre of gravity (CoGz) of the system has been assumed on 2.55 meters from the keel. The longitudinal centre of gravity (CoGx) has been assumed on 23 meters from the aft. These are indications for where the centres of gravity of the systems should be placed. If this is not possible, stationary ballast has to be placed or moved. As the dimensions are yet to be determined, it is convenient to normalize the CoG's to the relevant dimensions. With a length of 80m and a height of 6m, this gives a respectable normalized CoG of 42,5% from keel and 28,75% from the aft. [1]

2.3 Challenges of sustainable systems

In this section, definitions of harmful emissions will be elaborated. These are emissions that are likely to cause harm to people and/or the environment. The main harmful emissions produced by energy plants are Nitrogen, Carbon and Sulphur based. The latter two can be eliminated by choosing a fuel that does not content these elements. Nitrogen-based emissions are produced by the content in the air, and it is therefore more complex to eliminate these emissions.

In transport, harmful emissions categorised into direct and indirect emissions. The direct emissions are produced during operation by the combustion engine. The indirect emissions are produced by the production of the fuel and/or manufacturing of the system, in which the operational emissions are in principle, with the exception of nuclear energy, the dominating factor concerning total emissions.

At last in this section, the state-of-the-art systems to eliminate or minimise these emissions will be described.

2.3.1 Nitrogen-based emissions

Nitric oxides

Nitrogen monoxide (NO) is a gas that is created during all kinds of combustion processes. Chemical reactions occur at high temperatures, for example between nitrogen (N_2) and oxygen from the air. In the air, the nitrogen monoxide emitted is quickly converted into nitrogen dioxide (NO_2). The sum of nitrogen monoxide and nitrogen dioxide is called nitrogen oxides (NO_x). NO_x are mainly released during the combustion of fuels, for example by traffic. NO_x emissions are also indirectly a contributor to the greenhouse effect because they participate in the creation of ozone. [9]

Nitrogen dioxide can be harmful to humans. That's because it can penetrate the smallest branches of the lungs, which decreases the oxygen uptake. People can develop respiratory complaints and asthma attacks. It also happens that people become more susceptible to infections. For example, you will catch a cold faster. [9]

Nitrogen oxides are deposited in nature (deposition). This happens both through dry deposition and wet deposition (as nitrates in the rain). As a result, nature and the soil are enriched with nitrogen. Plants that grow well in nutrient-rich soil, such as grass and nettles, crowd out plants that grow on poor soil. When those plants disappear, the animals that live on those plants also die. Ultimately, there will be fewer species of plants and animals; biodiversity will decline. [9]

Ammonia

Ammonia is a colourless gas with a strong smell. It is a compound of nitrogen (N_2) and hydrogen (H_2). Ammonia (NH_3) is produced in large quantities all over the world. It is used, among other things, to make fertilizers, cleaning agents, and coolants for large cooling installations. It is also present in manure.

In high concentrations, ammonia is toxic to humans, animals, and plants. NH_3 emissions are also indirectly a contributor to the greenhouse effect because they participate in the creation of ozone. [9]

NH_3 can be produced in the exhaust system by steam reforming or the reaction between NO and H_2 from a water-gas shift. When ammonia is used as fuel, it can also be emitted by incomplete combustion and leakages. [10]

2.3.2 Sulphur based emissions

Sulphur oxides (SO_x) are the collective name for sulphur dioxide (SO_2) and sulphur trioxide (SO_3). It is a combustion product of sulphur with air. It is mainly released when burning sulphur-containing fossil fuels, such as some types of petroleum, lignite, or coal, and is one of the main components of air pollution and smog. It easily forms sulphur trioxide (SO_3) in the air in the presence of moisture and other compounds, a compound from which sulfuric acid forms in water. This rains down from the atmosphere on the earth (acid rain).

2.3.3 Carbon-based emissions

Soot

One of the fractions of particulate matter is called soot. Particulate matter consists of a few percent of soot. Research has shown that of all fractions of substances in particulate matter, it is precisely this component that causes the most damage. The term "carbon black" refers to a combination of carbon and carbon compounds. These are mainly released during the incomplete combustion of fossil fuels (diesel engines) and organic material (biomass, forest fires). These emissions also have a major social impact, because they develop the characteristic black smoke.

Soot is also a major contributor to climate change because it absorbs sunlight and heats the atmosphere. [10]

Carbon monoxide

Carbon monoxide, formerly known as coal vapor, is a polar inorganic compound of carbon and oxygen, with the chemical formula CO. It is a colourless gas that is produced, among other things, by incomplete combustion of carbon, fossil fuels or other combustible carbon compounds (most organic compounds). Carbon monoxide is poisonous, colourless, odourless and fractionally lighter than air.

Carbon dioxide

Carbon dioxide is in contrast with carbon monoxide an emission that is produced, amongst other things, by the complete combustion of carbon.

Because carbon dioxide absorbs infrared radiation, it reduces the radiation to space of solar heat reaching Earth. This is called the greenhouse effect because a similar effect occurs in a greenhouse: short-wave radiation can enter the Atmosphere where it is converted into long-wave radiation, which can no longer escape.

2.3.4 State-of-the-art sustainability

Recently, much effort is taken to fight air pollution and global warming. Because the energy demand of the world is still mainly relying on the combustion of fossil fuels, ways have been found to minimize its harmfulness.

Emission control systems

Emission control systems are primarily intended to reduce sulphur and nitrogen-based emissions. They can be subordinated into 2 categories. These are reducing the production of these emissions, and post-treatment.

A method to reduce the emission of nitrogen oxides and ammonia is by decreasing temperatures in the internal combustion engine. This can be done by adding water to the cylinder or Exhaust Gas Recirculation (EGR). [11] [12] [2]

Post treatment systems were initially used in the closed cycle diesel submarines, but for a different reason. The engine exhaust, which consists largely of carbon dioxide, water vapor, and nitrogen were cooled, scrubbed, and separated into its constituents. This process makes recycling possible and decreases exhaust volume. This method is currently used to “wash” the harmful emissions from the exhaust. Another method of reducing nitrogen-based emissions and soot is the use of Selective Catalytic Reduction (SCR). The latter can also be removed with the use of a conventional particle filter. [11] [12] [2]

Using a polluting free energy source

Aside from a treatment approach, a pollution-free energy source could exclude emissions in advance. Due to the recent energy transition, more of these methods become commercially available. The easiest method to prevent carbon-based emissions is to use fuel without carbon content. Another method is the use of carbon-neutral fuel. These fuels do produce carbon emissions, but these are recycled in the production of the fuel. The disadvantage of combustion is that the nitrogen from the air is converted into nitrogen oxides. Sustainable fuel cannot help for this.

2.4 Challenges by autonomous propulsion

The ALERD will be unmanned, which causes many challenges. This makes routine maintenance and inspections impossible, something that is performed several times a day in a conventional ship. Inspections are important to ensure safety and operation. Furthermore, there is no possibility to combat calamities with human skills. In other words; it takes a comprehensive idle system that cannot fail, or a system that is less prone to errors.

2.4.1 Conventional autonomous systems

Batteries are already in use for autonomous purposes, because they are classically reliable and require relatively low maintenance and inspections. Furthermore, fuel cells have already been considered as an autonomous energy supply system, from the end of the last century. [13]

2.4.2 State-of-the-art autonomous systems

There has not been any breakthrough innovations in autonomous energy supply systems recently. However, the autonomous operation of energy supply systems has been improved by the increasing need of autonomous transport. Innovations can be found in low maintenance and modular systems. Furthermore, the newly developed conventional batteries and fuel cell systems have excellent maintenance-free operating hours and reliability.

As mentioned in the cooling limitations, a conventional cooling system requires maintenance and inspections. So it is not just the system itself that needs to be looked at, but the entire powertrain and auxiliary systems that are required. [14]

2.5 Research gap

In first instance, it must be ascertained if the design requirements are realistic, whether or not they can be adjusted for a better result. One should consider, for example, the zero-emission requirement, since a large reduction of emissions is better than an unfeasible design. Furthermore it has to be determined to what extent maintenance and inspection free operation is desirable. When low-maintenance systems do not meet the other requirements, a modular system could be the solution. All the requirements has to be achieved in a financially feasible solution as well, which is a predominant design criteria. The dimensions of the system are critical as well, because the system should fit within the ALERD. The exact limitations will be determined by a research conducted in parallel.

The requirements for the cooling system are new as well. With an autonomous operation in a very polluted environment and possibly different operating temperatures from the energy system, a new solution might be considered and developed. When oxygen is required for the energy production, it must be ascertained how this will be supplied to the system.

The above requirements will initially act as a test of the system. If the system does not comply with this, the importance of each requirement will have to be determined. After this, a consideration will be made, which of these may be sacrificed in order to obtain a feasible design.

3 Energy systems

Literature review of energy supply systems, capable of powering the ALERD cleanly

3.1 Introduction

This chapter covers the systems that could supply the ALERD of electrical energy. The applications and characteristics of the systems are described. The following two paragraphs are separated in first the conventional systems, and afterwards the state-of-the-art systems and promising expected systems of the future. A summary of the specifications of the systems can be found in appendix B.

At the end of the chapter, the 2 most promising systems are elaborated and some decision making methods are given. The data and method from the literature study is used in the research.

3.2 Conventional systems and relevant applications

In this section different energy supply systems are reviewed, which are conventionally used in relevant appliances such as submarines, automotive and space travel.

3.2.1 Internal combustion

Applications

(Internal) combustion engines have taken human mobility to a higher level. This is partly due to the high power density and the use of high energy-dense fuel.

The internal combustion engine has 2 great precursors to the application. The (diesel) reciprocating engine has the edge in terms of efficiency, and thus reducing the fuel required. The gas turbine has an excellent power density. This allows 2 directions to be seen where they are applied. The reciprocating engine is most commonly found in the transport sector, such as merchant shipping, freight traffic, and the automotive industry. But this system is also widely used in conventional submarines, namely the diesel-electric submarines, including the Dutch submarine fleet. Gas turbines are today most commonly found in aviation and power plants. The second is striking because the efficiency plays an important role here. Gas turbines are applied in power plants, because they are combined with heat recovery which increases the total efficiency. Furthermore, they have more favourable maintenance characteristics, which makes it easier to plan the operating hours. This is also an important characteristic of the ALERD, because maintenance can only be carried out in the port.

Characteristics

Except for Thermo-Electric Generators (TEG), to generate electricity, multiple energy conversion steps are required. The weak link in this process is the conversion from heat to mechanical energy. This step, including all required sub-systems, decreases operational reliability considerably. Moreover, the use of these kinds of systems requires a generator, decreasing the efficiency.

This applies to both the (steam) turbine and the engine, where routine maintenance and inspections are unavoidable. The Maritime Unmanned Navigation through Intelligence in Networks study (MUNIN) [15] showed that with the current technologies, an engine can run for 500 hours without the physical interference of a person.

Araner has set the advantages and disadvantage of the gas turbine and internal combustion engine against each other, both driven by gas: [16]

Advantages of gas turbine	Disadvantages of gas turbine
No cooling water required	Lower mechanical efficiency
Lower emission	Higher noise levels
Higher power: weight ratio	Poor efficiency at low loading
Wider fuel range capability	Output affected by ambient temperature
Constant high speed enabling close frequency	May need long overhaul periods
Higher reliability	Premium fuels need to be clean or dry

Table 1 Gas turbine characteristics [16]

Advantages of gas engine	Disadvantages of gas engine
Higher efficiency over a wider range	Must be cooled
Wide range of unit sizes	Lower power: weight ratio
Fast start-up - as fast as 15 seconds	Requires substantially strong foundations
Can operate at low-pressure gas (1 bar)	Higher levels of low-frequency noise
Part load operation flexibility	High maintenance cost
Real multi-fuel capability	

Table 2 Gas engine characteristics [16]

3.2.2 Nuclear power

Applications

Nuclear power has proven itself in various maritime applications, such as in Russian icebreakers, submarines, and aircraft carriers. [17] [18]. Moreover, countries such as France derives approximately 75% of their energy from nuclear sources. [19]

Characteristics

Nuclear energy density is a factor 10^5 higher than diesel. Moreover, it is considered a clean method of electric power generation. However, the applications of these systems are considered as very complicated.

Proven by studies after studies in top scientific journals, nuclear energy is one of the safest methods of electric power generation. [20] [21]. Nasa made a graph to illustrate the annually prevented deaths by nuclear power generation, when the (indirect) deaths of pollution are taken into account.

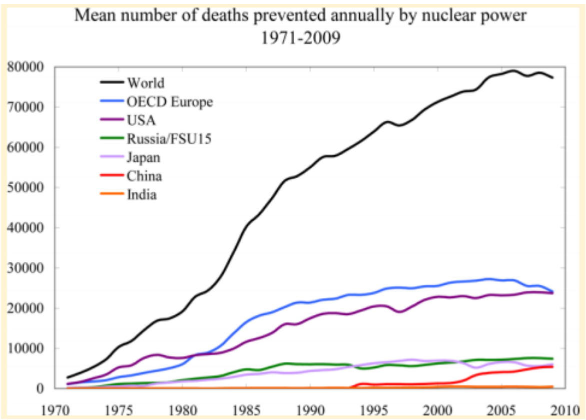


Figure 3 Annually prevented deaths by nuclear power [20]

Nevertheless, even when the safety standard is so high, disasters can happen. Especially in a submarine dredger, where collisions and other disasters cannot be ruled out. Reviewing the ethical issues of nuclear energy [22], the following has been concluded: Because the ALERD will be deployed as a maintenance dredger, people and animals will always be in its proximity. They may not be aware of the dangers, and therefore, together with the technical complexity, ethical considerations preclude the use of nuclear energy. The long-term effects of the radiation from current used nuclear fuels overrule the short-term risks of modern non-nuclear fuel. However, the authors never assess the long-term risks regarding climate change and pollution, caused by the use of fossil fuels.

Another setback is the Brussels Convention on the Liability of Operators of Nuclear Ships, developed in 1962. The convention made national governments liable for accidents caused by nuclear vessels under their flag, because the magnitude of possible damage is beyond the capacity of private insurers. This makes the application even more difficult than just the technical challenge. [23] [24]

3.3 State-of-the-art systems and relevant appliances

In this section different energy supply systems are reviewed, which are State-of-the-art in relevant appliances as submarines, and/or, automotive and/or space travel.

3.3.1 Combustion with alternative fuels

The alternative fuels that are considered in this section must at least meet the requirement that it is emission-free. In addition, it must also meet the possibility of being clean and economically feasible to produce it.

Applications

The advantage of combustion with alternative fuel is that it can be applied in the purposes of conventional fuels. The extent to which this is successful depends on the energy density, pre-treatment and ignition characteristics of the fuel. For example, alternative fuels have been successfully used in cars and shipping. A common drawback of alternative fuels for the application is that they are expensive and many fuels still have polluting emissions (which can sometimes be recovered during production). NOx emissions are with alternative fuels still a concern that has to be dealt with.

Characteristics

The characteristics and performance of the combustion engine/turbine depend on the fuel quality. They are assessed in this section according to promising fuels about round trip emissions.

The most promising method to run an engine without the emission of carbon dioxide is the use of ammonia as a fuel. Due to the poor combustion characteristics of ammonia, a pilot fuel is required for the operation of the engine. Hydrogen is the most promising pilot fuel with regards to combustion characteristics and emissions. The study showed that a ratio of 70:30 NH3:H2 is a good starting point for the design of the energy supply system. [25]

Gas turbines have similar problems caused by combustion problems. In attempts to reach 100% ammonia combustion, the flame blew off before reaching stable conditions. The conclusion was that a ratio of 50:50 ammonia:hydrogen is a good starting point for the operation. [26]

These systems have been operated with an ammonia reformer as well. This would not require a dual fuel storage system. However such systems have other problems described by the patent as: “The requirement for the combustion promoter fuel fluctuates with varying engine loads and engine speed, which can cause control issues”. [27]

3.3.2 Fuel cells

Fuel cell technology has been around for a while, but by new developments and fuel transition, it is used more often today as innovative solutions.

Applications

For its U212 class submarines, Germany developed 34 kW Proton Exchange Membrane Fuel Cell (PEMFC) modules, using a metal hydride to store hydrogen and LOx in cryogenic tanks outside the pressure hull. [28] [29]

Phosphoric acid fuel cells are in use in the Indian Kalvari class. [30] [12] [31]

Alkaline fuel cells had taken the Apollo 11 and her astronauts to the moon. The fuel cell was an ideal source of on-board electrical power with the additional advantage that the exhaust water could be used both for drinking by the crew and humidification of the capsule's atmosphere. [32]

Nasa is increasingly interested in the appliance of PEM fuel cells due to the aerospace challenges that include among others: Dynamic vibration, shock loads, and extended duration operations. For airless space applications, they aim at closed-cycle and regenerable PEM technology. Hydrogen is regenerated using electrical energy overcapacity. NASA is targeting space systems featuring power outputs in the kilowatt range and scalable to the 100 kW range at high power densities. The intention is to revolutionise the aerospace power generation towards new capabilities. [33]

Proton exchange membrane fuel cells have been applied in multiple cars, such as the Toyota Mirai, the Honda Clarity and the Hyundai Tucson. [34]

Solid oxide fuel cells seems to be one of the cleanest and most energy-efficient technologies for the direct conversion of chemical fuels in electricity. Nissan has already tested a prototype of a small van running on a solid oxide fuel cell. [35] [36]

With an electrical fuel preheater, the start-up time of the solid oxide fuel cell has been decreased substantially. However, thermal stress greatly reduces operational lifetime. [27]

Low- and high-temperature proton exchange fuel cells and the solid oxide fuel cell are seen as the most promising fuel cell types for nautical applications. [37]

Characteristics

Fuel cells are to date available in several types and characteristics. Recent innovations focus on common weaknesses, such as improving start-up, cost, longevity, fluctuating power, and poisoning.

Especially the low-temperature fuel cells are affected by poisoning of for example carbon oxides and sulphur. To eliminate the chance of fuel cell poisoning, pure hydrogen and oxygen are used. The use of pure fuel decreases the fuel production efficiency considerably. The use of pure oxygen (in tanks) adds weight and volume to the system, but increases the fuel cell efficiency as well. [3] [4]

Because fuel cells typically do not cope well with varying loads, they are often equipped with battery packs that are used for peak shaving. When the load is stationary, this is not required. However, stop and start-up processes have a negative influence on the lifetime as well. Therefore it could beneficial that the fuel cell can maintain its power output, where it would be switched off (for a short time) elsewhere.

Proton Exchange Membrane Fuel Cells (PEMFC)

PEMFCs provide high-power density and have several advantages related to its low weight and volume. They are typically fuelled with pure hydrogen supplied from storage tanks. They operate at low temperatures of about 80°C. PEMFC are suitable for mobile applications and other uses that require an initial high demand of power, which is of high density. The main advantage is that the FC can quickly reach the operation temperature starting from the ambient temperature. The main problem is the fact that they need the presence of a platinum catalyser to be able to operate, adding costs. Because of the low temperature, water management is a concern. These problems are solved in the high-temperature variant, which is still immature and under development. [3] [38] [39]

Solid Oxide Fuel Cells (SOFC)

SOFCs operate at very high temperatures, typically between 500 and 1000 °C. SOFCs have a wide variety of applications ranging from auxiliary power units in vehicles to stationary power generation, with outputs from 100 W to 2 MW. Can run on hydrocarbons or ammonia. By the use of this kind of fuel, the total system volume can be decreased substantially. The higher temperature Fuel cells have longer start-up times and can get problems with their sealings when a lot of start-up cycles are carried out. These problems are less of a concern when they operate at an intermediate temperature range of 500 to 750 degrees. Solid Oxide fuel cells seem to have a bright future, as the commercial production of direct ammonia fed fuel cells seems to start in the near future. This type of fuel cell has the great promises that it can work on an energy dense fuel, without the emission of polluting gasses. [3] [27] [40]

Alkaline Fuel Cells (AFC)
Newer AFC designs operate at lower temperatures of roughly 23°C to 70°C. One of the limitations of AFCs is that they are sensitive to carbon dioxide (CO_2) which may be present in the fuel or air. Because these systems often run at low temperatures, water is difficult to remove. [3]

Direct borohydride fuel cell (DBFC)
The fuel cell has great promises. However, the current efficiency of boron hydride recycling is so low, that it is unsuitable for transport applications. [3]

Direct Methanol Fuel Cells (DMFC)
For applications with low power output due to its low efficiency of approximately 20 to 30 percent. It has the downside that CO2 is a reaction product due to the content of carbon atoms in the fuel. [3]

A variation on the DMFC is the reformed methanol fuel cell, which is State-of-the-art and has great promises over the DMFC. The efficiency of the RMFC is much higher at approximately 50 to 60 percent. Methanol as a fuel has the advantage that it is much denser than hydrogen and that the fuel handling is better. However, CO_2 is again a reaction product for this type of fuel cell. Some methanol production methods capture CO_2 from the air, in this way the net CO_2 emission is zero. The downside of this method is that the production of methanol is more expensive. [3]

Phosphoric Acid Fuel Cells (PAFC)
PAFCs are for stationary usage, they operate at a range between 150°C and 200°C. Typically, PFACs are large and heavy. The interest in this technology is gradually disappearing because of the high production and operation costs and the lack of long-term operation reliability (related to cathode corrosion problems). [3]

Molten Carbonate Fuel Cells (MCFC)
MCFCs are for stationary usage. MCFCs can operate on fuels such as natural gas, biogas, syngas, methane, and propane. It has a working temperature of 650°C and above. Disadvantages include a low power density and the aggressiveness of the electrolyte. Short system lifetime is a problem for MCFC devices and constitutes the main limit to their commercial success. [3]

3.3.3 Batteries

Applications

Batteries are increasingly seen as normal in road transport. Due to the great developments of Li-ion batteries, there are fewer and fewer critics. The many studies into the emissions in the life cycle of the electric car have also contributed to this.

Batteries have been a proven energy supply since the first submarine. Recently, Li-Ion batteries are taking over lead-acid batteries as the new standard for every new-build submarine. The biggest reason to opt for Li-Ion batteries is that the power density is much higher. As a result, is that the total system size and weight decrease and thereby increasing the hopper capacity of the ALERD. [42] [43]

Most Remote Operated Vehicles (ROV's) have a lower propulsion power than 400 kW. Therefore a battery supply has been applied as an energy source. Other applications of ROVs use a direct connection with an energy source. This has however a complication because it reduces manoeuvrability. Recent innovations have created a wireless induction feed. [45] [46]

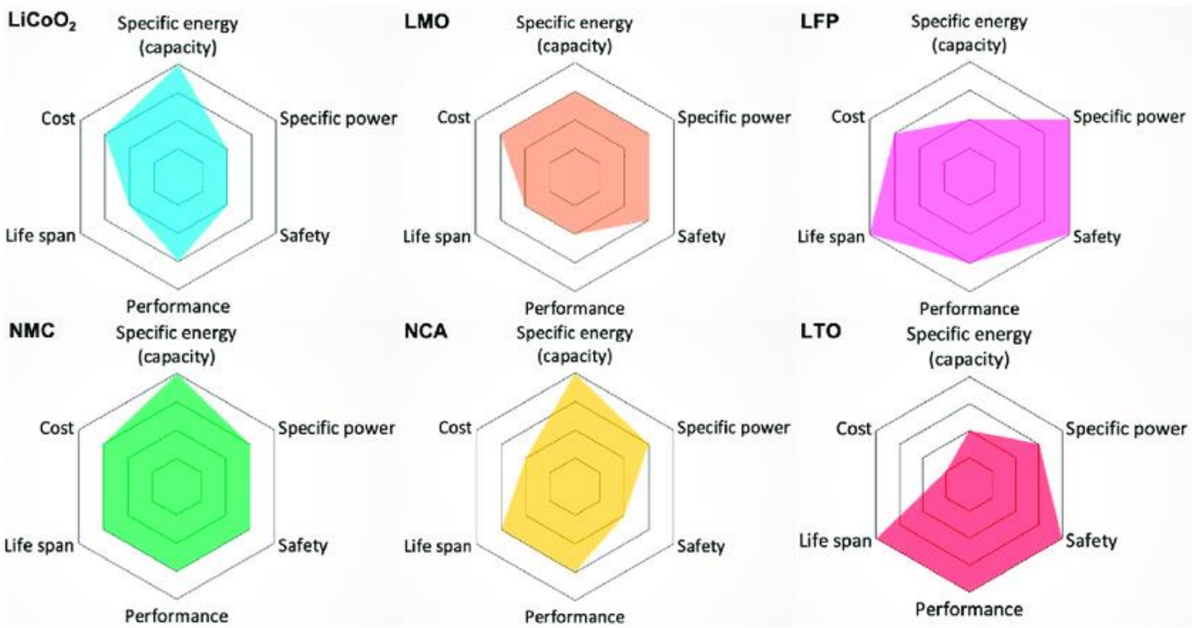
Characteristics

Batteries are a proven technique for the storage of electrical energy. Batteries have in general some main advantages over the other mentioned methods. These are primarily: No to little maintenance, and high efficiency. On the other hand, batteries have a low energy density and the investment costs for energy storage are high. Furthermore, the charging times are a restraining subject of success. The combination of both are the reason that this technique, as the main energy carrier, is not seen on ships.

Li-ion batteries

Researchers into the characteristics of batteries for the appliance in electric vehicles concluded that Li-ion batteries are still leading in terms of performance and availability. It is a known characteristic that Li-ion battery lifetimes are greatly improved if they are operated at around 30%-80%, or in other words that the storage capacity should be doubled with regards to the energy requirement. [47]

Within the Li-ion batteries, different routes of objectives are executed. For example, in road transport, the main goal is energy density. In other applications for example, safety, lifetime or power density is the main objective. Different types of compositions have their own specialties. Which of these is the most important depends on the properties of the ALERD. In the following figure, a summary of common types of Lithium batteries is given: [48]



$LiCoO_2$	LMO	LFP	NMC	NCA	LTO
Lithium cobalt oxide	Lithium manganese oxide	Lithium iron phosphorus	Lithium manganese cobalt	Lithium nickel cobalt	Lithium titanate oxide

Figure 4 Li-ion battery types [48]

It can be predetermined that the specific energy, cost and life span should be maximized as much as possible, with keeping the safety and specific power within acceptable limits. Life span works indirectly in favour with costs, as less battery replacements are required. From this it can be concluded that the LTO and LFP Li-ion batteries are not useful for the purpose of the ALERD. With the NMC as a common type of battery used in cars, this will also be a good option for the ALERD.

Lead-acid batteries

A more classical type of battery is the lead acid battery. The Li-ion battery is superior in most characteristics, however there are some reason to choose a lead-acid battery in a submarine.

When the submarine has an average density less than natural buoyant, the implementation of Lead-acid batteries could be beneficial because these batteries have a higher density and lower investment cost. Additionally, lead-acid batteries are safer in terms of fire and explosion danger. This is a characteristic that is of great importance, because there is no personnel onboard who can notice and prevent this from occurring. [49] [42] [44]

Near-future developments

Aside from the mentioned technologies, there is a lot of developments with respect to safety, cost and charging capabilities. The most promising and near-future orientated options are listed below: [50]

Vertically aligned carbon nanotube electrode

NAWA Technologies has designed and patented an ultra-fast carbon electrode. They claim that it is a breakthrough in the battery market and says it can increase battery capacity tenfold, increase energy storage by a factor of three and extend battery life five times. The company sees electric vehicles as the main beneficiaries, as they reduce the carbon footprint and cost of battery production while improving performance. NAWA says a range of 1000 km could become the norm, with charging times reduced to 5 minutes to get to 80 percent. The technology could be in production as early as 2023.

Even more than with cars, the short charging time will be an important feature in the success of the ALERD. Ideally, this will be as little as possible at the loading station, because the ship must be dredging as much as possible to keep costs down.

Lithium-sulphur batteries

Researchers at Monash University have developed a lithium-sulphur battery that can power a smartphone for 5 days, 2-3 times better than lithium-ion. The researchers have manufactured this battery, have patents and the interest of manufacturers. The group has funding for further research in 2020 and says continued research into cars and grid use will continue.

The new battery technology has a lower environmental impact than lithium-ion and lower production costs, while offering the potential to power a vehicle for 1000 km, or a smartphone for 5 days. Since the same characteristics are required from batteries in cars and the ALERD, this will also become a valid option in the near future.

3.4 Preselection of the systems and working principle

Based on the data of the systems from the literature, which can be traced in appendix B, only a few systems are capable to efficiently power the ALERD of electric energy.

Classic mechanical power conversion methods, the engine and turbine, will not be included in the research. This decision is based on the inability to operate emission-free, due to the required maintenance and the complexity of the air supply. the most plausible systems for the ALERD will be batteries and fuel cells. More specifically, the li-ion and PEMFC have the greatest promises at the moment, which is why they have been most widely used in similar applications. In the following sections a small description is made about the working principles of these systems.

3.4.1 Fuel cells

Fuel cells are electrochemical devices that directly convert chemical energy from an ongoing reaction into electrical energy. The chemical energy therefore does not have to be converted into thermal energy and mechanical energy first, so that hardly any losses occur and the fuel cell generates energy in a very efficient way. A redox reaction takes place in the cell. In this respect, a fuel cell resembles a battery or accumulator; yet there is an important difference between a battery or battery and a fuel cell. In a fuel cell, reagents (for example: hydrogen and oxygen) can be continuously supplied from outside, while the reagents in a battery or accumulator are stored in a closed system.

Hydrogen and oxygen are supplied to the fuel cell separately from each other. The hydrogen at the anode and the oxygen (oxidizer) at the cathode. In the cell, these two substances are separated by a membrane. Using a catalyst, the hydrogen (H_2) at the anode is split into two H^+ ions (protons) and two electrons (e^-). The electrons then flow through an electrical circuit to the cathode: this is the electrical current that can be used to drive an electric motor, for example. The protons flow through the electrolyte to the cathode. The protons and electrons reunite at the cathode and react with the oxygen (O_2) introduced at the cathode. This creates water (H_2O). Below is an overview of the chemical reactions that take place in a fuel cell:

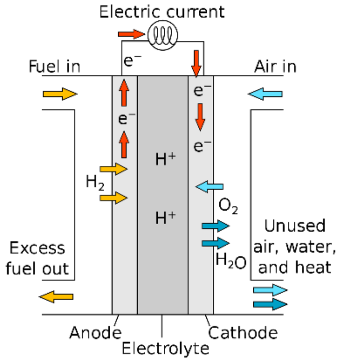


Figure 5 PEMFC schematic drawing

3.4.2 Batteries

In a battery cell, electrons are released at the negative terminal via a chemical reaction, while at the same time electrons are bonded to the positive terminal via another chemical reaction. The resulting potential difference is used to allow a current to flow through a component connected to the battery.

With a rechargeable battery, the chemical processes are reversible: by applying an electrical voltage, an electron flow can be forced in the opposite direction and the chemical reactions will then proceed in the opposite direction: energy is thus stored.

A battery consists of electrochemical cells. The cells may be connected in parallel or series, or a combination thereof. Cells connected in parallel provide the same electrical voltage as a single cell, but can supply a greater electrical current. Cells connected in series deliver a higher voltage, but can deliver the same current as a single cell. Many batteries used in practice, such as the 9-volt battery in consumer electronics and the 12-volt battery in cars, consist of cells connected in series. In both the series connection and the parallel connection, the energy stored in the battery is equal to the sum of the energy stored in the individual cells. A battery whose reacting components can still be supplied during operation is called a fuel cell, see section above.

The voltage at the terminals of a battery, the terminal voltage, depends on the state of charge, the internal resistance and the load of the battery. When loaded, a battery has a lower voltage than unloaded because the supplied current causes a voltage drop across the internal resistance. The internal resistance can change due to discharge and aging of the battery.

Below is a schematic drawing of a Li-ion battery, in figure 6.

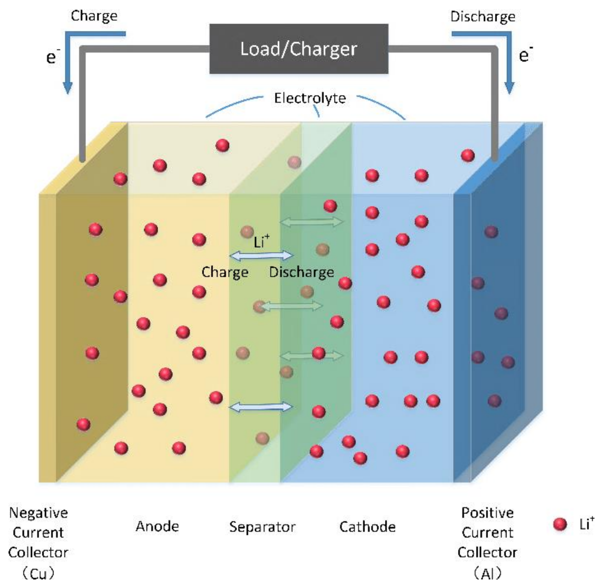


Figure 6 Li-ion battery schematic drawing

3.5 System comparison

This paragraph covers the differences among the two chosen types of systems. This involves looking at the differences outside the system itself, such as bunkering/charging the ship.

3.5.1 Recharging/Bunkering

Recharging Batteries

Inductive charging has some promising prospects, because it offers a better possibility to charge autonomously. Wartsila has developed such a system, with main purpose to charge ferries without the interference of a person. If this system can be adapted for the ALERD, it can also be attractive for other electric vessels near the coast where charging is still an obstruction. It is believed that inductive charging is at the moment the best option to refill the energy stock of the ALERD. Ongoing projects are for example in the port of Rotterdam, which recently got awarded for the innovation. It involves facilities for batteries and green E-fuels such as ammonia and hydrogen. [51]

The possibility to replace empty batteries instead of recharging has also been looked into. This has the convenience that the off-time during mooring can be much smaller. However, this is at the cost of being a complex procedure. Forklifts and electric buses are known for these systems in the transport sector. A large difference in this aspect is that the vehicles of the batteries are fixed in place.

Due to the large weight of the batteries, low placement will be inevitable to ensure good stability of the submarine. It can therefore be assumed that replacing the batteries, while the ALERD is upright, will be very difficult due to the large vertical distance through the ship. In addition, the stability will also be reduced by removing the empty battery. When the battery is removed horizontally, the low location will allow seawater to enter the ship, with all the associated consequences. The only solutions that can be proposed is to put the ALERD upside down or on the side by means of ballast water, in order to be able to change the batteries via the bottom or side. This is however hindered by the telescopic snorkel and communication equipment at the top of the ship. In addition, the batteries still have to go through a double hull, one of which is the pressure hull. It can be concluded that this will not be the best solution, due to the complexity. Moreover, instant battery replacements will be infeasible and a considerable replacement time can be expected, especially in bad weather. Possibly, it can fit for a solution in the future, when all other challenges of the ALERD are solved and an updated version of the ALERD will be build.

Bunkering hydrogen

Hydrogen is one of the hardest types of fuel concerning fuel handling. However, it is still transportable and a high energy flow is feasible, reducing off-time from bunkering.

Given the expected costs that a hydrogen production and bunkering station will cost, it may not be feasible to construct several of these along the coast of the Netherlands. However, it is quite possible to transport hydrogen by means of bunker boats/barges from one or a few locations.

Because Rotterdam is the largest port in the Netherlands, and its location in relation to the Dutch coast is attractive, it only makes sense to place such a station here. Furthermore, locations as Flushing, Ijmuiden, Den Helder and Groningen are sensible as well, due to the large traffic flow of vessels in these areas.

To this end, it must be considered whether the production is done on the coast or in the vicinity of the port on land. This will be the most attractive on the coast for the ALERD and sea-going vessels that will be sailing on hydrogen, but for inland vessels the port is attractive. This is an on-going dilemma, in which engineers in the Netherlands are struggling with. For both options, plans are already on the table.

TNO has the idea to develop a hydrogen production centre on an old oil platform, 10 km from the coast of Den Hague. This project is called posHYdon, and has won the “innovation of the year” award 2019. If this plan succeeds in being allowed to be developed, it could be interesting for both parties to use as a hydrogen supplier for ALERD.

The second plan is the production of hydrogen in ports. Aside from the port of Rotterdam, Den Helder is also willing in the development of such a production plant. Due to the beneficial location of both ports, the ALERD could bunker here, which has a number of advantages. Think of the less required staff, no constant energy consumption of bunker boats, and lower initial development costs. These advantages will limit the preferred choice of bunkering locally. In addition, it is always possible to add bunker locations in a later stadium.

The feasibility of the hybrid powered ALERD is depended on the development of these stations and therefore it should be closely monitored.

[52] [53]

Energy stock refilling comparison

Batteries have greater feasibility to charge autonomously, mainly with the help of an inductive charger, whose are already successfully applied on ferries. Expected is that this is infeasible for the bunkering of fuel, due to safety and environmental concerns.

Bunkering has the advantage over charging due to the mobility of hydrogen storage. Furthermore, the expected time is lower for bunkering in comparison with charging.

The production of hydrogen and electricity near the bunker/charging station is feasible. Because of the large investment costs for hydrogen production plants, it is expected that for some regions bunker ships or trucks are required. This is comparable with charging, where remote charging locations can be required, for optimal operation.

3.5.2 Maintenance

Battery maintenance

Batteries require little maintenance and inspections. However, maintenance and inspections are required for safe operation. As a result, extra space or solutions will have to be taken into account in order to be able to fulfil these activities. In addition, the life of the batteries will be shorter than the life of the ship, which will necessitate replacement. Due to the relatively long recharging times, it is possible to carry out inspections during this time. If this results in maintenance being required, this can be planned or remedied immediately due to the nature of the system.

PEMFC maintenance

Maintenance and inspections are considerably lower than Diesel engines, which makes it suitable for autonomous operation. Maintenance consist of filter replacements, valve checks and repairs, stack replacements and other common activities.

Inspections will be required over the complete system. Sensors have to be checked and calibrated where necessary. Due to the dangers of the fuel and oxygen, this will be an important part that must be performed regularly. This could be done during bunkering or scheduled in a port.

To be able to comply with these activities, sufficient space will have to be kept around the systems and pipes. It is expected that in total, more space will be required for this than with batteries alone

Maintenance comparison

Because both systems require routine inspections and small maintenance, the differences between these systems are considered indefinite. The required maintenance for the dredging equipment are such that inspections and minor maintenance can be carried out during this time.

3.5.3 Cooling

Battery cooling

Due to the high efficiency, there is a low cooling capacity required. However, the temperature range of Li-ion batteries is very important. The optimal operating temperature of the Li-ion battery is between 15 to 35°C, for the longest lifetime and performance. Due to the relatively small temperature difference with seawater, a relatively high flow and cooling surface can be expected to maintain sufficient cooling capacity.

PEMFC cooling

The PEMFC has an advantageous operating temperature of about 80 degrees. This makes demineralized water an excellent agent for removing heat from the fuel cell. Fuel cells operate at a lower efficiency (than batteries), requiring relatively more cooling. Due to the larger temperature difference, more heat can be dissipated for a given flow and cooling surface.

Cooling comparison

Because cooling capacity is proportional to the temperature difference and the surface of the keel coolers, the following relation can be set up for an equal cooling system:

$$A_{PEMFC} = A_{Battery} \frac{\eta_{battery}}{\eta_{PEMFC}} \frac{\Delta T_{battery}}{\Delta T_{PEMFC}} \tag{3.5.1}$$

Where:

A is the surface of the keel coolers

η is the efficiency

ΔT is the logarithmic mean temperature difference between the system and seawater

Using a seawater temperature of 15 degrees Celsius, the mean temperature difference of the heat exchanger for the battery powered ALERD can be calculated with: [54]

$$\Delta T_{mean} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{T_1 - t_2}{T_2 - t_1}} \approx 8{,}4°\text{K} \tag{3.5.2}$$

Where:

T_1 is the energy system inlet cooling water temperature

T_2 is the energy system outlet cooling water temperature

t_1 is the keel cooler inlet cooling water temperature

t_2 is the keel cooler outlet cooling water temperature

And for the fuel cell:

$$\Delta T_{mean} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{T_1 - t_2}{T_2 - t_1}} \approx 34{,}6°K \tag{3.5.3}$$

Which is a comparable result of a diesel engine cooling system.

By substituting 3.71:

$$A_{PEMFC} \approx 0{,}36\ A_{Battery} \tag{3.5.4}$$

The problem of battery cooling has been made with a small calculation. A result that is not immediately clear at first sight. In combination with the cooling problems found in the problem analysis, this could be a serious design consideration.

3.5.4 Energy to power distribution

Battery energy to power

A battery has the capabilities to directly transform energy to electrical power. After the batteries power conversion will be required to deliver the right voltage for the switchboard. Recently, a Direct Current (DC) grid has been used for this, because many electronic users and the power supply are DC. As a result, fewer conversions are needed and the entire efficiency can be increased.

PEMFC energy to power

Due to cathode poisoning and salinity erosion, and the obstruction and structural challenges of a snorkel reaching water depths of 30+ metres, it is believed that both fuel and oxygen will be fed from storage tanks. [43]

Liquid oxygen has to date the best storage characteristics with respect to energy density and bunkering time. However, due to the insulation of the tanks and the large power requirement to liquify the hydrogen, it is not the most common method of hydrogen storage. Hydrogen storage in metal hydrides are still under development, and therefore is compressed hydrogen storage, as in most applications, the starting point. Compressed hydrogen can be stored to date in tanks of up to 700 bar. The higher the pressure, the higher the storage density. A counter argument of increasing the storage pressure is that the tanks are more expensive and that the compression losses become larger. Research can determine if the these high pressures are required, or that a more common solution, the 300 bar hydrogen tank is feasible. [54]

Oxygen is best stored in liquid form, which is the standard in submarine applications. The use of oxygen also increases fuel cell efficiency. As a result, the extra space of the oxygen tanks is moderated by a decrease in hydrogen tank volume. At last, the reaction product water must be remove. This is done in a submarine by means of storage tanks, which maintain the neutral buoyancy.

The fuel and Oxygen systems of the fuel cell primarily consists of regulator valves. There will be a humidifier system required for good operation, where the required water can be retrieved from the exhaust products. The fuel cell requires control valves to deliver sufficient hydrogen and oxygen, as requested by the power management system. This works passively, which can cause stability problems in the control system. Partly for this reason, it is recommended to equip a fuel cell as a hybrid.

The fuel cell delivers power, which requires conversions to deliver the right voltage for the switchboard. This is similar to the battery power conversion.

Energy to power comparison

The battery system requires a significant smaller stored energy to power distribution system. in fact, the starting point of the battery is in the same place in the system as the fuel cell. Everything before this, the most complex and custom made for the ALERD, is only needed for the fuel cell. Here the components are available off the shelf, and they only have to be installed.

3.5.5 Redundancy and safety

Battery redundancy and safety

Redundancy of the supply system is majorly determined by the control system. This will have to be designed in a way so that individual or clustered cell breakdowns does not affect the entire system. In addition, the packages will have to be placed in separate rooms, so that in case of calamities in one room, enough energy remains to get to a safe location and to keep emergency systems in use. Due to the operating range between 30 and 80%, to increase battery life, it is believed that redundancy should not be an issue. This is why there will always be a minimum of 30% state of charge in the battery, which can be used during emergencies.

Safety is more of a concern for the Li-ion batteries, which largely comes from fire and or explosion. The risks can be minimized, partly through good cooling and inspections. When a fire occurs, Li-ion batteries are best extinguished with foam. Every room where the batteries are located will have to be equipped with such an installation.

A secondary risk, is the risk of poisoning. Li-ion batteries can emit poisonous gasses and for this, protective equipment and knowledge will be required from the maintenance and inspection technicians. In addition, sensors can help detect leaking cells, which then need to be replaced with the necessary safety equipment.

[54]

PEMFC redundancy and safety

Equal to batteries, fuel cells are redundant by itself because they can operate with broken cells. However, leakages and calamities must be taken into account here. When a leakage occurs, it must be possible to seal parts of the system without shutting off all energy supplies. The hybrid batteries can help with this as emergency backup. This can be solved by placing the fuel, fuel system and fuel cells in multiple rooms. In contradiction to the batteries, when an emergency occurs, it is possible that 0% energy is left in the form of hydrogen. To avoid running dry when an emergency occurs, additional hydrogen should be carried on board. With a hybrid system using batteries, it is possible to use the energy from this system, reducing additional hydrogen for this purpose.

Hydrogen carries a great risk on board due to its explosiveness and flammability. In addition, pure oxygen has the property that it will react with almost everything. For this reason, it must be prevented that these gases can be released, and if this does happen, it is immediately detected. In addition, this must also apply in the event of an accident or fire. These problems also apply to other purposes, such as cars where this also works without any problems. It can be assumed that such calamities are of a greater nature.

Redundancy and safety comparison

Both systems are redundant and carry considerable risks in the form of fire and explosion. It is expected that the risks are larger with batteries, because inspections are harder to carry out. When a fire occurs in the Li-ion battery, it is almost impossible to extinguish the fire.

However, when a calamity occurs, the effects of a hydrogen explosion is more disastrous because it can happen more instantly with no way to counter it. Moreover, it could form an enormous risk while it occurs in the port.

3.5.6 Energy source and sustainability

The only emissions for both system depend on the energy source. The PEMFC uses hydrogen and the battery uses electricity as energy source.

Electricity

Green electricity is already in an advanced stadium and multiple solutions are currently available. In the Netherlands the most common solutions are the wind turbine and solar panels.

In order to actually use "green power" for the ALERD, investments will have to be made in order to generate this. In the Netherlands this will therefore be wind turbines and/or solar panels.

Hydrogen

Hydrogen is the most abundant element in the universe. Under normal circumstances it is gaseous and we speak of hydrogen gas. Hydrogen is also the lightest gas we know, but it has a high energy density of 120 MJ per kg. That is almost three times as much as natural gas (45 MJ per kg). Due to the low density of 20 kg/m3 at 300 bar, hydrogen has a volumetric energy density of 2,4 MJ per litre. This is almost ten times lower than liquified natural gas.

Aside from liquifying hydrogen, pressurizing (compressing) hydrogen gas also costs the necessary energy (about 10% of the lower heating value from production to tanks). In comparison, this costs more than three times less energy than liquifying hydrogen. [55]

Grey and blue hydrogen

Virtually all hydrogen that is currently produced worldwide is so-called 'grey hydrogen'. Production is currently done via Steam Methane Reforming (SMR). Here, high-pressure steam (H_2O) reacts with natural gas (CH_4), resulting in hydrogen (H_2) and the greenhouse gas CO_2. In the Netherlands, approximately one million tons of hydrogen is produced in this way, for which four billion cubic meters of natural gas is used and results in CO_2 emissions of 12.5 million tons. [55]

One speaks of 'blue hydrogen' or 'low carbon hydrogen' if the CO_2 released in the process of grey hydrogen is largely (80 to 90%) captured and stored. This is also known as CCS: Carbon Capture & Storage. That could happen in depleted gas fields under the North Sea. At present, nowhere in the world is blue hydrogen produced on a large scale. Grey and blue hydrogen are because of the production process less pure, which could cause poisoning for example in the PEMFC fuel cell. To overcome this, purification is required. [55]

Green hydrogen

Green hydrogen, also called 'renewable hydrogen', is hydrogen produced with sustainable energy. The best known is electrolysis, in which water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) via green electricity. A large number of parties in the Netherlands are experimenting with these electrolysers on a megawatt scale. Hydrogen is also released during high-temperature gasification of biomass. [55]

Turquoise hydrogen

TNO is working on technological breakthroughs for scaling up in the Faraday laboratory

Hydrogen produced from natural gas via the so-called molten metal pyrolysis technology is called 'turquoise hydrogen' or 'low carbon hydrogen'. Natural gas is passed through a molten metal, releasing both hydrogen gas and solid carbon. The latter can find a useful application in, for example, car tires. This technology is still in the laboratory and it will take at least ten years before the first pilot plant is realised. [55]

Energy source comparison

Blue and green hydrogen is at the moment the most feasible option. Blue hydrogen does not contribute to the greenhouse effect when CO_2 is captured, and only a small portion of CO_2 is released in the air at current state of technology. Because it uses methane fuel, it can be said that the use of blue hydrogen has a negative emission as the methane will not be burned or worse released in the air. However, the use of methane is not sustainable, and this would make the implementation of green hydrogen as fast as possible. Green hydrogen is the purest and can be used immediately into a fuel cell.

Green electricity will always be better than green hydrogen because of the efficiency of hydrogen production. However, because of supply and demand hydrogen could have a more efficient overall picture. The storage of hydrogen is easier than the storage of electrical energy. For the fuel cell the efficiency can be improved at constant operation of approximately 60%. Another benefit from this is that it would allow degradation of the cells. Batteries operate in general at a much higher efficiency, and at a more constant level. [28]

3.6 Decision making

Because the systems have each have their own good and bad characteristics, there will be no unambiguous best solution. This is why a choice has to be made and values given to certain characteristics. Some distinctive choice making tools are the house of quality/ the quality function deployment and the decision matrix.

3.6.1 House of quality

QFD (Quality Function Deployment) is a method for translating customer wishes and market demands into design requirements. The method ensures that an organization concentrates on the customer's wishes. The result of this method is a data matrix. This data matrix is also called the house of quality. The representation of the quality house (image) is very diverse. What matches is that it resembles a house. Usually the matrix contains the fields indicated in the figure.

3.6.2 Decision matrix

The decision matrix is characterized by providing visual insight into the factors and the alternative choices. The horizontal rows show the possible options and the vertical columns show the different factors. Weightings are applied to these factors; the most decisive factor for the organization gets the highest score. It can be determined in advance that 1 is considered least important and increases in gradation to 5, which is seen as very important.

In the end, the option with the highest ranking is the best solution for the project.

3.6.3 Risk analysis

Threats are often detected in time and adequately anticipated, but sometimes organizations suffer significant losses due to poor risk management, of which risk analysis is a part. Risk analysis helps organizations to identify the threats, after which appropriate measures can be taken. One method to identify threats is the SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. This analysis identifies vulnerabilities, weaknesses and threats. It must then be determined how great the risk is that the threat will become a reality and what consequences this has for the business processes. Then it must be considered whether the costs of the measures outweigh the costs of the incident or consequence. Forms of risk analysis In general, a distinction is made between two types of risk analysis: In a quantitative risk analysis, the financial risks of a threat are calculated, based on theoretical models. In a quantitative risk analysis, the risks are always expressed in measurable criteria. Often it is the computer that simulates the risks in such a way. For example, quantitative risk analysis is used by investors who want to justify an investment by demonstrating the relationship between risk and return. In qualitative risk analyses, estimates are made of the risks incurred. Qualitative risk analyses often start from possible scenarios, after which a 'worst case' and 'best case' scenario often arise. Among other things, it provides a better insight into the behaviour and culture of the people in an organization. Qualitative risk assessments are more common in small businesses. The threat is often estimated by using rules of thumb or by gut feelings. [56]

3.6.4 Decision based on costs

This method is probably the most common way to make a choice, both consciously and unconsciously.

The ALERD project feasibility depends on cost, this is an overarching way to determine the best choice. Assuming that the variable environmental impact is constant, the 'cheapest' solution will be a good indication of the best solution. A variable to be determined that must be kept in mind is the practical implementation of the system. This means that relatively no more problems should arise in the operation of the ship. Think of regular overhauls which is difficult to perform due to the small dimensions within the ship. Furthermore, the energy stock refilling is an important factor in the operation of the vessel.

A side not to this method is that this method requires adjustments to take into account customer requirements, ethical aspects and practical considerations. This can be in the model as well as in a post-assessment. Costs can also be given for, for example, CO_2 emissions and safety. This is also known as the ethical movement "Utilitarianism". As a result, the costs and benefits are weighed against each other using an overarching method. Here it is difficult and debatable how much value can be given to each element. [57]

3.7 Research gap

There is no unambiguous answer as to which system is the best, or whether it is a hybrid system. Research must be carried out which system suits de ALERD and requirements the most. With the help of a simulation, the energetic requirements can be determined. To create the model, the design data of the AUMD and the characteristics of the systems can be used. It still has to be determined what kind of simulation this will be and how it will be made. Based on the data obtained, systems could be excluded, or other options could become possible. When costs are linked to the results, the best system could also emerge. From the literature study, the battery and fuel cell would be the first to be considered for this, because they meet the requirements from the problem analysis. In addition, these are the most common state-of-the-art systems that are successfully applied in the transport sector. It is therefore wise to first determine the results of these systems and simulations, before a lot of time is spent on all other options that have not yet been successful. An alternative is the direct ammonia SOFC, which is a much-discussed energy converter. It is therefore also interesting to see how the systems weigh up against this benchmark.

When the data and optimal operating points are determined, the requirements can be simulated. This consists of the data such as stored energy, powers, volume/weight, number of required ships and cooling requirement.

4 Research plan and method

Research plan and method to achieve the research goal

4.1 Introduction

This chapter describes the plan of action of approach to the development of the sustainable electrical energy supply of the ALERD.

In chapter 2 the challenges of the research, with some conventional and state-of-the-art solutions were given. In chapter 3, the promising energy systems were reviewed. Together, they form the foundation of the research; the data and guiding routes towards the optimal solution.

In the following paragraphs in this chapter, the research outline, research questions and methodology are given.

4.2 Research outline

The research consists of three main steps. Below, these steps are elaborated:

1. Create a simulation model for the AUMD

The information of the energetic characteristics of the ALERD is not yet fully known, therefore it still has to be determined by research. The proposed method is a simulation model, using the data from the AUMD. The initial design of the AUMD uses batteries, and therefore this will also be the starting point here.

In first instance, the model uses the data from the AUMD to develop an operational profile which can be used as a benchmark and validity test. The model requires distances to simulate the replenishment among the Dutch coast. This includes the locations of the mooring/charging station. A wish from C-Job is to determine if these locations are possible near the dredging location instead of a port, to minimize energy loss due to transits.

To generate useful information, equations will be implemented to estimate volume, weight, cost and energetic data. Furthermore, the cost and size estimations are an important factor to determine the best system for the ALERD.

The simulation model for the AUMD is discussed in chapter 5 of the report.

2. Adapt the model to the ALERD and optimize the variables

In this part of the research, the above mentioned model is updated to comply with the ALERD. This includes an adaptation to the different dredging characteristics (soil and depth), together with a study towards the best hopper volume, operational profile, transit speed and dredging flow. A variable study is required to relate the input data towards the electric load balance, dredging capacity and energetic data. Implementing the variable dependences in the model, together with the cost calculation, gives the ability to optimize the results.

Aside from the optimization, the hybrid PEMFC-Battery system will be implemented in the model as well. This requires a power management, which requires additional attention.

The adaptation of the simulation model to the ALERD is discussed in chapter 6 of the report.

3. Effects of varying input data

The simulation model is non-dynamic, meaning that simulation uses time independent input values. In reality, these values are dependent on time with primarily costs and transit distances as major concerns on the outcome. To simulate these varying data, multiple methods can be used. For the cost development, the simulation data can be used directly. The simulation can be connected consecutively with a cost adjustment for the corresponding date. This includes the replacements of the systems and energy costs.

The changing transit distances require a different approach. Because only one set of distances is used in the profile, multiple simulations are required. By combining the results of the simulations, an estimation is generated of the varying distances. To validate if the stored energy found in step two are the optima with alternating distances, the simulations are executed with varying stored energy as well.

The effects of variable input data is discussed in chapter 7 of the report.

The data from the research are used to develop the design data of the systems, which are required for the development of a sustainable electrical energy supply for the ALERD. The research questions, corresponding by the research goal, are given in the following section.

4.3 Research questions

From the literature review, research gap and research plan, the following research questions are established. For each research question 3-6 sub questions are given to steer the direction and focus in each part/step of the research. Each question matches a chapter of the research.

1. What are the energetic and economical simulation results of the AUMD?
   1.1 What are the input data?
   1.2 What does the operational profile look like?
   1.3 What are the involved transit distances?
   1.4 What is the corresponding dredging/replenishment capacity?
   1.5 How does it compare to a conventional dredger?
   1.6 What could be done to improve the results?

2. What are the optimized simulation results for the ALERD, among different hopper capacities?
   2.1 How do the variables affect the input data?
   2.2 How do the input variables influence the electric load balance for the ALERD?
   2.3 What are the optima of the input variables?
   2.4 How do future developments influence the outcome?
   2.5 What are the differences in operating costs?

3. What are the effects of the varying input data?
   3.1 What are the effects of cost development?
   3.2 How does the SOFC compare to the other systems?
   3.3 What are the effects of variable transit distances?
   3.4 How well does the static simulation approach the variable input data?

4. What are the design data of the best energy supply system(s) for the ALERD?
   4.1 What are the energetic data of the system(s)?
   4.2 What are the weight and volume of the system(s)?
   4.3 How can sufficient cooling capacity be acquired?

This answers the main research question:

Which sustainable system has the best capabilities to supply the ALERD with electrical energy, and what are the design data?

4.4 Methodology

The thesis uses quantitative research to determine the results. Quantitative research is applied in the operational profile calculations and simulations. Furthermore, it is applied in the result processing. For the operational profile simulation and cost determination, database research, report analysis and number analysis was required.

Literature was acquired from Elsevier, Science Direct and other technical sources. Numerical values were checked on consistency along different reports. The database of the MARIN was a guideline for testing or including values. During the research, some state-of-the-art developments had just been released. These developments have been included by the use of news articles and webinars.

After the literature research, the research started on April 1^{st} , 2021. The first step was the generation of a working simulation model in Simulink. The simulations in Simulink were troublesome, time consuming and inconsistent. Therefore, the simulation model was recreated in excel, which solved the problems. Many simulations have been made to optimize the parameters and to implement several cases. In addition, the model was used to simulate the variable data. At last, the same model was also used to calculate all data from the systems. The research ended on September 1^{st} , 2021.

The SPEC tool, which has been made available by the MARIN, showed problems too. The tool was just released and still having issues. In addition, it was not possible to enter a submarine, because the tool makes a resistance calculation for surface ships. The program was used to check afterwards whether the correct choices were made in systems. Ultimately, the SPEC tool and the research uses the same database for most of the system characteristics and therefore it is likely that they generate similar results.

The research consists of three parts: Create a working model, optimize the model, and adapt the model to varying input data. This method is chosen because a static model was created, and to simulate a true situation. This is change from the initial research plan, because Simulink would be used. In order to be able to include the advantages of Simulink (dynamic computations), several simulations are made on different static values. Together, this is an approximation of a dynamic process, similar to a Riemann integration versus an integral calculus in mathematics. A side note here is that it is not possible to make an infinitely long simulation in Simulink and the results are therefore also based on samples. As a result, the outcomes in excel are equivalent, but it is achieved with more steps using the chosen method. A disadvantage of this method is that many results and simulations are necessary to get a valid outcome. With a single update of input values, all results are invalid and all simulations must run again for the correct result. Unlike Simulink, these simulations must be performed manually, and cannot be done in the background.

The model was able to generate all required results, given in the research. Because so much data can be extracted from the simulation, it has also been used for other purposes. The model was used, for example, as a substantiation of the financial feasibility and the estimated costs.

When a working model was acquired, the power and time calculations were implemented. A lot of work was required to optimize the model and to increase the accuracy of the results. This involved in depth study of values and comparisons with reference values. The increase of accuracy and data gave the opportunity to make a cost estimation, including the TCO comparison with a conventional ship. By adding the future cost estimation of the system components and fuels, an accurate TCO estimation was created as a final result in the simulation research. Together, the optimized results include the design data of the energy system.

In the following three chapters, the simulation model, the optimization and the adaptation to dynamic scenarios will be explained. These chapters will be followed by the results; the design data.

5 AUMD simulation

Creating and running the simulation model for the AUMD

5.1 Introduction

This chapter focusses on answering the research question:

"What are the energetic and economical simulation results of the AUMD?"

In doing so, a simulation model is created which will be described in this chapter. In first instance, the data from the AUMD are applied to create a working model. As a reminder, the AUMD (Autonomous Underwater Maintenance Dredger) is an equivalent variant of the ALERD (Autonomous Low Energy Replenishment Dredger), but designed for maintenance of waterways in ports, while the ALERD is meant for coastal maintenance. Furthermore, the operational profile and corresponding dredging capacity is determined here as well. The chapter ends with the cost calculation from the simulation model, which will be used as a benchmark for the optimization and adaptation to the ALERD. Furthermore, the energetic data from the simulation can be used as a validity test of the model. The optimization and adaptation of the model to the ALERD will be discussed in chapter 6.

This chapter focusses on retrieving data for the AUMD, which includes an Li-ion energy supply system. The proposed model in paragraph 5.3 is largely used for the ALERD as well, therefore a combination of terms is used there. Research has been carried out on the operational profile and electric load balance of the AUMD. The operational profile and electric load balance of the ships are based on the existing dredgers, adjusted to the characteristics of the AUMD. The data of this study by C-Job and the MARIN forms the basis of this research, and will be described in the following paragraph.

5.2 AUMD data

The operational profile has been based on comparable dredgers in size,. The operational profile of the dredger is performed in 12 hours per day. However, this does not have to be a precondition for the design, because there is no need to take daylight and working hours into account. From the energetic study of the AUMD, an energy consumption of per operation day/energy cycle was observed. In the estimated time-span hours, this resulted in an average power demand of. [1]

In the figure below is an example of the operational profile, as estimated by Rolph Hijdra. The figure is used to determine the energy requirement per cycle, and comparable results should be found from the simulation model. The data from the study can be found in figure 7 and table 5. [1]

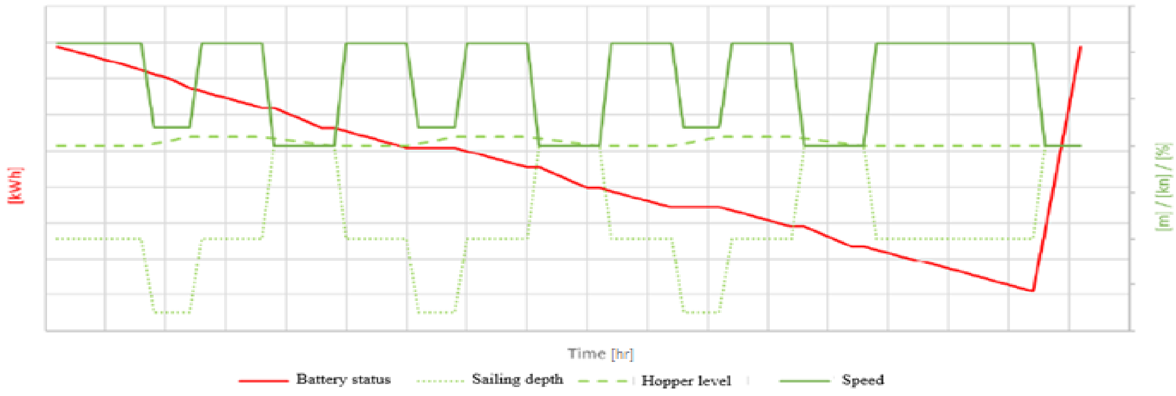


Figure 7 Operational profile [1]

With the corresponding electric load balance:

Electric Load Balance				Transit		Dredging		Unloading bottom doors		Unloading shore press	
Systems	#	Installed electric power (kW)		# in service	Average absorbed power (kW)	# in service	Average absorbed power (kW)	# in service	Average absorbed power (kW)	# in service	Average absorbed power (kW)
Propulsion Systems											
Azimuth motor											
Tunnel thruster motor											
Propulsion support											
Sea water cooling pumps											
Lube oil pumps											
Dredging Systems											
Main Dredge pump											
Jetwater pump											
Jetpump draghead											
Digital valves											
Bottom doors											
Ballast system											
Snorkle											
Trim pumps											
Navigation Systems											
Sensors											
Computers											
Coolers											
Total power (kW)											

Table 5 Electric load balance of the AUMD [1]

The electric load balance is calculated for a transit speed of 11 knots and a pump flow of 3,23 cubic metres per second, which will be used in the simulation as well. [1]

5.3 Operational profile (AUMD & ALERD)

With the known power demand and design data from the AUMD, the only variables left are the operational profile of the dredger and the corresponding replenishment capacity.

To determine the operational profile, dredging capacity and energetic requirements of the AUMD/ALERD, a simulation model in Excel has been created. This program has been chosen because a non-dynamic, input-output model gives instant results and it can be optimized by means of the built-in solver function. A disadvantage of a non-dynamic system is that it is not physical and consequently, a larger margin of error has to be taken into account. Because calculations are made with average values, the accuracy of the energy determination will suffice. However, a margin should be taken into account by dealing with peak powers, which mainly affects the sizing of the systems.

A distinction is made whether the ship is refilling the energy stock in the port or locally (near the dredging location). This is a wish of the client, to determine if local charging is desirable. These locations are referred to as “mooring stations”. The simulation starts at the mooring station with the initial condition of the energy state equal to the energy state when the simulation ends by arrival at the mooring station. When the ship has entered the mooring station, it leaves when the energy state is 100%.

A dredger has characteristically only a few activities. The AUMD/ALERD will have the capability to unload the dredge through the bottom doors (dumping/foreshore replenishment) or to pump the hopper content to the coast (discharge/coastal replenishment). In combination with the dredging operation and recharging, it is possible to base the operational profile on three principles. These principles are as follows:

Current activity	Next activity (option 1)	Next activity (option 2)
Mooring (charging)	Dredging	
Dredging	Dumping	Discharge
Dumping/Discharge	Dredging	Mooring (charging)

Table 6 Operational profile

Dumping or discharge is determined by a predetermined plan and dredging or mooring is determined by the energy state of the system. The assumption has been made that for each energy cycle, alternately, the hopper content will either be dumped through the bottom doors or discharged towards the coastline. This means that from 50% of the energy cycles the hopper content will be dumped, and that from 50% of the energy cycles it will be discharged. It is indefinite when these operations are performed, because it is related to the dredging project. For example, it can be executed alternately, day and night, 50% per month, or even per year. This will be dependent on the current project and can be adjusted accordingly.

The calculated autonomy consists of two energy cycles, because this covers all activities. The calculations from the autonomy of two cycles are extrapolated up to the desired operating time. This does not take off-time into account, due to maintenance or other circumstances. However, with conversion rates, this can be simulated to retrieve the correct results.

When there is sufficient energy available after a dredging cycle, it will repeat the dredging process. Otherwise, the AUMD/ALERD will return to the mooring station, to refill the energy stock. Due to this assumption, an optimal profile can be obtained from any given stored energy and it is therefore impossible to run out of energy as well. This method gives the possibility to optimize the results, as calculated later in chapter 6. By means of the minimum state of charge (SoC) in the used profile, the simulation gives the required energy for the AUMD. This value, as calculated by an iteration, is used as the required battery capacity for further calculations.

By using both discharge and dumping in the simulation, the ship can be optimized for both activities. Each time the dredger has accomplished the dumping/discharge activity, the moved dredge in cubic metres is noted and added to the total. The calculation includes the losses due to maintenance time, hopper density and a margin, which will be elaborated in paragraph 5.4: *model assumption*.

The replenished dredge in volume, or the productivity of the dredger, is calculated using to the following equation:

$$Replenished\ dredge = n_{dredging}\frac{t_{simulation}}{t_{2\ energy\ cycles}}Vol\%_{hopper} \tag{5.3.1}$$

Where:

$n_{dredging}$	is the amount of dredging cycles during the 2 energy cycles
$t_{simulation}$	is the total simulation time, for example the operational lifetime of the ship
$t_{2\ energy\ cycles}$	is the required time for 1 dumping and 1 discharge energy cycle
$Vol\%_{hopper}$	is the volumetric sand content in the hopper of 90%, as found in the literature [58] [60]

Based on the two determined activities, a sailing distance is determined and executed. The distances are determined with the use of a chart of and information about locations of ports and wind farms:

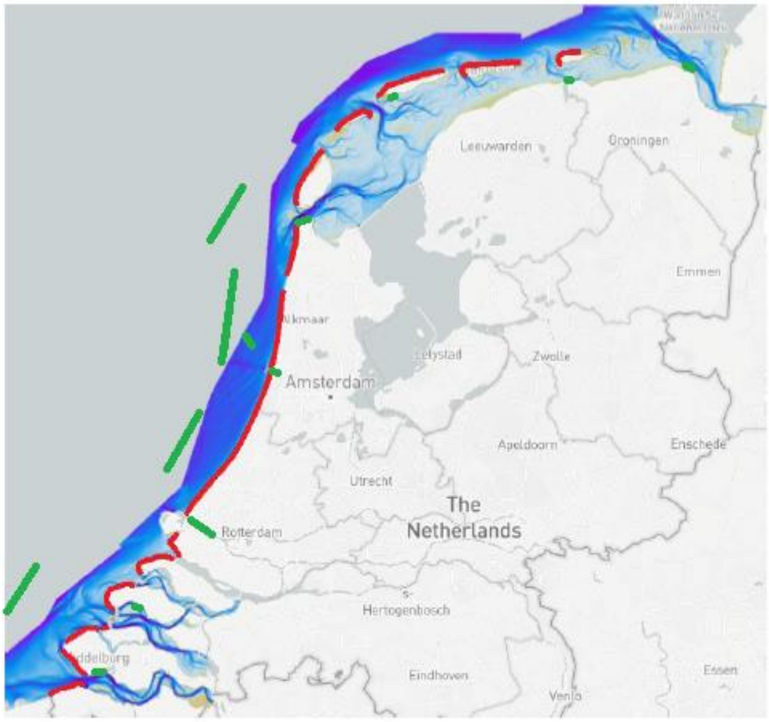


Figure 11 Sedimentation regions (red) and Existing windfarms and ports (green) [59]

The red area is the coast of the Netherlands, where replenishment is required. The green areas represent charging areas, such as wind farms and ports. Wind farms are chosen because of the direct availability of green electricity. In addition, the green areas could also be used as bunkering locations (for the ALERD, using fuel cells), when a bunker ship for green fuel is used. In the ports there are various options for charging/bunkering. The approach to the port can also be used as a charging and bunkering location. This is an interesting option, because it can be used for merchant shipping and it saves on sailing distance.

The combination of wind farms and shore/port approach are considered as Local Charging (LC). When the energy stock is refilled in the port, it will be referred as Port Charging (PC).

Concluding from the study, the following distances have been represented in the operational profile:

Transit	Distance with local refilling	Distance with port refilling
Mooring ←→ Dredging	20 km	50 km
Dredging ←→ Dumping	15 km	15 km
Dredging ←→ Discharge	20 km	20 km
Dumping ←→ Mooring	20 km	50 km
Discharge ←→ Mooring	25 km	55 km

Table 7 autonomy

The assumed distances are chosen as upper limit to assure validity and reliability over all standard transit distances in the profile. For example, it is undesirable that it regularly occurs that the ALERD can dredge inefficiently (with less dredging cycles) because of longer sailing distances.

The assumptions, required to run the simulation and retrieve results, are given in the upcoming paragraphs.

5.4 Model assumptions

This chapter uses the main assumption that the data are retrieved for the AUMD, if it would be applied for coastal maintenance. This consists of the characteristics of the AUMD, including an Li-ion energy supply system and the electric load balance, from table 5. This has the advantage that it is a validation for the model, when similarities in the results can be found. Furthermore, it enables to visualize the effects of the optimization, as discussed in chapter 6. It is expected that the dredging power is underestimated, because the densities are different from inland waters.

It is assumed in this part of the research to run the simulation on port charging and a combined discharge and dumping profile. The following paragraphs contains the assumptions, which had to be made to retrieve results.

5.4.1 Simulation assumptions

- A soil density of 1,9 t/m³ as retrieved from the literature [59] [60]
- A hopper density, which is the average density of the sand-water mixture within the hopper, of 1,7 t/m³ as retrieved from the literature and corresponding with the 90% sand volume in the hopper. [58][60]
- A maximal hopper content of 4458 tons, which is equal to the design hopper content of the AUMD (at a hopper density of 1,3 t/m³).[1] [1]
- A pumpable sand-water mixture density for dredging and discharging of 1,45 t/m³, as found in the literature. [58] [60]
- A hopper loss of 20%, which is the loss from pumping through the hopper (overflow losses) to increase the sand content in the hopper, as found in the literature [58][59][60]
- For equality with the studies of the AUMD, an operational profile of three times dredging per energy cycle, with port charging.
- Batteries operate at 30-80% SoC, for improved lifetime and decreased charging time.
- Batteries can operate for 6000 cycles or 8,5 years, whichever is less, as found in the literature. [61]

[1] This is an assumption which have been made at the request of Rolph Hijdra. The assumption has the additional benefit that the dredging time is reduced, equalizing the required energy for dredging.

- Batteries charge at 85% efficiency and deliver energy at 90% efficiency[2], as found in the literature [62]
- An operational time of 25 years, which is a common expected lifetime of ships.
- A mooring time of 1 hour. A maximum charging power of 5 MW, or a minimum of 2 hours charging. The data are retrieved from the commercially available induction charger of Wärtsilä. [41]
- Maintenance costs 10% of productivity[3]
- An additional 20% loss of productivity due to unforeseen circumstances[4]

Because the simulation is non-dynamic, constant values are used in the assumptions. These values are averages to retrieve the mean results for the operations.

The operation windows of the systems are chosen such that the lifetime and maintenance free window can be increased to a maximum. In this way the capacity of the batteries can be maximized and the redundancy is increased.

The productivity (off time) assumptions affects the number of required ships for the project. To be sure that the fleet has the required capacity, the values have been estimated conservatively. It is possible that within the first years, relatively more problems persist and that they decrease as time goes on. It is not realistic to design the ALERD for this, as this will result in overcapacity as the lifespan progresses. In addition, it is not likely that all ships will be put into operation at the same time, because this will be an implementation process. This provides the opportunity to phase out the conventional ships, which will help to overcome the problems of the first ALERDs.

5.4.2 Time assumptions

For the operational profile, time determinations were required that goes as follows:

$$t_{mooring\&charging} = t_{mooring} + \max\left(\frac{E_{cycle}}{P_{charging_{max}}}; t_{loading_{min}}\right)[hr] \quad (5.4.1)$$

With:

$$P_{charging_{max}} = 5MW$$

$$t_{charging_{min}} = 2hr$$

$$t_{mooring} = 1hr$$

And:

$$t_{transit} = \frac{X_{transit}}{v_{input}} \quad (5.4.2)$$

$$t_{dredging} = \frac{V_{hopper}}{Q_{filling}} \quad (5.4.3)$$

Where:

[2] A constant efficiency is not true. However, because it is an energy calculation, an average efficiency, together with a low power rating it is considered as a sufficient assumption.

[3] 10% is a conservative assumption, because it is expected that most maintenance/inspections can be done during the charging time.

[4] An assumption which involves off-time due to extreme weather, system malfunctions and other unexpected problems.

$$Q_{filling} = Q_{dredging} \frac{Vol\%_{mixture}}{Vol\%_{hopper}} (1 - hopper\ loss) \tag{5.4.4}$$

$Q_{filling}$, the filling flow of the hopper, uses the assumed volumetric mixture concentration of 35%: 35% sand and 65% seawater, or a mass mixture concentration of 50%. [60] [63]

And:

$$t_{dumping} = 600s$$

$$t_{discharge} = 150\% t_{dredging} \tag{5.4.5}$$

Where:

150% is the assumed relation, made in collaboration with Rolph Hijdra, of:

$$\frac{t_{discharge}}{t_{dredging}} = \frac{Q_{dredging}}{Q_{discharge}}$$

5.4.3 Cost assumptions

The choice has been made to select the system based on costs. The reason for this is that it covers multiple aspects of design choices. A side note to this is that additional assumptions had to be made with respect to the cost estimate, these are:

- Complete Li-ion NMC battery electrical energy storage costs are €600 per kWh, as found in the literature [64]
- Green electricity production costs are €0,05 per kWh, as found in the literature [65]
- Dredging equipment maintenance costs are annually, as found in the literature: [66]

$$0{,}055(ship_{cost} - energy\ system_{cost}) \tag{5.4.6}$$

- Annual insurance costs are, as found in the literature: [66]

$$0{,}025 ship_{cost} \tag{5.4.7}$$

- Series ship production costs follow the 90% series curve, as found in the literature: [67][5]

$$0{,}999 n_{fleet}^{-0{,}152} \tag{5.4.8}$$

- Fuel costs in Rotterdam (conventional ship, MDO) are currently €450 per ton, as retrieved from ship and bunker [68]

With the following data retrieved from the economic feasibility study of the AUMD: [1]

$$CAPEX_{hull_{design}} = \text{Million}$$

$$CAPEX_{propulsion_{design}} = \text{Million}$$

$$CAPEX_{Dredging_{design}} = \text{ Million}$$

$$CAPEX_{Auxiliary_{design}} = \ Million$$

[5] The 90% series curve is chosen because it is expected that there is a steep learning curve and that the ratio of custom-made, high technology parts is large. Expected is that the costs per series build decreases at a high rate.

And using following input and simulation data:

$OPEX$ is the summation of energy costs, insurance and maintenance

$building\ costs = 20\%$ of the material costs [69]

Many assumptions are not required to be able to choose the best system, but are necessary to apply a value to it and to be able to relate. In addition, this gives the option to test against the requirements and to draw a comparison with a conventional ship. Furthermore, this also gives the result of whether the system is economically feasible. If not, other options should be taken into consideration and the requirement of sustainability should reconsidered.

By applying the assumptions in the model, the results were calculated as described in the next paragraph.

5.5 Simulation results AUMD

According to the yearly dredging volume of 12 million cubic metres and port charging, 3,4 AUMDs are required. Figures are in this stage not rounded (to 4), because it could give an unfair comparison of the systems, profile and ship types. For example, the differences between a project that requires 3 or 3,1 ships is small, however due to rounding (to 4) the differences rise with 30% for a given yearly replenishment. In order to be able to solve this problem, matching of ship sizes with the project will be discussed at a later stage in this report.

When the AUMD is used for coastal maintenance, it requires MWh to be able to carry out the operational profile. Due to the operation range and efficiencies, this accumulates to a battery capacity of MWh.

The TCO is created towards the expected lifespan of the AUMD/ALERD; 25 years. The TCO follows the following equation:

$$TCO = CAPEX + OPEX * t \qquad (5.4.9)$$

Where the OPEX consists of the electricity costs, maintenance and insurance as stated in the assumptions. The OPEX is incomplete. However, the largest operational costs are included to enable a comparison with a conventional dredger.

It was chosen to not include depreciation, as the total initial investment is made in year zero. Furthermore, the residual end of life costs are excluded. The cost calculation includes only the expenses for operating the ship as mentioned in the assumptions, which does not include shore personnel and licenses.

The calculations use the assumption that the AUMD is Port charging, because there is no information which investment is required to facilitate charging stations at sea. Moreover, the local stations can be used for other purposes, so that they could generate income. This makes it difficult to estimate the required initial investment and TCO of the stations, which comes on top of the ships themselves.

The conventional dredger uses the assumption that the cost per ship is €30 Million, and using the simulation tool, a calculated 1,72 ships are required for an equal size ship. This implies some concerns, because twice as many ALERDs are required, compared to conventional dredgers at equal hopper size. According to the model, each dredger has a diesel consumption of approximately 3000 ton per year. [70] [71]

The TCO of the conventional dredger is estimated using the dredging tool and combining the data with the dredger cost prediction from Wowtschuk and the current MDO price. [71] [66] [88] [70]

The TCO is calculated by running the simulation in steps of 0,2 years. Whenever a battery replacement is required, this added to the total. The simulation results in the following comparison:

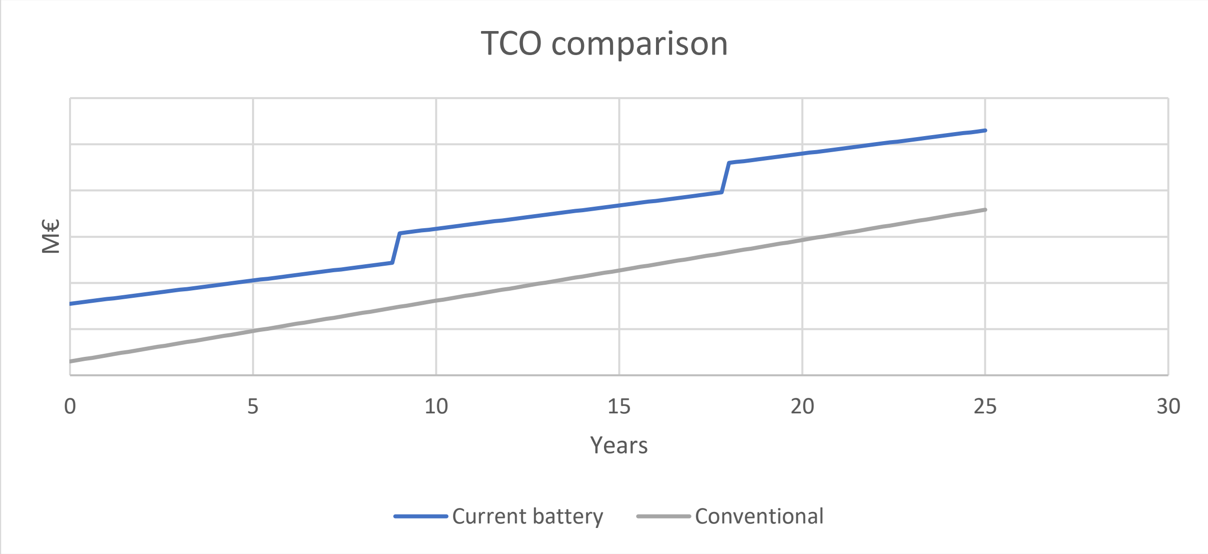


Figure 8 TCO AUMD and Conventional, 4458 tons hopper content and complete fleet

The jumps in the graph represent the battery replacements of the AUMD.

When the AUMD is used for coastal maintenance, it will not be competitive with a conventional dredger and the feasibility of the ALERD can be questioned. The large battery investments seem to make it impossible to return the investment.

The total cost of ownership for the 25 years lifetime of 3,4 ALERDs are million euro. With a total replenishment of 300 million cubic metres (25 years; 12 million m^3 per year), this results in an average cost per m^3 of .

5.6 Conclusion

Based on the above mentioned results, the following research question can be answered:

"What are the energetic and economical simulation results of the AUMD?"

The answer to the research question is: An electrical energy consumption MWh and an average dredging cost per cubic metre of .

The design characteristics of the AUMD are insufficient to develop a financial competitive design. The high transit speed is expected to have a major impact on costs. Due to the large sailing distances and power, a lot of energy is required from the batteries. When the transit speed goes to a more economical speed, the energy consumption and battery capacity will be reduced. In contrast to conventional ships, this therefore has a double effect on energy costs. The energetic simulation results are comparable with the given estimations (MWh estimated and MWh by simulation). Therefore it can be assumed that the model works properly and that it can be used for further research. The small differences can be explained by the difference in operational area. The transit distances are different due to the coastal operation instead of inland operation and some deviations will be found with the dredging operations due to a change in dredge material density.

In the next chapter, the data of the AUMD is used to find an optimum that reduces the TCO. Battery investments seem to make the AUMD not financially feasible in comparison to conventional dredgers. This means something will have to be done about the battery investments, in order to become financially feasible. However, the elimination of harmful emissions are also worth an higher investment. The model will be adapted to find the best characteristics of the ALERD. This will concern new calculations for the dredging, propulsion and ballast capacity. In addition, an optimum in sailing speed and pump flow will be looked at and a new type of energy system will be added. Finally, different size ships are also looked into, because it is not yet known which size ship gives the best results. The size of the ships can also influence the best energy system for the ALERD.

6 Scaling and optimization

Adaptation of the model to the ALERD

6.1 Introduction

This chapter focusses on answering the research question

> "What are the optimized simulation results for the ALERD, among different hopper capacities?"

The adaptation of the previous described model towards different hopper volumes and input variables are treated here. Because the electric load balance is dependent on these variables, it had to be adjusted according to the new data and input. Furthermore, the electric load balance is determined for the AUMD at inland operation, instead of the ALERD at sea. This results in a deviation in dredging mixture density, which primarily influences the dredging and ballast power. This chapter focusses on finding the results to determine which system, the battery or hybrid, has the best capabilities to power the ALERD. Furthermore, the results are used to determine the financial feasibility as well.

At first, the variable dependences will be elaborated. Afterwards, an electric load balance can be generated for different hopper volumes, speed and dredging flow. When the adaptation to the ALERD is completed, the assumptions and optimization of the input variables are discussed. This answers the last open questions, in order to obtain results for the ALERD.

6.2 Variable dependences

This section covers the variables in the load balance and how these influence the outcome. Furthermore, it deals with the methods how the simulation results can be improved.

6.2.1 Variables that influence the operational profile

Propulsion power

The propulsion power is a function of the speed, resistance and inertia. [72]

$$P_{prop} = v(R_t + ma) \tag{6.2.1}$$

Where:

P_{prop}	is the propulsion power
v	is the speed
R_t	is the towing resistance
m	is the total mass
a	is the acceleration

A variable in the propulsion power consumption is the towing resistance of the dredger. This is in general the sum of the elements: Frictional resistance, Eddy Resistance, Wave resistance, and Air resistance. The latter two elements can be eliminated by diving to sufficient depths.

Frictional resistance can be described with the equation: [72]

$$F_W = Cv^2 = R_t v \tag{6.2.2}$$

In which the constant C is a function of hull shape, appendage drag, wetted surface, and fouling. Eddy losses are generated by flow separation. This can be reduced by decreasing abrupt changes in hull form. When submerged, the total resistance is dominated by the drag and frictional resistance, as the Eddy losses are only in de order of a couple of percent, for low-speed vessels.

The last variable is the acceleration of the ALERD, which works in opposite directions at the beginning and end of the trajectories. In this way, these can cancel each other out to minimize the influence on the required energy. Additional power will be required to reach the transit power, which implies an overcapacity in propulsion power.

The used propulsion energy over one trajectory is the integration of P over the transit time: [72] [73]

$$E_{prop} = P_{prop}\frac{X_t}{v} = X_t c v^2 \tag{6.2.3}$$

Where:

E_{prop}	is the propulsion energy over the transit distance
P_{prop}	is the propulsion power
X_t	is the transit distance
v	is the constant transit speed
c	is the resistance coefficient

Scaling effect on propulsion power

In general maritime applications, Froude similarity is applied to scale the gravimetric forces appropriately between scaled ship sizes. The representative speed is calculated using the input speed and Froude similarity. However, the gravimetric forces are found in the wave making resistance of the ship, whose are non-existent while diving at sufficient depths. Froude scaling must only be applied while the ship is surfacing. Effects from Froude scaling will affect the smaller hopper sizes the most, as the scaling ratio will be the largest. For the purpose of this research, Froude scaling is ignored based on the submerged operation and transits.

A fully submerged submarine at sufficient depth has only viscous and friction resistance, which requires Reynolds scaling. Studies have proven that the effects of Reynolds scaling on submarines are negligible, which results in a resistance coefficient that is proportional to hull surface for a given hull shape. [74]

As a conclusion, the propulsion power will be a function of hull surface and transit speed to the third power.

Draghead resistance power

During dredging, the drag head cuts its way through the sea bottom. The resistance of the drag head, at constant speed, has been determined: [63]

$$P_{drag} = v_{drag} R_{drag} \tag{6.2.4}$$

Where:

P_{drag}	is the draghead resistive power
v_{drag}	is the constant dredging speed
R_{drag}	is the draghead resistance

The total propulsion power is the summation of the drag head resistance power and the transit propulsion power at that speed. The resistance from the drag head is proportional to the surface cutting through the soil.

$$E_{drag} = P_{drag} t_d \tag{6.2.5}$$

$$t_d = \frac{V_{hopper}}{Q_{filling}} \tag{6.2.6}$$

Dredging power [75]

The dredging power is dependent on the system characteristics and the flow.

$$P_{dredging} = Q_{dredging} \Delta p \tag{6.2.7}$$

Where:

$P_{dredging}$	is the dredging power
$Q_{dredging}$	is the flow of the dredge mixture
Δp	is the head pressure of the pump

Where Δp consists of the head, the pressure to accelerate the dredge and the pressure loss by resistance in the system. The head is dependent on the vertical distance between the seabed and the dredger. The pressure fall can be described with the Darcy Weisbach empirical equation multiplied by the system length. The Darcy Weisbach formula uses a friction factor, fluid velocity, and diameter to calculate the pressure loss per unit length. The Darcy Weisbach equation is implicitly dependent on the liquid velocity which can be traced back to flow:

$$\Delta p = \Delta \rho g \Delta h + \frac{8\rho}{\pi^2 D^4} Q^2 + f_d \frac{16\rho L}{\pi^2 D^5} Q^2 \tag{6.2.8}$$

Where:

$\Delta \rho g \Delta h$	is the head
$\frac{8\rho}{\pi^2 D^4} Q^2$	is the inertia of the mixture
$f_d \frac{16\rho L}{\pi^2 D^5} Q^2$	are the resistive losses of the system

With: [60]

$$f_d = \frac{0.316}{Re^{0.25}} \; for: 3000 < Re \leq 2 * 10^4 \tag{6.2.9}$$

$$Re = \frac{vD\rho}{\mu} = \frac{vD}{\upsilon} = \frac{4}{\pi} \frac{Q}{D\,\upsilon} \rightarrow \tag{6.2.10}$$

$$\Delta p = \Delta \rho g \Delta h + \frac{8\rho}{\pi^2 D^4} Q^2 + \frac{3{,}58\rho \upsilon^{0{,}25} L}{\pi^{1{,}75} D^{4{,}75}} Q^{1{,}75} \tag{6.2.11}$$

Where:

f_d	is the friction factor of the system
Re	is the Reynolds number
v	is the speed of the fluid-dredge mixture
Q	is the flow of the fluid-dredge mixture
μ	is the viscosity of the fluid-dredge mixture
υ	is the kinematic viscosity of the fluid-dredge mixture
ρ	is the density of the fluid-dredge mixture
D	is the diameter of the piping system
L	is the length of the piping system

The energy to fill the hopper is the integration of P over the dredging time.:

[12] [60][75] [76] [77]

$$E_{dredging} = P_{dredging} \frac{V_H}{Q_{filling}} = V_H \Delta p \tag{6.2.12}$$

Where:

$E_{dredging}$	is the dredging energy
V_H	is the hopper volume

Ballast power [75]

The ballast power of the ALERD is a large contributor of the total power consumption of the ALERD. Similar to the dredging power a relation can be set up:

$$P_{ball} = Q_{ball} \Delta p \tag{6.2.13}$$

Where:

Q_{ball}	is the flow of ballast water
Δp	is the head pressure of the pump

Where Δp is the pressure difference between the hopper and surrounding seawater and the pressure loss off the system. The pressure loss of the system is a summation of the ballast system and snorkel system:

$$\Delta p_{loss} = \frac{8\rho}{\pi^2 D^4} Q_{ball}^2 + f_d \frac{16\rho_{sw}}{\pi^2} \frac{Q_{ball}^2}{D_{ball}^5} L_{ball} + f_d \frac{16\rho_{air}}{\pi^2} \frac{Q_{air}^2}{D_{snorkle}^5} L_{snorkle} \tag{6.2.14}$$

With:

$$f_d = \frac{64}{Re} \; for\ laminar\ flow \rightarrow \tag{6.2.15}$$

$$\Delta p_{loss} = \frac{8\rho}{\pi^2 D^4} Q_{ball}^2 + \frac{3{,}58\rho_{sw} v_{sw}^{0{,}25} L_{ball}}{\pi^{1{,}75} D^{4{,}75}} Q_{ball}^{1{,}75} + \frac{256\mu_{air} L_{snorkle}}{\pi^2 D_{snorkle}^4} Q_{air} \tag{6.2.16}$$

$$\Delta p = \rho_{sw} g z - p_{hopper} + \Delta p_{loss} \tag{6.2.17}$$

Where:

$\rho_{sw} g z$	is the pressure at diving depth z
p_{hopper}	is the pressure inside the hopper
Δp_{loss}	is the pressure loss in the ballast system

A submarine has to remain neutrally buoyant, by keeping the total mass inside the hull constant. When the submarine wants to dive or surface, it has to respectively increase or decrease the mass inside the hull. Classically this is done with the use of ballast water.

The idea in the ALERD is that water is pumped in/out the hopper with the use of the ballast pumps. At the same time, air is passively sucked in or blown out through the snorkel. Arriving at the dredging location, the hopper is filled with seawater as ballast. During the dredging process the hopper is filled with sand and air is supplied to remain neutrally buoyant. [8]

If the dredging operation is assumed as the dominating factor in mass transfer the following equation can be set up: [8][12] [75] [76] [77]

$$\dot{M}_{in} = \dot{M}_{out} \tag{6.2.18}$$

Gives:

$$\Delta\rho_{hopper} Q_{filling} = (\rho_{sw} - \rho_{air}) Q_{Ball} \tag{6.2.19}$$

Or:

$$Q_{Ball} = \frac{\rho_{hopper - \rho_{sw}}}{\rho_{sw} - \rho_{air}} Q_{filling} \tag{6.2.20}$$

With substitution of (6.2.13):

$$P_{ball} = \frac{\rho_{hopper} - \rho_{sw}}{\rho_{sw} - \rho_{air}} Q_{filling} \Delta p_{ball} \tag{6.2.21}$$

With substitution of (6.2.12):

$$E_{ball} = P_{ball}\frac{V_H}{Q_{filling}} = \frac{\rho_{hopper} - \rho_{sw}}{\rho_{sw} - \rho_{air}} V_H \Delta p_{ball} \tag{6.2.22}$$

6.2.2 Methods to change/improve the outcome of the results

Scaling in size

Because the actual size of the ALERD is yet to be decided, scaling in displacement is useful concerning the operational profile estimation.

The block coefficient (C_B) is the most important coefficient to express the shape of the hull. This is defined as the ratio between the displacement volume and volume of the box as surrounding the submerged volume:

$$C_{B,WL} = \frac{\nabla}{LBT} \tag{6.2.23}$$

The method of scaling is geometrical scaling, which means that the shape of the ship, and thus the block coefficient remains constant. As a result, length dimensions will scale with displacement to the power one-third and the surface dimensions scale with displacement to the power two-third. Furthermore, the hopper volume will be scaled proportionally with the displacement. Geometric scaling is chosen because the resistance coefficient C will be proportional to the surface dimension of the ALERD. Furthermore, the hull surface of the ALERD is optimized to reduce resistance, and therefore it is undesirable to change the shape. For consistency and the same reasons, the other length units are also scaled in this way. Think of dimensions of the dredging and ballast system.

Geometric scaling also affects the power train and efficiencies brought with them. It is assumed that the efficiencies remain constant, as it is believed that the influence is only minor.

The scaling ratio is found in the towing resistance, thus it influences the transit profile. Furthermore, when the displacement changes, the hopper capacity changes accordingly. Therefore, it influences the dredging and ballast profile as well. Furthermore, due to the influence of pipe diameter and length on the system flow resistance, it is traced back here as well. As a conclusion, the displacement of the ship is connected everywhere in the operational profile. In addition, there is also the connection with the amount of dredge that can be transported per ship per time.

Changing dredging flow

Changing the dredging flow influences the pressure losses in the system. Because of the strong relationship with the ballast system, it indirectly affects the pressure losses there as well. The optimal dredging flow is a function of energy efficiency and dredging capacity. A cost optimization can determine which capacity is the best for the ALERD

Changing the transit speed

Speed is a variable that has a great influence on the power and energy consumption of a vessel. In first instance, it might seem that decreasing the speed will inherently improve the efficiency of the dredger. However, several other things must also be taken into account. The ALERD is subject to a constant power of approximately 200 kW by the auxiliary systems. Therefore, the optimal energy efficiency will be achieved at a speed greater than 0. By decreasing the transit speed, the overall dredging capacity decreases as well. Therefore a consideration has to be made between energy efficiency and dredging capacity. Likewise, the optimization based on cost can determine the best transit speed. Because there is no hotel power and wages for on board personnel, it is expected that the optimal transit speed is lower than conventional dredgers.

Changing the transit distances

The transit energy consumption is proportionally dependent on the transit distance. The operation of a dredger has 3 main transit distances to cover. These are: Mooring-Dredging, Dredging-Dumping/Discharge, Dumping/Discharge-Mooring. In this profile, the second step can be performed several times, which means that the ALERD can dredge and dump/shore press multiple times before the remaining energy runs low.

The resulting positive effect is that the total transit distance is decreased and thus more time can be performed with dredging activities, increasing the replenishment capacity. The negative side of increasing the dredging repetitions is the increment of the total amount of energy usage per cycle, which has the effect of increasing the energy storage system costs. Because more energy storage costs space and money, and because more stored energy increases the operational effectivity, it is expected that an optimum can be found in the amount of dredging cycles per energy cycle.

Furthermore, decreasing the mentioned transit distances will inherently reduce the energy requirement. However, the transit distances are restricted, because these are geographically determined.

6.3 Power and time calculations

Now the variable relation to power is clear, the electric load balance of the ALERD can be created. The calculations combine the variable dependences with the data from the AUMD, which can be retrieved from table 5,

The equations have been separated in main equations and secondary equations. The main equations are overarching equations per activity, which consists of the specific consumers, the secondary equations. Likewise as the electric load balance for the AUMD, the main equations describe the transit, dredging, dumping and discharge power (and time).

In the equations, the *input* annotation is intended to display the input variables and the *design* annotation is intended to represent the known design data from the electric load balance. All dimensions are scaled linearly, so the hull shape remains the same and the hopper volume is proportional to the displacement. Furthermore, this assumption is applied to the dredging and ballast systems and equipment as well.

Because the AUMD was designed for inland operation, new calculations are made to determine the dredging and ballast characteristics, whose will differ for the ALERD by the different soil density of both purposes.

Because the ratio between the input displacement and the design displacement is a frequently recurring factor, it was decided to use the ratio factor r:

$$r_{scaling} = \frac{\Delta_{input}}{\Delta_{Design}} = \frac{V_{hopper_{input}}}{V_{hopper_{design}}}$$

Where:

Δ_{Design} is the design displacement, equal to 10830 ton [1]

$V_{hopper_{design}}$ is the design hopper volume, equal to 2623 m³ [1][6]

Because the method of scaling is geometric scaling, there is sufficient data to calculate the electric load balance for different hopper volumes, transit speed and dredging flow. The equations are inserted into the model to automatically calculate the electric load balance for the input variables used.

[6] A correction has been made to include the same amount of dredged material (by weight) in the hopper, as described in the assumptions from chapter 5. The AUMD has a hopper volume 3430 m³ with a hopper density of 1,3 t/m³, against a hopper density of 1,7 for the ALERD.

6.3.1 Main equations

Transit

During transit, the main consumers are the propulsion system, ballast and navigational equipment.

Navigational power is assumed independent of hopper volume. 20% nominal ballast power is approximately the required power for transit ballast, according to the electric load balance.

The transit power is calculated by the summation of the following consumers:

$$P_{transit} = P_{propulsion} + 0{,}2P_{Ballast} + P_{nav_{design}} \tag{6.3.1}$$

Where:

$P_{nav_{design}}$ is the design navigation equipment power, equal to [78]

The corresponding transit time is calculated using equation (5.4.2)

Dredging

The dredging power is calculated by the summation of the following consumers:

$$P_{Dredging} = P_{pump} + P_{ballast} + P_{dredging\ head} + P_{propulsion_{dredging}} + P_{nav_{design}} \tag{6.3.2}$$

The corresponding dredging time is calculated using equation (5.4.3)

Dumping

The required power for the dumping of the sediments in the hopper is equal to:

$$P_{Dumping} = P_{ballast} + P_{propulsion_{dumping}} + P_{nav_{design}} \tag{6.3.3}$$

$$t_{dumping} = t_{dumping_{design}} r_{scaling} \tag{6.3.4}$$

Where:

$t_{dumping_{design}}$ is the assumed design dumping time, equal to $600\ s$

Discharge

The power required for the discharge of the sediments in the hopper is equal to:

$$P_{discharge} = P_{pump} + P_{Ballast} + P_{nav} \tag{6.3.5}$$

Where the corresponding time is calculated using equation (5.4.5)

It is assumed that discharging uses 100% of the dredging pump power. When the power is insufficient for the sedimentation of the coast, a shore located booster pump can increase the sedimentation distance. This is an assumption made during the design of the AUMD and will be used for the ALERD accordingly, to minimize the installed power and stored energy for the discharge operation.

Bunkering/recharging

Recharging uses the same assumptions as made in chapter 5.

Refilling the energy stock uses the following equations:

$$P_{Bunkering/recharging} = \frac{-E_{input}}{t_{charging/bunkering}} \tag{6.3.7}$$

$$t_{bunker\ station} = 3\ hours\ (hybrid\ ship) \tag{6.3.8}$$

Where:

E is the stored energy in the ALERD

t is the time, assumed using relevant applications. [41] For hydrogen additional time is taken into account for the more complex procedure and routine small maintenance/inspections. For the battery powered ALERD, equation (5.4.1) is used.

6.3.2 Secondary equations

These equation are to determine the component power requirements, such as the pump and ballast power.

Transit propulsion power

Because the simulation is non-dynamic, the power requirement for acceleration is disregarded in the equations. The propulsion power is determined using geometric scaling and the relation of speed. [79]

Propulsion power is determined using speed to the third power and hull area:

$$P_{propulsion} = r_{scaling}^{\frac{2}{3}} \left(\frac{v_{ALERD_{input}}}{v_{ALERD_{design}}}\right)^3 P_{propulsion_{design}} \tag{6.3.9}$$

Where:

$v_{ALERD_{design}}$ is the design ship speed, equal to $11\ kt$ [1]

$P_{propulsion_{design}}$ is the design propulsion power, equal to [1]

Dredging and dumping propulsion power

The dredging and dumping propulsion power is a function of hull surface and surface cutting through the sea bottom. It is assumed that the dredging and dumping speeds are at the same speed as the AUMD, because they are determined by dredging characteristics rather than an economical speed.

Because it is assumed that the dredging head scales geometrically, the dredging head frictional resistance is also scaled with $r_{scaling}^{\frac{2}{3}}$ [79] :

$$P_{prop_{dredging}} = r_{scaling}^{\frac{2}{3}} P_{prop_{dredging_{design}}} \tag{6.3.10}$$

$$P_{prop_{dumping}} = r_{scaling}^{\frac{2}{3}} P_{prop_{dumping_{design}}} \tag{6.3.11}$$

Where:

$P_{propulsion_{dredging_{design}}}$ is the design dredging propulsion power, equal to:kW [1]

$P_{propulsion_{dumping_{design}}}$ is the design dumping propulsion power, equal to: [1]

Dredging pump power

Pump power is calculated by the multiplication of the flow and pressure difference:

$$P_{pump} = \frac{Q_{dredging} \Delta p}{\eta_{pump+motor}} \tag{6.3.12}$$

Where:

$\eta_{pump+motor} \approx 70\%$ [80]

The pressure difference is calculated using the height difference, acceleration of the dredge and the frictional losses of the system: [60][75] [76] [77]

$$\Delta p = \Delta\rho g\Delta h + \frac{8\rho}{\pi^2 D^4}Q^2 + \frac{3.58\rho\upsilon^{0,25}L}{\pi^{1,75}D^{4,75}}Q^{1,75} \tag{6.3.13}$$

Using geometric scaling and an Under Keel Clearance (UKC):

$$\Delta p = \Delta\rho g\left(UKC + r_{scaling}^{\frac{1}{3}}d_{design}\right) + \frac{8\rho}{\pi^2\left(\left(\frac{\Delta}{\Delta_{design}}\right)^{\frac{1}{3}}D_{Design}\right)^4}Q^2 + \frac{3{,}58\rho\upsilon^{0,25}r_{scaling}^{\frac{1}{3}}L_{design}}{\pi^{1,75}(r_{scaling}^{\frac{1}{3}}D_{design})^{4,75}}Q^{1,75} \tag{6.3.14}$$

Where:

Δp	is the head of the dredging pump
ρ	is the density of the 50% mass concentrated dredging mixture: $\frac{1{,}9+1{,}025}{2} = 1{,}46\ \frac{ton}{m3}$
$\Delta\rho$	is the density difference between the dredging mixture and seawater: $\rho - 1{,}025\ \frac{ton}{m3}$
g	is the gravimetrical constant: $9{,}81\ \frac{m}{s^2}$
ukc	is the under keel clearance, equal to 2 m [1]
D	is the diameter of the dredging pipe system: 0,85 m [1]
υ	is the kinematic viscosity of the dredging mixture: $10^{-4}\ \frac{m^2}{s}$ [76]
L	is the length of the dredging pipe system: 27,5 m [1]
d_{Design}	is the draft of the design, equal to 6 m [1]

Substitution gives:

$$\Delta p \approx 8{,}6 + 25{,}8r_{scaling}^{\frac{1}{3}} + 2{,}4r_{scaling}^{\frac{-4}{3}}Q_{dredging}^2 + 4{,}2r_{scaling}^{\frac{-3,75}{3}}Q_{dredging}^{1,75}\ [kPa] \tag{6.3.15}$$

With $Q_{dredging}$ in [m³/s]

Dredging head

The dredging head has a power consumption, which is calculated in the electric load balance of the ALERD. It is assumed that the relation is proportional to the third power of dredging flow:

$$P_{dredging\ head} = r_{scaling}^{\frac{2}{3}}P_{dredging\ head_{design}} \tag{6.3.16}$$

Where:

$Q_{dredging_{design}}$	is the design dredging pump flow, equal to 3,23 $\frac{m3}{s}$ [1]
$P_{dredging\ head_{design}}$	is the design dredging head power, equal to [1]

Ballast

Ballast power primarily consists of the main and trimming power. It is assumed that the trimming power is proportional to scaling ratio. For the main ballast power, similar calculations are used as with the dredging power using: [8] [60] [75] [76] [77]

$$P_{ballast} = \frac{P_{MainBallast}}{\eta_{pump+motor}} + r_{scaling} P_{trim_{design}} \tag{6.3.17}$$

Where:

$P_{trim_{design}}$ is the design trim pump power, equal to kW [1]

$r_{scaling}$ is the assumed proportional relation between trimming power and scaling ratio

And:

$$\Delta p_{MainBallast} = \Delta\rho g \Delta h + \frac{8\rho}{\pi^2 D^4} Q_{ball}^2 + \frac{3.58\rho_{sw} \upsilon_{sw}^{0.25} L_{ball}}{\pi^{1.75} D^{4.75}} Q_{ball}^{1.75} + \frac{256\mu_{air} L_{snorkel}}{\pi^2 D_{snorkle}^4} Q_{air} \tag{6.3.18}$$

With geometric scaling and the assumption that the frictional losses in the ballast and snorkel system negligible:

$$\Delta p_{ball} = \Delta\rho g \Delta h + \frac{8\rho}{\pi^2 \left(r_{scaling}^{\frac{1}{3}} D_{Design} \right)^4} Q_{ball}^2 \tag{6.3.19}$$

Where:

$\Delta h = 25\ m$ [59]

$\eta_{pump+motor} = 85\%$ [81]

$\Delta\rho$ is the density difference between seawater and air:

$$1{,}025 - 0{,}001 = 1{,}024\ \frac{ton}{m3}$$

Gives:

$$\Delta p_{ball} \approx 251{,}1 + 102{,}6 r_{scaling}^{\frac{-4}{3}} Q_{ball}^2\ [kpa] \tag{6.3.20}$$

With:

$$Q_{ball} = \frac{\rho_{hopper} - \rho_{sw}}{\rho_{sw} - \rho_{air}}\ Q_{filling}\ [\frac{m3}{s}] \tag{6.3.21}$$

The adaptation to the ALERD, has more influence on the results than only the electric load balance. To be able to compare the results, additional assumptions are required to estimate the costs. Furthermore, the implementation of the fuel cell-hybrid system requires assumptions to retrieve data. These assumptions are discussed in the upcoming paragraphs.

6.4 Model assumptions and optimization

6.4.1 System types and power management

Based on the literature study, the Li-ion battery and PEMFC have been chosen for the electric power supply. They were chosen for their low maintenance, system readiness, power and energy density and redundancy, among other criteria. These systems are nowadays characteristically seen as the main sustainable power supplies in the transport sector. Li-ion batteries are capable of supplying the energy on their own, but the PEMFC is often found in combination with Li-ion batteries. Here, the batteries are used for peak shaving of the power demand, which reduces fuel cell size and wear. Because the ALERD has a large variable power demand, such as acceleration, dredging, manoeuvring and dumping of the hopper content, this will also be applied here.

Different models have been created, because with batteries the costs are largely determined by stored energy and with a fuel driven system, this is largely determined by the installed power. The characteristic differences between the two create different optimal design parameters.

For the simulation the following reasonings are made:

The battery powered ALERD uses Li-ion batteries with constant efficiencies and operates between 30-80% SoC to determine the requirements.

To overcome the main limitations of a fuel cell and battery, a hybrid system is proposed to retrieve the best results. The hybrid (PEMFC – Li-ion) simulation uses the assumption that the PEMFC delivers constantly the minimal power requirement of the operational profile, which is usually during transit. The supporting battery supplies the remaining power demand, which is usually the largest during dredging. During bunkering, the fuel cell output can be used to recharge the batteries. This setup has multiple advantages which are:

- Low power output by fuel cell results in low investment and maintenance
- Low amount of battery charge cycles results in low wear of battery
- Constant fuel cell output results in long lifetime and high efficiency
- Applicability to stationary fuel cells

The fuel cell recharges the batteries during the time at the bunker station. When the fuel cell power is insufficient to recharge batteries in the given time, an electrical shore connection is required for the remainder. This is implemented in the model as well, using the same assumptions as for the AUMD in chapter 5. Other control systems have been looked into as well. Primarily battery recharging during the transits, which can be incorporated by increasing the fuel cell power, has promising, but comparable results. By doing so, the installed battery capacity and thus the costs can be reduced. The side effect of this is that more fuel cell power is required and that more charging cycles are made. The results of this are an increase in fuel cell costs and more frequent battery replacements. Another point of attention here is that if the battery capacity is reduced too much, the power demand of the batteries can become too great. For these reasons, it was chosen to create the power management not accordingly. Furthermore, the power management is not within focus of the research, because there are programs and tools available that can mathematically optimize the power management of a hybrid energy supply system. A point of attention from this is that the hybrid ship may have some room for improvement.

The operational profile can be used for further explanation of power management. This is given in Appendix A of the report.

6.4.2 Additional assumptions

Additionally to the assumptions in chapter 5, the following assumptions have been applied in the model:

- Fuel cells can operate for 60000 hours stationary, as found in the literature [67][82]
- Hydrogen has 10% loss of energy, due to compression losses and needs to be supplied by electricity [83]
- Fuel cells costs are €3200 per kW and H_2 + LOx storage at €50 per stored kWh, as found in the literature. [64]
- Fuel cells operate at 60% load for high efficiency and longer lifetime. [61] [84]
- At this load and supply of pure oxygen, fuel cells operate with 60% efficiency, as retrieved from commercial available fuel cells [39] [84] [7]
- Green hydrogen costs are €3,33/kg (9,9 cents per kWh) and oxygen costs are €0,1/kg (2,4 cents per kWh), as found in the literature. [85] [86] [87]
- Capital costs are scaled to the power 0,8 with respect to the relevant variables, as found in the literature. [67] [70]

6.4.3 Optimization equation

The following equation is minimalized, which is further referred as the dredging cost [€/m³]:

$$\frac{ship\ costs + propulsion\ system\ costs + dredging\ equipment\ costs + OPEX + building\ cost + CAPEX_{Auxiliary_{design}}}{Dredging\ capacity} \tag{6.4.1}$$

With: [67] [70]

$$ship\ costs = CAPEX_{hull_{design}}\, r_{scaling}^{0,8} \tag{6.4.2}$$

$$propulsion\ system\ costs = CAPEX_{propulsion_{design}} \left(\frac{P_{prop}}{P_{prop_{design}}}\right)^{0,8} \tag{6.4.3}$$

$$Dredging\ equipment\ costs = CAPEX_{Dredging_{design}} \left(\frac{Q_{dredging_{input}}}{Q_{dredging_{design}}}\right)^{0,8} \tag{6.4.4}$$

6.4.4 Input variables optimization

Results show that the optimal dredging costs is a function of the variables: Dredging cycles (amount of stored energy), transit speed, dredging flow, and hopper volume. Using the multi-variable solver on equation (6.4.1), the optimal speed, flow and stored energy can be determined for the simulation. By calculating the optimal speed and flow for a given hopper volume, the following results were acquired:

[7] To limit the size and the need for the snorkel as much as possible, oxygen is fed from LOx tanks. The starting point of the ALERD is a snorkel for the ballast system, to draw in air. Due to the large sailing depths, new research is being conducted to completely eliminate the snorkel, which will bring many structural benefits.

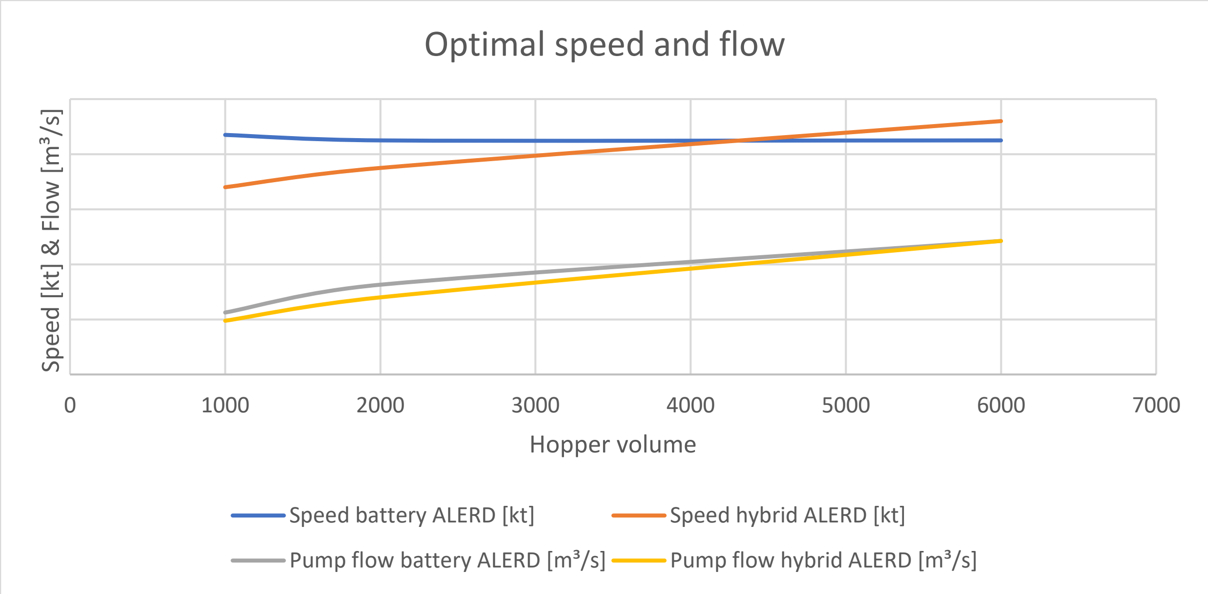


Figure 9 Optimal speed and flow

The hopper volumes between 0 and 1000 are not included in the optimization, as non-linearities form at the smaller hopper sizes. They can be excluded from the optimization, because it has been found out that hopper capacities smaller than 1000 increases the dredging costs drastically and are therefore infeasible, as noted in the results.

As expected, the optimal transit speed is decreased from 11 knots to a more economical speed. It is found out that the optimal speed for the hull form is approximately independent of ship size. This has been concluded from the battery powered ALERD, where the optimal speed is almost a constant function. Notably, the optimal speed for the hybrid is not constant.

The hybrid system uses battery power when the power demand is above the fuel cell output, which is (normally) the highest during dredging operations. The variable optimal speed comes from the amount of required battery capacity, which is a dominating factor in the energy system costs. Ideally, it is decreased as much as possible, together with a low fuel cell output power. The increasing dredging power and time of larger ships, raises the required energy from the battery system. By increasing the transit speed and thus the fuel cell output, the growth of battery capacity is reduced. Consequently, an optimum with respect to costs, can be found at a different optimal transit speed than the battery powered ALERD.

The optimal pump flow is a function of dredging time and dredging power, which ideally are both minimized as much as possible. Increasing ship size and hopper volume increases the dredging time. However, the increasing ship size and thus dredging equipment size allow larger pump flow for the same dredging power. The combination of both, create the rising optimal pump flow function with hopper volume. To be able to pump the mixture, by preventing silting, a limitation of dredging flow has been set up. For a 40% mass mixture, or a 35% volumetric mixture, a minimum flow speed of 3 m/s is required according to *figure 3.5 in Flow of mixture in a pipeline* [60]. Therefore, to ensure pumpability of the mixture using:

$$v_{flow} = \frac{4Q}{\pi D^2} \tag{6.4.5}$$

Where:

v_{flow} is the speed of the dredging mixture

Q is the flow of the dredging mixture

D is the diameter of the dredging pipe system

With a minimum flow speed of 3 m/s gives:

$$Q_{dredging} = \max\left(Q_{optimum\ dredging\ flow}; \pi\left(\frac{3}{4} r_{scaling}^{\frac{1}{3}} D_{design}\right)^2\right) \tag{6.4.6}$$

By optimizing the speed and flow for a given hopper volume, the simulation could decrease the number of variables from three to one, namely the dredging cycles per energy cycle (n) (and local/port charging).

This gave the opportunity to solve required energy when the cycle is fixed at: n=1,2,3,4… times dredging per cycle. The number of dredging cycles n is based on the lowest number of dredging cycles per energy cycle in the profile, which is during the dredging-discharge cycle. It has been found out that, in general, the dredging-discharge cycle requires approximately 1,5-2 times more energy.

In order to prevent the vessel from being unable to achieve a dredging cycle, and thus not using the stored energy optimally, it is checked within a margin of 5% whether the number of dredging-dumping cycles is favourable for the amount of stored energy. For example, when the number of dredging cycles n=2, and the dredging-dumping cycles requires 1,45 less energy than the dredging-discharge profile, the stored energy capacity will be increased slightly, to be able to dredge 3 times in the dredging-dumping profile. It has been found out that this “smoothens” the differences between consecutive dredging cycles, and more predictive results are gathered.

By calculating the required energy for a chosen profile in advance, the battery capacity can be calculated and used as an input parameter. The simulation is now able to solve the most cost-efficient solution instantly by entering a hopper volume and system type. Because results can now be generated much faster, this has given the opportunity to take more samples and to compare different dredging profiles. The sketches and an explanation of the operational profiles can be found in Appendix A.

Similar to the hopper size dependence, the amount of dredging cycles influences the transit speed of the hybrid powered ALERD. More dredging cycles increase the battery usage, which requires a different optimal speed to reduce the battery investment costs. To reduce the battery capacity, the transit speed will be increased and consequently the fuel cell output. Resulting in a change of optimal speed for the hybrid type:

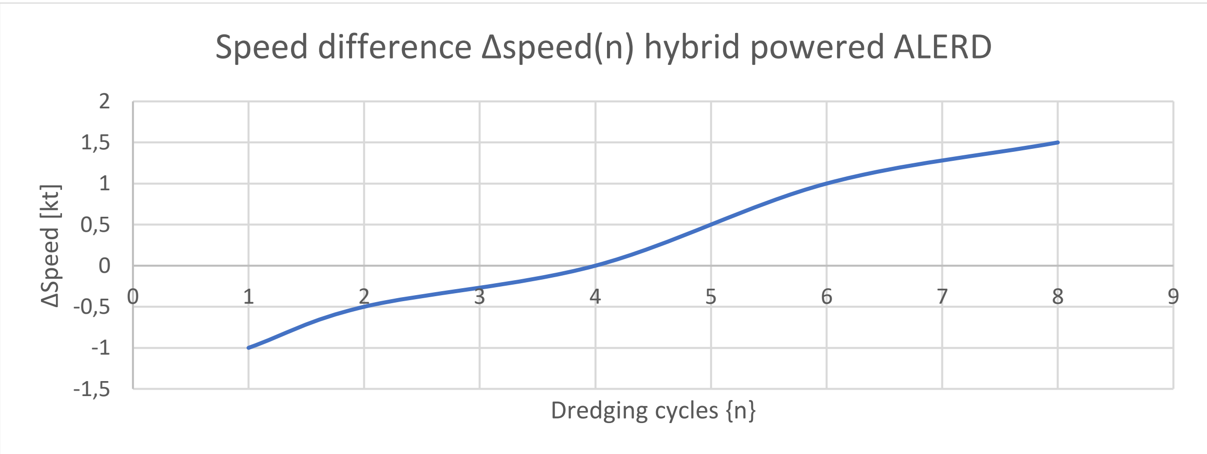


Figure 10 Delta speed dredging cycles, compared to optimum n=4

It has also been found out that the optima of the variables are equal for the ship, when it charges/bunkers locally or in the port. This is a result from an optimum speed, which is independent of transit distance.

With the input parameters known to achieve the optimized results, the results can be gathered as discussed in the following paragraph.

6.5 Simulation results ALERD

The results are calculated for hopper capacities 500 to 6000 m³. For both systems the optimum results are within this region. Hopper capacities smaller than 500 are cost ineffective and larger than 6000 will be limited by their dimensions due to coastal water depths.

The results are the best results from the optimization. More results from other profiles can be found in Appendix B.

6.5.1 Local charging/bunkering

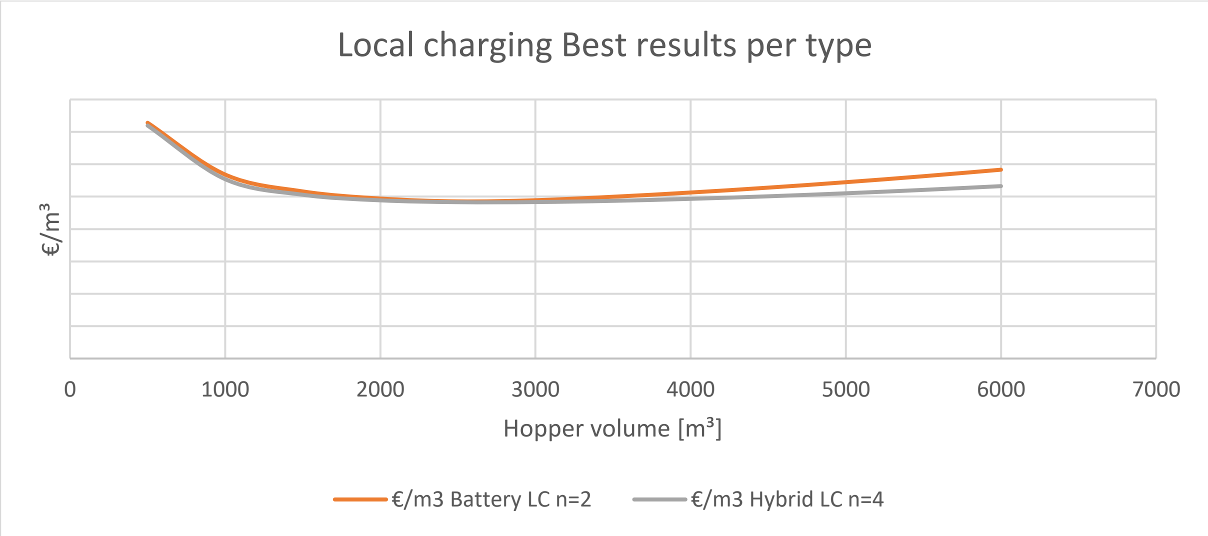


Figure 11 Costs local charging/bunkering

As can be seen in the graph above, the battery and hybrid powered ALERD are competitive to each other at hopper volumes until 4000 m³. Furthermore, an optimal hopper volume can be found at 2500 m3. The costs seem to fall exponentially at the hopper volumes 500 to 1500 m³. This can be explained by the ratio difference of smaller hopper volumes, which affects the amount of required ships with approximately the same ratio. Theoretically, a hopper size of zero would give a number of required ships, and thus cost per m³, of infinite.

Dredging favours larger hopper capacities, because relatively less transit is required. This increases the useful operational time and thus the dredging capacity. However, the larger ships require more energy to fill/empty the hopper and during the transits. At an equal number of dredging cycles, this requires more stored energy per cycle, because a smaller ship could recharge more often. As a result, larger hopper capacities require relatively more stored battery energy on board. Due to the high corresponding costs, an optimal point can be found in terms of hopper capacity.

The hybrid system is more constant over the hopper volumes. This is a result from the various variables that are changing, whose primarily are the fuel cell power output versus the stored battery energy. Due to the optimization that affects these variables, a larger optimal region is created. This is impossible for the battery powered ALERD, and consequently a larger curvature is found in this graph.

6.5.2 Port charging/bunkering

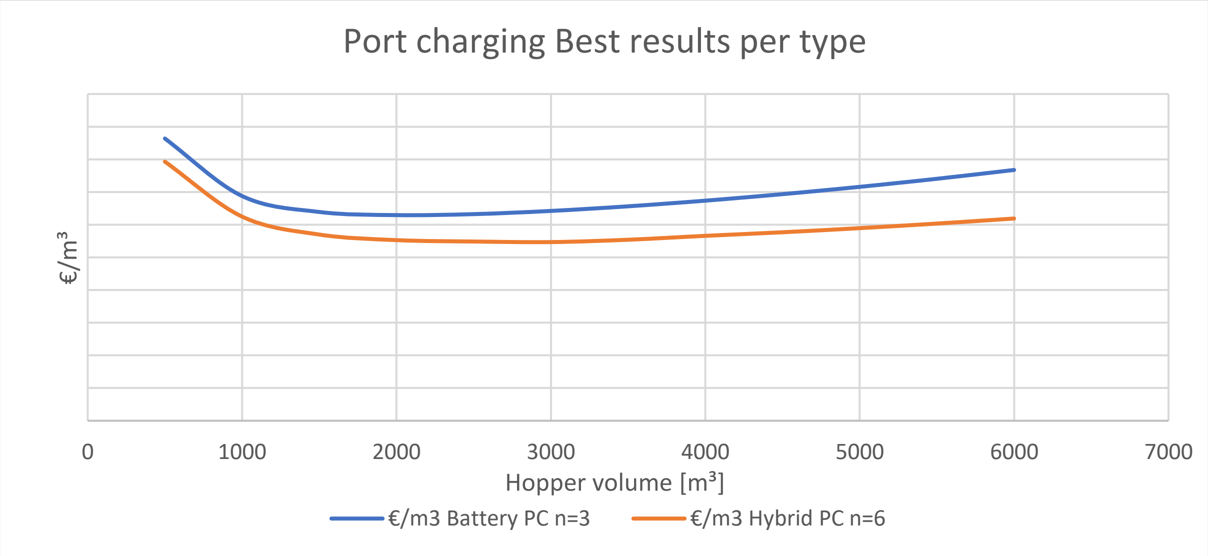


Figure 12 Costs Port charging/bunkering

Port charging benefits the hybrid powered ALERD. This results from the costs per stored energy, which are the driving costs for the battery system. Port bunkering does not directly affect the required battery capacity for the hybrid ship, because the fuel cell power output is sufficient during transits. However, the increasing number of dredging cycles does. These costs are however much smaller than with the battery powered ALERD, reducing the penalty for port charging.

As mentioned before, larger ships and more dredging cycles need to sail relatively less far. To overcome the negatives from the increasing transit distances from local to port charging, the dredging cycles and hopper volume can be increased. For the hybrid powered ALERD, both are raised from local to port bunkering. However, this is not true for the battery-operated ALERD. This is because there is a trade-off to get the best results. Since they have the same effects (relatively decreasing sailing distances and increasing required energy capacity), they interfere with each other. There is an optimal relationship between dredging cycles and hopper capacity. From this relationship, when one is increased the other will go down to stay at an optimum. As a result, good results can be achieved for different numbers of dredging cycles, at different hopper volumes. This can be clearly seen in the graphs in Appendix B.

Interestingly, it has been found out that the costs per cubic metre replenishment, is for the hybrid type ship very competitive with the profiles n=5 until n=9. The stored battery capacity is dependent on the number of dredging cycles for the hybrid ship. Because port bunkering prefers (relatively) more dredging cycles, it influences the required battery capacity. It is concluded that the cost decrease of the more efficient profile, weighs approximately equal against the increase in costs for the stored energy.

The increase of port charging over local charging resulted in a cost increase of per m³ against m^3 for local bunkering of the hybrid system. Against an operational life of 25 years, these results sums up to a cost of respectively and million euro.

6.5.3 Rounded number of fleet

A correction has been made for an integer number of ships, rounded to the nearest integer above.

This function is chosen because it rounds to a value which has an overcapacity to assure that sufficient dredging capacity is available. Because the ALERD cannot be developed in decimated number fleet, the results are adjusted to represent the costs for an integer number of ships. To better represent the results, they have been approximated with a 5th degree polynomial for interpolation. The results are extracted from this in steps of 100 cubic meters of hopper volume, which clearly shows the jumps between the rounded number of ships required.

Rounding of the required number of ships in the fleet for the project, results in the following graphs:

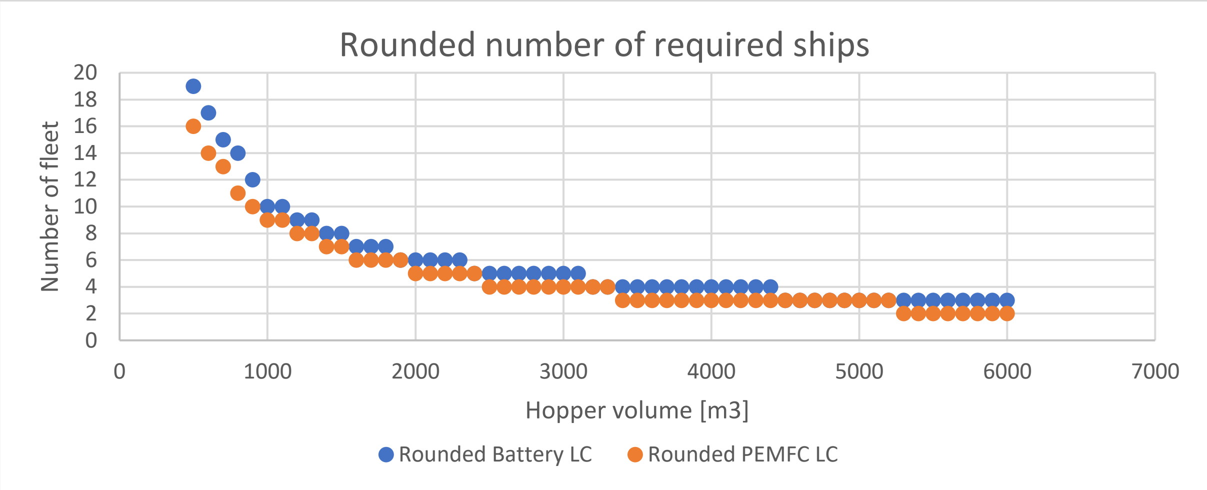


Figure 13 Number of required ships LC

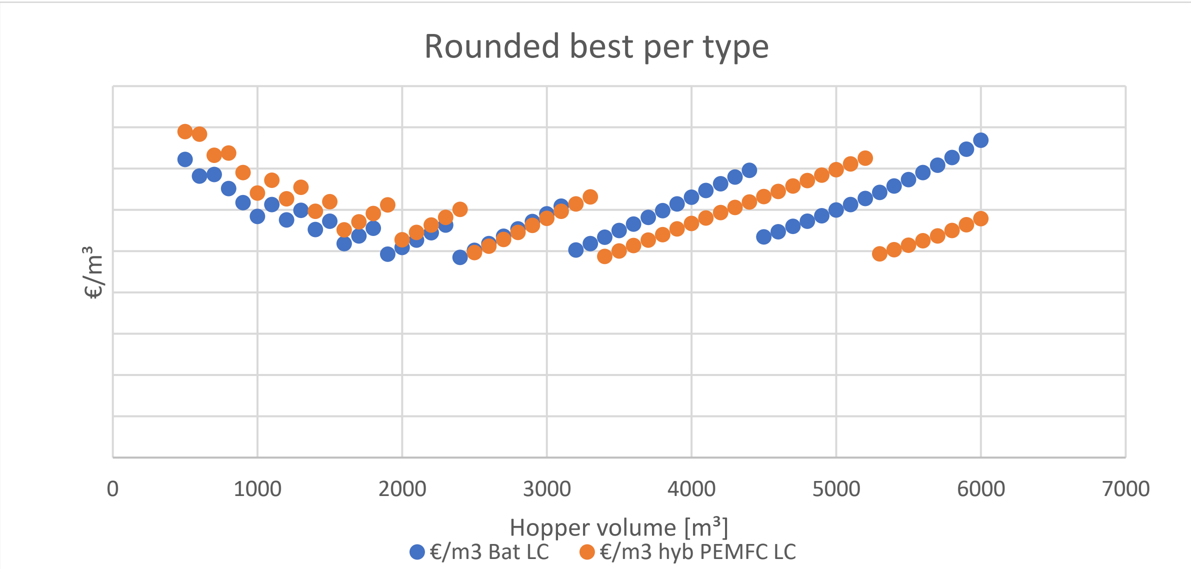


Figure 14 Costs rounded number of ships

The graph shows the costs per m³, when a rounded number of ships is used. The dots represent samples from the non-continuous €/m³ replenishment function (steps of 100 cubic metre hopper volume). Each continuous section represent a number of fleet size required for the project, which can be retrieved from figure 13. The graphs make clear that matching of the number of ships is an important factor in the determination of the system and hopper volume. When an integer number of ALERD's are used, a matching between hopper size and project size is required to retrieve the same results as in the unrounded results.

For each rounded number of ships, the optimum is at the smallest sized ship. This is as expected, because there is no need to dredge more than the project requires. As a result, larger ships at the same number of fleet size would result in more off time of the ship, increasing the costs per cubic metre sedimentation. A counter side of the optima, is that there is less margin and there is no space for an increment of the project size. Furthermore, it would limit the capabilities to make up for lost work, due to a lack of overcapacity. A margin has already been calculated for this in the assumptions, but the exact value is impossible to determine in advance.

Equally, the results for port charging and bunkering are calculated as well with a rounded number of fleet.

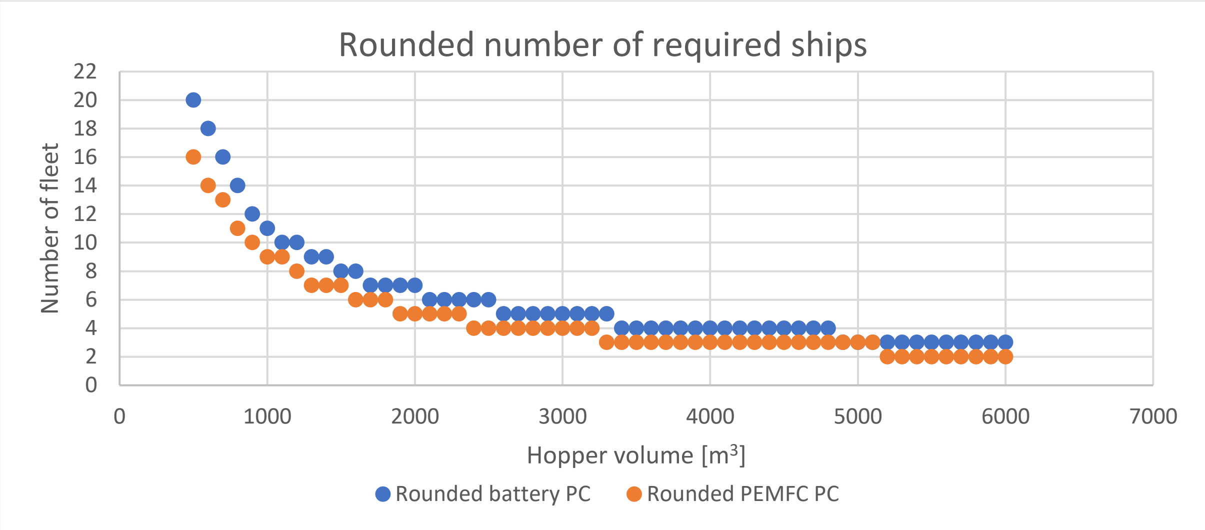


Figure 15 Number of required ships PC

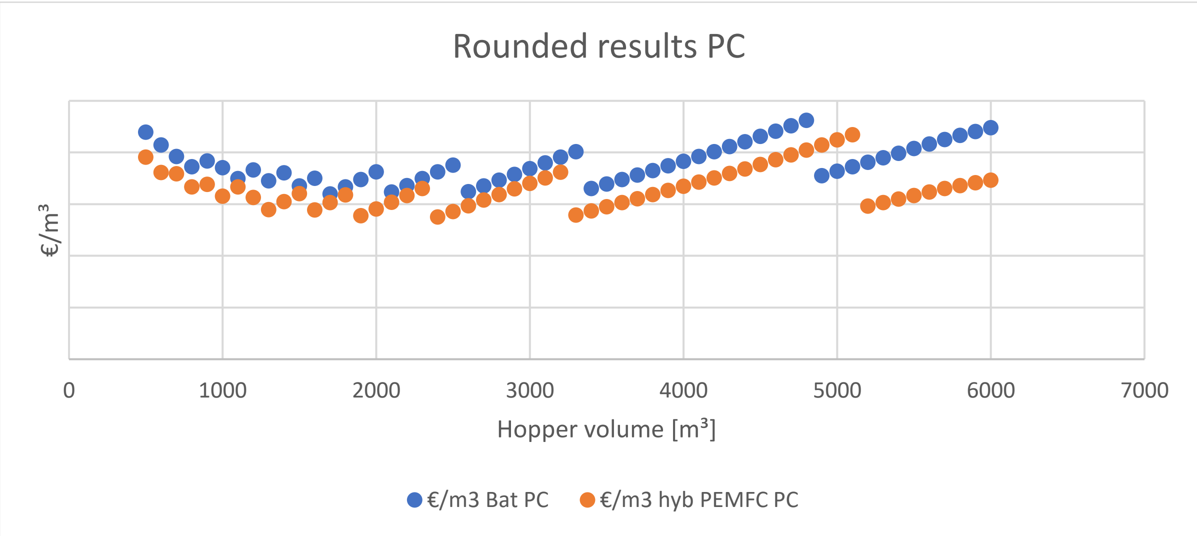


Figure 16 Costs rounded number of ships

Where the results benefit the hybrid system for almost all hopper volumes. Interestingly, the number of fleet for the hybrid powered ALERD is lower with port bunkering in comparison with local bunkering. This comes from the higher number of dredging cycles per energy cycle, which decreases the overall transit distance and consequently more dredging capacity is acquired per ship. The battery powered ALERD requires approximately the same number of ships, for the same reason.

6.5.4 TCO comparison

With the data from the simulation, a TCO could be generated, which can be compared to the AUMD and a conventional dredger using data from and THSD financial studies.

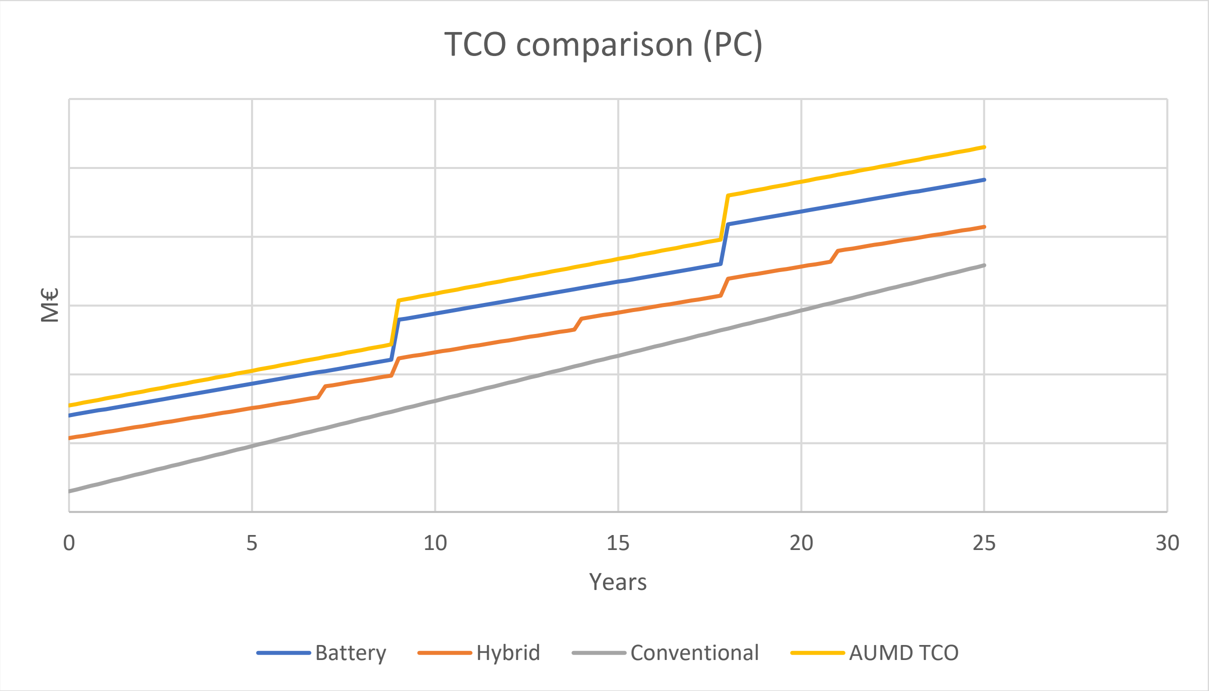


Figure 17 TCO comparison

The graph is generated using the costs for port charging, because the additional costs for local charging are difficult to estimate and the results for port charging are reliable.

The jumps in the graph represent major replacement maintenance of the energy system. All other costs are linearised. The expected total cost of ownership is calculated from the results of the operational profile. From the graph it can be noted that the CAPEX is much larger for both ALERDs. The conventional dredger CAPEX is smaller because the price per ship is lower and because dredging capacity of a conventional dredger is better, resulting in less required ships. The OPEX of the conventional dredger are higher, which primarily comes from the personnel costs.

The AUMD loses from the ALERD on the initial investment and the operational costs. Because the higher transit speed requires additional battery capacity, the initial investment and battery replacements are higher. Furthermore, the larger battery increases the charging times and the larger energy consumption increases the electricity costs. The electricity costs are however only a small portion of the total costs per cubic metre.

6.6 Conclusion

Based on the above mentioned results, the following research question can be answered:

"What are the optimized simulation results for the ALERD, among different hopper capacities?"

The answer to the research question is: For the battery and hybrid powered ALERD a dredging cost of respectively and euros per m^3 is expected. These results are found at a hopper volume of 2000 and 3000 m^3 and port charging/bunkering. For local charging/bunkering, the costs drop for both systems to euros per m^3 at a hopper volume of 2500 m^3.

The cost difference between local and port charging/bunkering allow large investments to be able to bunker/charge locally. However, because the costs for local charging/bunkering station are expected to be very high due to the complexity, it is recommended to develop the stations together with other stakeholders. It is expected that the development of the stations takes longer than the deadline of the ALERD. Therefore it is advised to initially go for charging and bunkering in the port. It is possible to implement and use local charging stations at a later stage. The initial investment for a hybrid powered ship is nearly equal when it is designed for either port or local bunkering at the same number of dredging cycles. This is not true for the battery powered ship, there is a significant rise in costs between a local and port charging ship. In contradiction, when the hybrid powered ALERD is designed for local bunkering, it becomes, due to the lack of energy and the corresponding dredging profile, inefficient while port bunkering. Due to the large cost increase for the battery powered ALERD while port charging, the advantage is again at the hybrid powered ALERD.

It has been observed that the battery system requires an operational profile of n=2 and n=3 for the best performance. For the hybrid solution, the profiles n=5, until n=9 give the best results with respect to costs. The number of dredging cycles are primarily limited by the corresponding battery capacity, which has a dominant role in the total costs of the system. It can be assumed that the profile with higher number of dredging repetitions is desired, because it gives more operational freedom. For example, many trips to the port for charging/bunkering can be an obstruction, because it requires personnel, operation of sea locks and the ALERD can be considered as an obstruction for maritime traffic. More dredging repetitions require additional volume and weight for the energy systems, therefore it should be checked to see if this is feasible. This counts especially for the battery capacity in the ship, which is influenced most by the number of dredging cycles. Because the optimal number of dredging cycles are for both systems primarily determined by the specifics of the battery, it is expected that developments will not influence the outcome considerably. Therefore, the advantage in the operational profile is at the hybrid powered ALERD, regardless future developments.

The battery powered ALERD has the lowest operational expenses, but is compromised by the large battery investments. As a result, reduced expenses can be made when there are developments in these systems. Furthermore, developments will improve the operational profile, where profits are relatively the largest at the lower and less efficient number of dredging cycles. When a system replacement is required, a switch to another battery system would be possible. This makes the choice more difficult. Consideration must be given to what can be more easily built in the future. A ship that is built to run on batteries will be more difficult to switch to a ship that runs on fuel and vice versa.

Due to rapid developments in sustainable energy supplies, the stated values have been estimated conservatively. This will apply to both systems mentioned, because a lot of research is currently being done on this. This will have to be taken into account in the choice and development of the system, so that the ship can be adapted to this later. In the next chapter, a new TCO created, which has included the developments, as how they are expected today. The calculations and optimization made in this chapter are calculated for static values. Meant with these static values are constant costs, sailing distances, system characteristics and developments. In reality, none of these are constant and are variable over time. The next chapter discusses these topics and simulates these variables and their consequences.

7 Impact of variable scenarios

Adjustments to ensure the validation of correct simulation of variable inputs

7.1 Introduction

This chapter focusses on answering the research question:

"What are the effects of the varying input data?"

Until this point, all simulations and calculations are made on static values. This includes the optimization and the characteristics of the ship. This chapter covers the dynamic situation with respect to costs, transit distances and developments and how they influence the costs per cubic metre sedimentation. This has been done with the original simulation model and applying a bandwidth of input variables or varying computations. These steps are followed to determine if the model and chosen optimization points are sufficient. When a time dependent simulation was chosen, it could have been implemented within the model.

In the next paragraph the expected developments are discussed and included in the simulation results. After this, the variable transit distances in the profile with their influence on the results are discussed.

7.2 Expected developments

This paragraph covers some expected developments of each system type and afterwards a new TCO comparison is given, including the developments. At last, a comparison is made with a promising, future system, the direct fed ammonia SOFC.

The TCO is calculated using the simulation with steps of 0,2 years, and for each sample the cost development is taken into account. Furthermore, when a system replacement is required the costs, with cost development taken into account, are added to the total. The TCO simulation runs from the year 2025 to 2050. The year 2025 is chosen because the aim for the ALERD is to be in production by then. This has some influences on the TCO as well, because some large developments are expected. In Appendix B are the cost calculations of the components. These are used in this paragraph and retrieved from the MARIN.

7.2.1 Developments for the battery powered ALERD

Batteries are believed to make a revolution in the coming years. Major gains are expected with regard to lifespan, costs, charging time and energy storage. It is expected that adding the new systems will not be very complex in relation to other energy supplies. All this can help the future ALERD, after the Li-ion batteries have to be replaced, to possibly the cheapest and most practical solution for coastal sedimentation. However, producers and developers are known for overestimating the capabilities and underestimating the development time, which make it hard to implement reliable data in the model. Because the ALERD must be developed quickly, it is not included in the simulations. Nevertheless, it is useful to stay informed about this.

The developments will attract electric vessels, which thereby increases the number of charging stations. This has a strong positive effect on the operational profile of the battery-driven ALERD and local charging.

Furthermore, there are developments expected soon in a new type of battery, the Lithium Sulphur (Li-S) battery. Expected is that these developments are coming as soon as autumn 2021 with rapid progression in the characteristics from then on. Advantages of these batteries are energy density and the absence of rare metals such as: Cobalt, nickel, copper and manganese.

According to the MARIN, Li-ion battery costs decrease with approximately €15 per kWh per year. This results in a cost decrease of 75% from 2025 to 2050.

It is assumed that the costs to generate green electricity remains constant during the lifetime of the ALERD, as the costs are already very low. [64] [89] [50]

7.2.2 Developments for the hybrid powered ALERD

Direct ammonia fed SOFC's are one of the main contenders of future marine propulsion systems. Ammonia has the advantage that it has much higher volumetric energy density and is much easier to carry. Ammonia is liquid under relatively good conditions and the availability is better than that of hydrogen. The first fuel cells are expected to be commercially available soon.

Further developments are mainly aimed at improving the properties where they are not yet commercially competitive. These are mainly focussed on lifespan and investment costs. The fuel cell developments will not be as much of a revolution as for batteries, but they will increase the strong characteristics of the system in the ALERD.

Aside from the fuel cell, there are developments in hydrogen storage. These developments aim majorly at the volumetric energy density and bunkering time.

PEMFC costs are expected to drastically reduce in the coming years. An exponential decrease from 3200 to 400 €/kW is expected according to the MARIN.

Hydrogen costs are expected to reduce as well. The MARIN expects that the price of hydrogen + oxygen drops to €2 per kg in 2050, which is a cost decrease of 43%. [85]

The cost developments mentioned for the battery powered ALERD applies for the hybrid powered ALERD as well.

7.2.3 Developments for a conventional dredger

A conventional dredger and power train is at the end of the development process, and not much more can be improved. However, there will be developments in the operational expenses of these ships.

The MARIN also has a cost estimate for diesel prices, which are expected to rise in the coming years. This will raise the TCO of the conventional vessel.

In addition, it is also possible that costs will be incurred for the use of polluting fuels, for example a CO_2 tax. Wages are also expected to rise, which has the largest influence on the OPEX, relative to the ALERD. According to Steve Hatfield-Dodds, wages are expected to rise 13-15% per year. It is chosen to take a conservative approach to these values, therefore a 1% wage increase per year is assumed. [93]

A linear MDO cost development from 475 to 730 euro per ton is expected. [68]

7.2.4 Influence on TCO

A summation of the cost expectation and the used cost deduction equation is given in appendix B.

With the mentioned developments taken into account, a new TCO comparison is created, which can be found in figure 18. [90] [70]

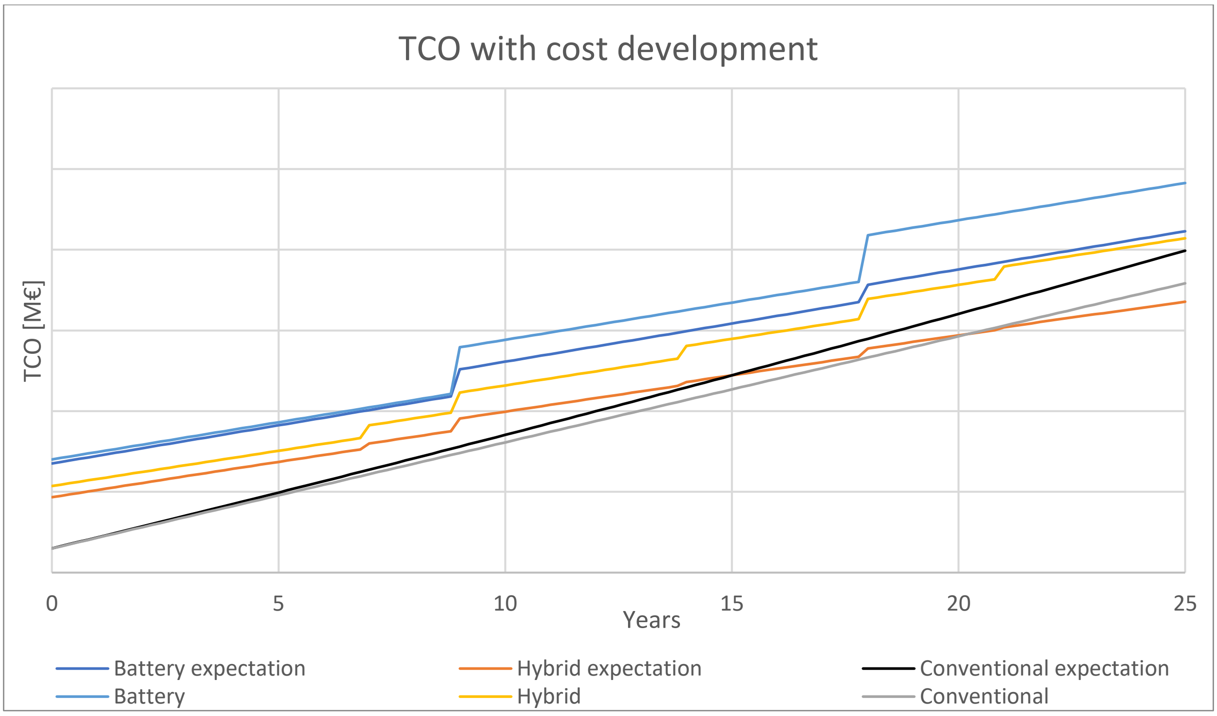


Figure 18 TCO comparison, future developments, port charging/bunkering

The expected developments gives the hybrid system a more clear advantage. The advantage of the low energy costs of the battery system is being negated by the developments in hydrogen production. Together with the faster decreasing fuel cell costs, the hybrid has the best prospect. This advantage is partly due to the more efficient profile, which for the battery remains on 2-3 dredging cycles per energy cycle. This could change in the future due to new batteries.

The conventional dredger will see a significant increase in TCO due to wage increases and diesel price increases. Taking current developments in fuel price increases in mind, this could have an even greater impact than calculated here.

Even with the cost development of batteries taken into account, the battery powered ALERD will only break even with the hybrid powered ALERD, without developments taken into account.

With €/m³ of dredging costs for the PEMFC hybrid, it exceeds the requirements.

7.3 Direct ammonia SOFC for the ALERD

This case uses the assumption that the direct ammonia SOFC technological readiness is within the development time of the ALERD. The operational profile uses the same simulation as the PEMFC hybrid, because it is designed to run the fuel cell stationary. The optimal speed of the SOFC hybrid at 9 dredging cycles and 2500 m³ is 11 knots, the optimal dredging flow is equal to the PEMFC. Using the database of the MARIN, including financial developments, the following TCO has been generated: [64]

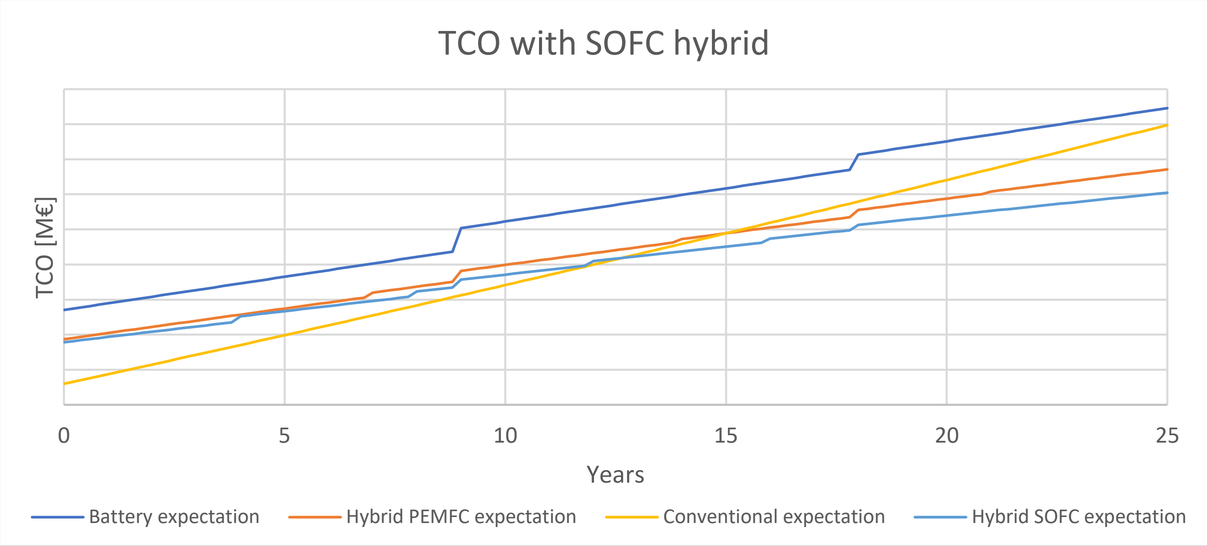


Figure 19 TCO with future developments and SOFC

The energy storage of the SOFC hybrid ALERD requires less volume and weight and cheaper bunker tanks, compared to both the PEMFC hybrid and the battery powered ALERD. This results in the possibility to have more dredging cycles per energy cycle and reduce the penalty of port bunkering. For the SOFC hybrid, the optimum was at 9 dredging cycles, port bunkering. Port bunkering has the advantage, because the benefit of local bunkering has decreased for the SOFC hybrid to per m³. Similar to the PEMFC, most of the cost deduction is from the port transit times itself, and not from the change in ship costs.

More importantly, the direct Ammonia SOFC has some practical benefits compared to the weaknesses of hydrogen. These are easier fuel handling, fuel availability and high fuel density. The better fuel handling and availability increases the opportunity to decrease the initial investment for fuel supply. The higher density is convenient for the neutral buoyancy, as it is expected that the submergibility and available volume in the ALERD can be a concern. The return of investment and initial investment is the best for the direct SOFC hybrid, which is of great importance to investors. With €/m³ of dredging costs, it exceeds the results of the PEMFC with cents per cubic metre.

Equally to the battery and PEMFC hybrid ships, the rounded number of fleet and cost per cubic metre are given for the SOFC hybrid.

7.3.1 Rounded number of ships and costs

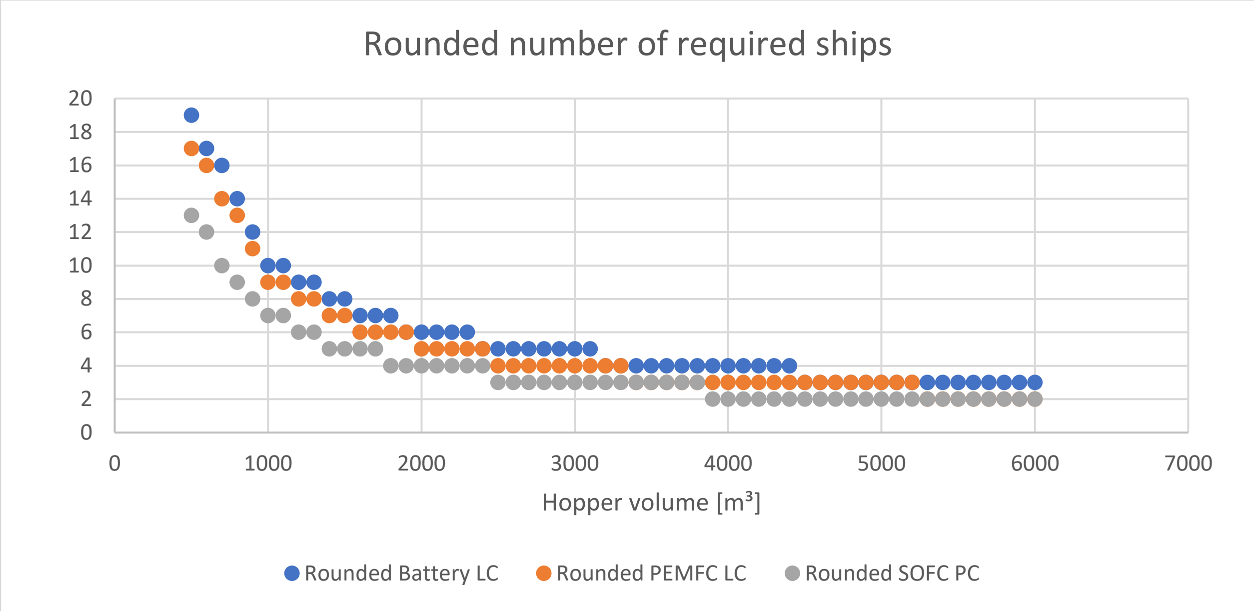


Figure 20 Required number of ships, rounded

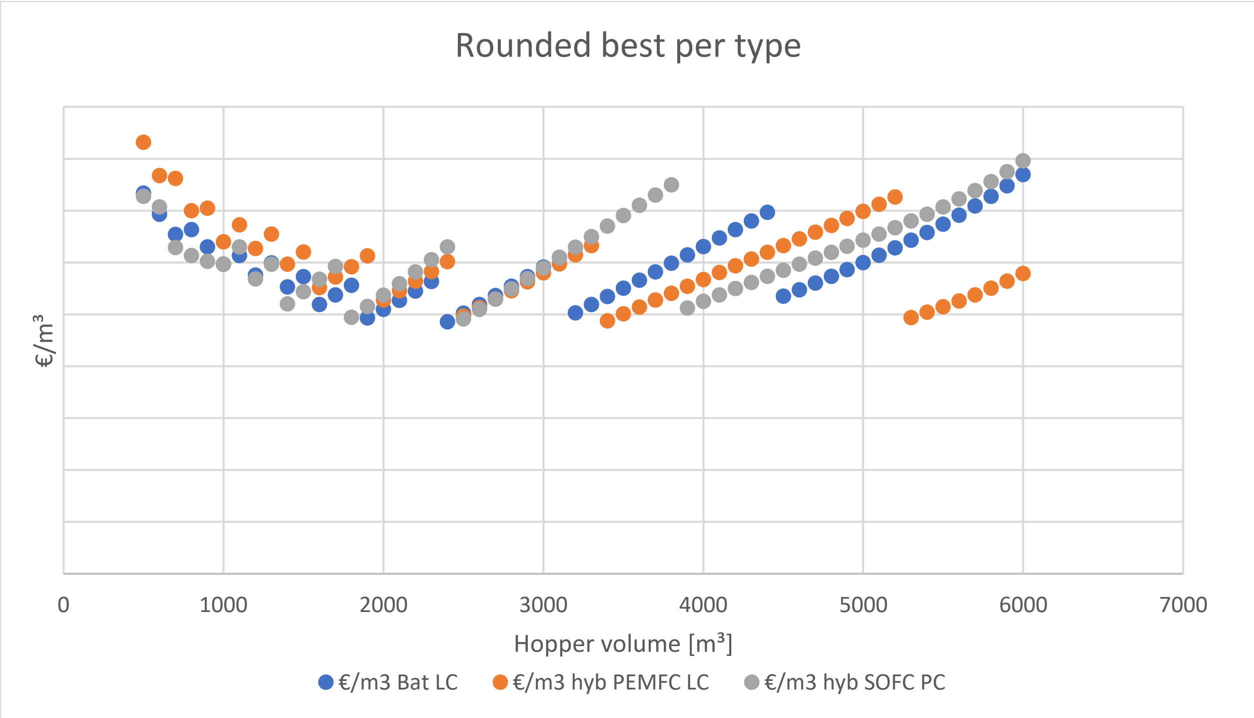


Figure 21 Costs, rounded

The SOFC hybrid ALERD has the ability to dredge efficiently 9 times per energy cycle, while bunkering in the port. Due to this advantage, less ships are required for the same amount dredging capacity. These graphs compare the port bunkering characteristics of the SOFC, with the local charging/bunkering characteristics of the other two systems. By dredging so often in an energy cycle, the ship is dredging relatively more than the other types of ships with local charging/bunkering.

The local charging/bunkering costs of the PEMFC and Battery are expected to increase relatively, according to the initial investment for the charging/bunkering stations.

7.4 Effects from varying transit distances

The optimization is based on regular and static operation, taking higher values as distances. This does not take into account special cases like unavailability of ports and accessible waterways. Furthermore, the sailing distances are not constant, meaning that the distances vary according to the precise dredging and replenishment locations.

7.4.1 Influence of varying transit distances and stored energy on board.

Possibly the most important variable input value, are the transit distances in the profile. The approach to simulate the effects of different sailing distances in a profile, is done with the use of probability.

The ALERD is designed to a singular transit distance, taking the furthest distance in the dredging replenishment location according to figure 11. The used distance is thus an upper limit in normal operation. It is assumed that the distance is sometimes exceeded, for special cases, or for the simulation of current. Ship speed and current must be added vectorially to arrive at the destinations. As a result, currents also effectively influence the sailing distances (through water). The most frequent and average transit distance is assumed on 75% of the given distances in table 7.

In reality, the ALERD has a dynamic profile with different transit distances. These distances have an upper and lower limit, and a probability for each distance to occur. Together, the average of these results can simulate the actual costs per m³ during the lifetime of the ship. In the optimization it has already been found out that the optimal speed and flow are not influenced by the transit distances (variables are equal for LC & PC). Therefore, no additional research is required for them.

The following distances have been assumed to determine the weighted averages:

Table 1 Occurance transit distances

Transit%	25%	50%	75%	100%	125%	150%	200%
Amount%	1%	10%	50%	25%	10%	3%	1%

And visualized:

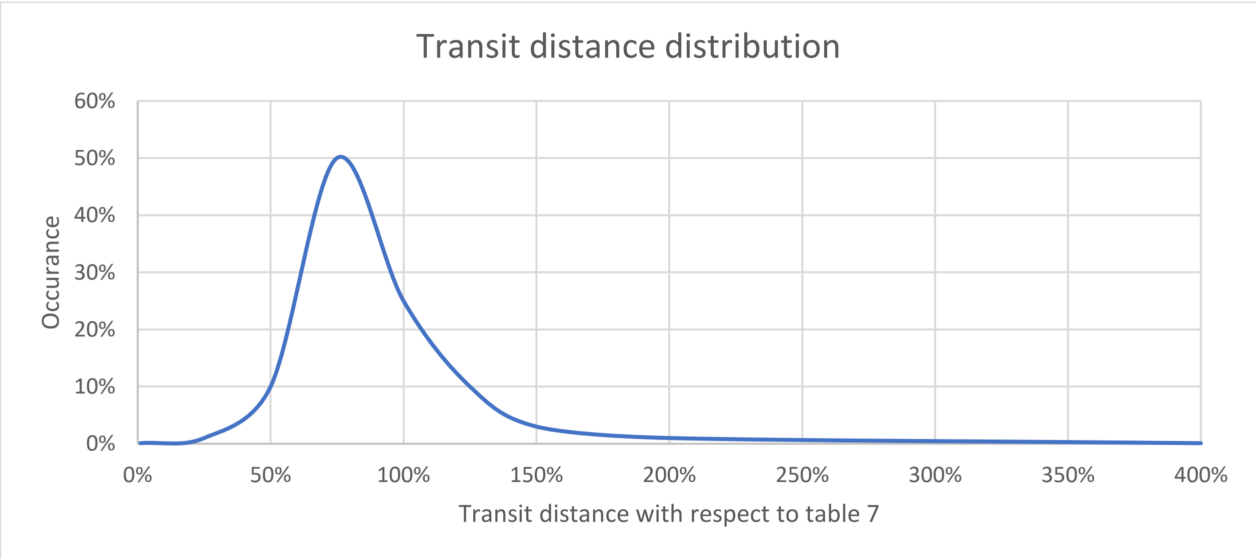


Figure 22 Transit distance distribution

To retrieve relevant data for the research, the amount of stored energy taken on board have been varied. With this, it can be shown that the chosen values in the included energy have been correctly chosen in the optimal point, or that another optimal point must be taken.

By calculating the cost per cubic metre for different transit distances and stored energy on board, an average cost per m³ can be estimated. The variable on the x-axis, the %E, is the relative energy capacity on board, in comparison with the calculated energy for a given profile. For example: 90%E for the battery powered ALERD means that the batteries are 90% size for a given ship and profile (as calculated in chapter 7).

The calculations are made for the most efficient ship size, an ALERD with 2500m³ hopper volume. The results of the research are given below:

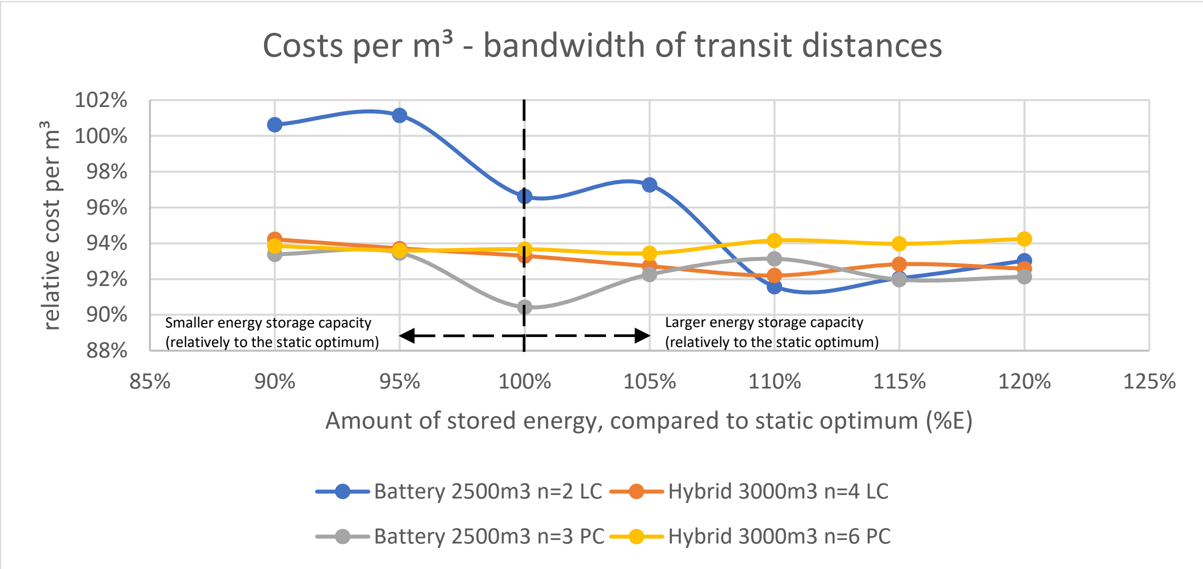


Figure 23 Costs with variable transit distances and energy input

In this graph on the x-axis, the 100% energy is the energy found in the optimal points calculated in chapter 6 (figure 9 & 10). The corresponding y-ordinates are the costs relative to the static values, as found in chapter 6 (figure 11 & 12). For example, if the battery powered ALERD has a static optimum (100%E) with 20 MWh of battery capacity, the 110%E calculates the results when a 22 megawatt hour battery is built into the ship. Through this method, it can be determined whether the chosen optimum with regard to stored energy is also valid for varying sailing distances.

The results at the same amount of energy taken on board (100%E) are lower than found in chapter 6. The cost deduction is a result from the shorter transit distances in the operational profile. The weighted average of the transit distances decreases the dredging costs relatively from the singular 100% transit distance. The differences in costs from the optimization results and weighted averages are up to 10%, in favour for the variable situation. An increase of <10% of productivity is believed as an acceptable overcapacity, to make up for backlog work, or to have sufficient capacity in busier times. If this is undesirable, the overcapacity has an almost linear influence on hopper capacity or fleet size. This means that the ships or fleet size may be smaller by the same percentage, in order to reach the same dredging capacity.

Interestingly, the costs per m³ depends hardly on the %E for most types of the ALERD. This does not include the battery LC variant, where an optimum is found at 110% of taken energy on board. The reason for this can be found in the vulnerability of the chosen profile and the high cost for storage capacity. When the transit distance is more than 100%, it has to decrease the amount of dredging cycles to be able to complete the profile. Because the cost increase from dredging profile n=2 towards n=1 is so large, the small occurrence of the transit distances further than 100% has a great influence on the average outcome of the costs. This can also be seen in the cost increase of the ship with less than 100% stored energy on board, which implies that the ship cannot dredge multiple times per energy cycle at the design transit distance. Furthermore, the relation between the energies for n=3 and n=2 is large as well, it requires a large distance decrease to be able to go from the profile n=2 to n=3. For the other profiles these effects are so small, that the matching of stored energy on board and the calculated energy is less of a concern.

The reason that the effects of varying energy are so small is that for each distance in the profile, there is a match of stored energy and required energy for an optimal dredging profile. Because the range of transit distances are divided into multiple samples, some non-linearities from the above mentioned matching occur, which can be noted in the graph. As the costs rises relatively sharp for distances further than 100% and decreases slowly below 100%, the chosen distance during optimization lays around the chosen optimization point of the transit distance distribution.

Another result of this research is that it improves the reliability of the simulation results, because a larger margin is accepted in the calculated stored energy. This provides a greater guarantee that the model can be used in reality, and that a mismatch in stored energy on board is of less concern than expected.

7.4.2 cost per m³ relation transit distance

This part visualizes the effect of transit distance on the costs per m³. The results are calculated using the optimal points for the ALERD and the best profiles. By calculating the results over a bandwidth of transit distances

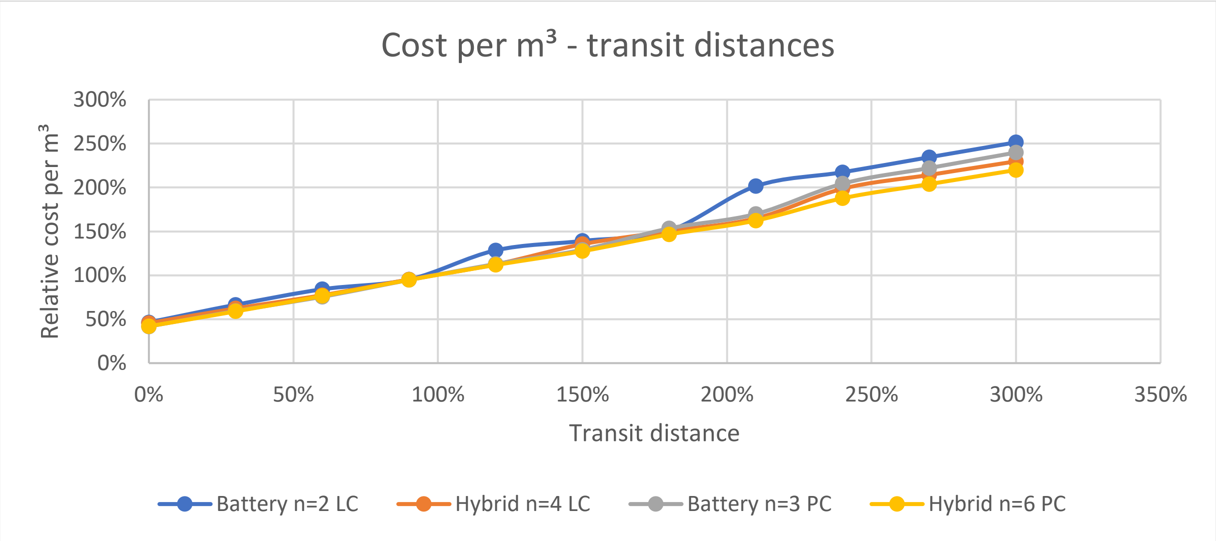


Figure 24 Costs, transit distances

The graph shows the costs per cubic metre for the ALERDs with the characteristics of the ALERD in the optimal results of chapter 6. The transit distances influence the amount of dredging cycles possible in the operational profile, and decreases the unproductive time during transits. Together, they determine the costs with respect to nominal transit distance.

Non linearities occur with the battery system. This is a result from the lower amount of dredging cycles per energy cycle. Because the profiles consist of dumping and discharging, there are several changes in the amount of dredging cycles per energy cycle. These do not always coincide, because dumping allows approximately 1.5-2 times more dredging cycles per energy cycle. The larger the transit times, the less dredged material can be deposited. This is represented by the proportional relationship between transit distance and costs per cubic metre.

The graph starts at 0% transit distance. This is only theoretical, because all operations will be performed at the same location. Concluded from this case is that 50% of the nominal costs are produced by the transits. The costs are from the energy consumption and the lost operational time (reduced replenishment capacity).

7.4.3 Hopper volume relation transit distance

To determine the hopper volume relation to transit distance, 3 samples are taken. These are the 100% distance, half distance and double distance (50% and 200% of the optimization distance) curve. The previous calculations are made for a given hopper capacity. To show the influence of hopper volume, the following graphs have been created:

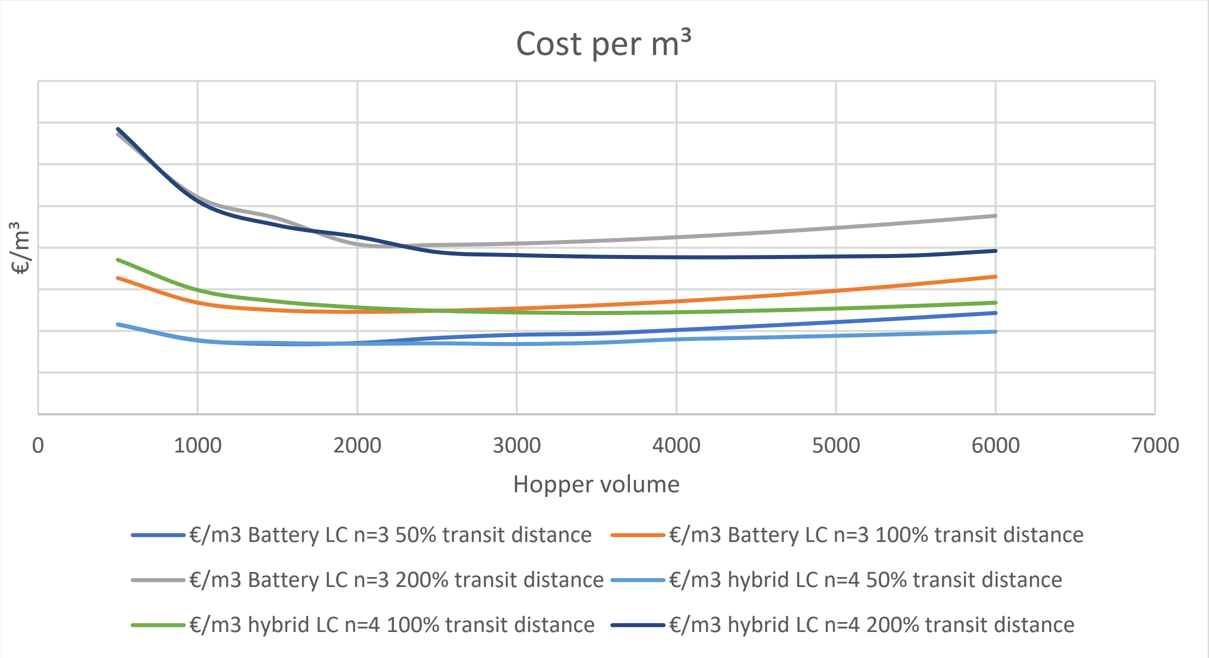


Figure 25 Costs, transit distance & hopper volume LC

This graph shows the costs per cubic metre for different transit distances, when the ship is local charging. The hybrid system has the advantage over all regions, except at 100% transit distance and hopper capacities under 2500m³. The largest advantage can be found at the larger sized ships, which seem unsuitable for the battery powered ALERD at all transit distances. The results show that the costs responds evenly to sailing distances among hopper volumes. Because larger ships require less transits, the optimal hopper volume increases with the transit distance. Therefore, shorter distances give the advantage to smaller ships. In the next graph, the results are given for the port charging bunkering results.

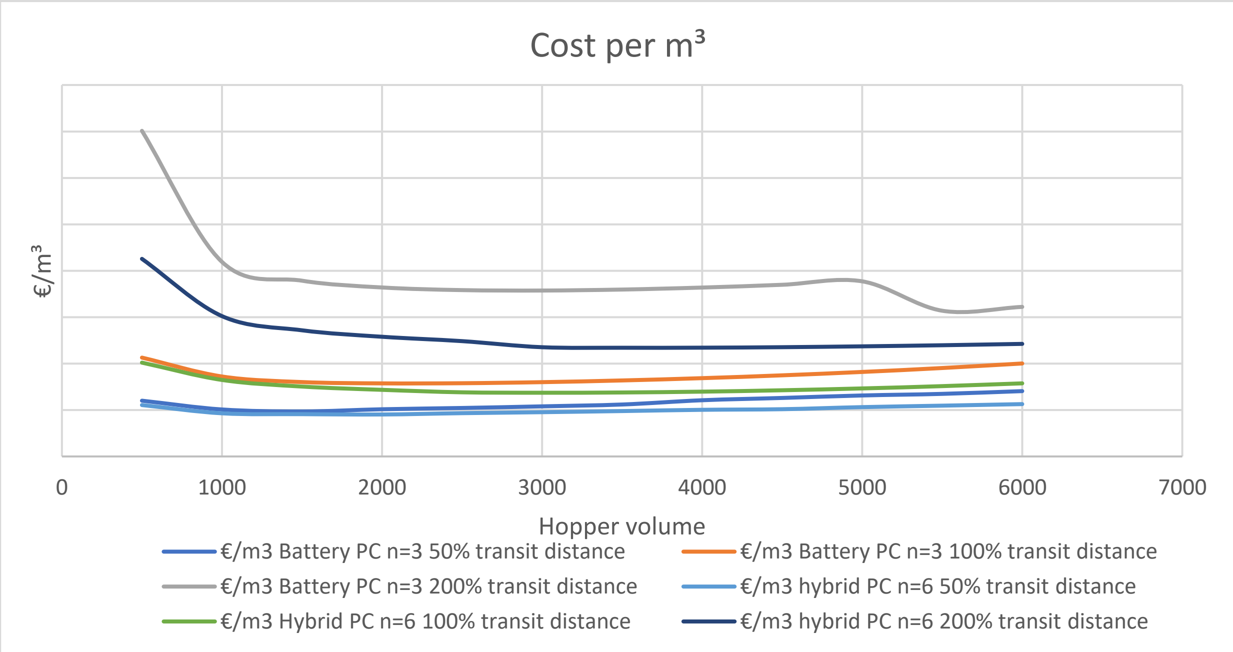


Figure 26 Costs, transit distance & hopper volume PC

Likewise as the calculations in chapter 6, the hybrid system is the best starting point for ALERD. Especially at larger distances, where it is impossible to dredge multiple times for the battery powered ALERD due to the amount of energy taken on board. For example, the Battery powered ALERD n=3 PC has difficulties to dredge multiple times in one energy profile. Only the largest hopper volumes have this ability, and therefore a large cost decrease is found at a hopper volume of 5500 m³. The effects are in general even over hopper capacities. However, smaller ships are affected the most by the changing transit distance, because they require relatively more transits.

7.5 Conclusion

Based on the above mentioned results, the following research question can be answered:

"What are the effects of the varying input data?"

The answer to the research question is: The variable input data have a small positive effect on the results of the ALERD, without interfering with the optimization points. These effects decrease the TCO and increase the dredging capacity of the fleet.

The cost developments and variable transit distances have a positive effect on the outcome. With the cost developments taken into account, the ALERD becomes financially competitive with a conventional dredger. The variable transit distances increases the dredging capacity per ship by the reduced transit times and improved dredging profiles. This results in either a reduction of hopper size/number of fleet, or an increment of the margin. The direct ammonia SOFC-hybrid has with all developments taken into account the best prospects. In addition, the use of ammonia as a fuel has a number of distinctive advantages due to its properties compared to hydrogen. However, the PEMFC-hybrid system is still competitive with respect to costs and has the advantage in terms of development stage and certainties.

The next chapter discusses the characteristics of the energy supply system, as retrieved from the simulations. The results are given from the three best and most feasible design operational profiles, and port charging/bunkering.

8 Results

Design data of the energy systems, as retrieved from the simulations

8.1 Introduction

This chapter focusses on answering the research question:

"What are the design data of the best energy supply system(s) in the ALERD?"

The chapter covers the design data and technical suggestions. At first the general data of the energy supply system is given for the most competitive operational profile. Afterwards an instruction is given for the placement and reserve capacity for calamities. A suggestion is given for the cooling system, because some issues were expected by the autonomous underwater operation and the difficult operating temperature of batteries, as found in literature review.

The data chosen are the optimal input variables as found in chapter 6, because it has been confirmed in chapter 7 that these points are valid for variable scenarios. The given results are calculated from the port charging/bunkering simulations, because this is expected as the most feasible solution. Both systems are involved in the results, to compare the results and because the results of the volume and weight study could still influence the outcome of the research. Furthermore, the battery system has the best round trip efficiency, because of the losses of hydrogen production and electrical energy conversion. Therefore, the battery system has the lowest ECI (Environmental Cost Indicator), something that cannot be ignored.

8.2 Energetic data

The given energies are the total stored requirement, including efficiency and a 30-80% state of charge operation for the batteries and the efficiencies for hydrogen. The given powers are the output powers, after the efficiencies. For an efficient operation, it is advised to run the PEMFC at approximately 60% load, increasing the design power to 166% of the given numbers.

8.2.1 Battery ALERD

The Battery powered ALERD is the most effective at 2 or 3 dredging cycles per charge. For these profiles, the following relations can be set up, which is retrieved from the operational profile study.

Battery power

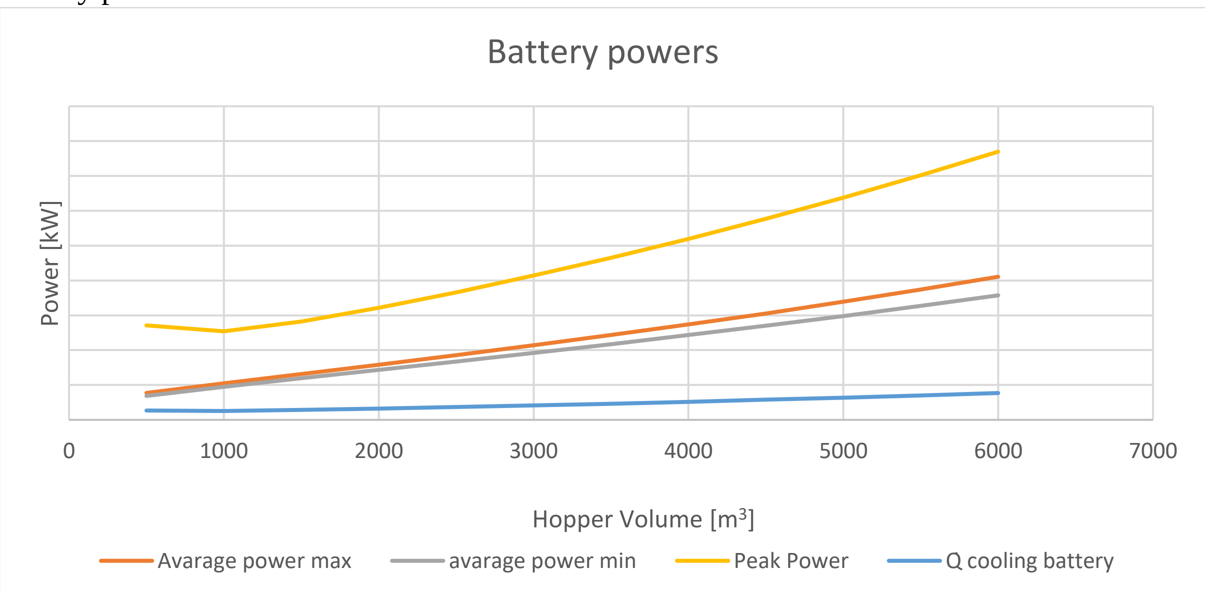


Figure 27 Powers Battery ALERD

There are some small deviations between the average powers in between different profiles and local and port charging. As these differences are rather small and vary as predicted, only the minima and maxima are given in the graph. The upper limit of average power ("average power max") will be found with profiles with more dredging cycles, because more dredging cycles require relatively less (low power) transit time. In contradiction, the lower limit of the average power ("average power min"), will be found at profiles with less dredging cycles, because it requires relatively more (low power) transit time.

The peak powers, during dredging, and thus the cooling capacity of the system are only a function of the hopper capacity and therefore equal for all profiles.

The peak power of a 500 m^3 ALERD is higher than a 1000 m^3 ALERD, which feels contradictory. The peak powers are found during the dredging operation. Due to the geometric scaling of the dredging equipment, an asymptote will be found at the vertical axis. This comes from the resistance and acceleration of the dredge, whose are infinite for a pipe diameter of zero. Together with the decreased dredging capacity per ship, this affects the costs per m^3 mostly.

"$\dot{Q}$ cooling battery" is the required cooling capacity in kilowatts. The function is calculated using the efficiency and maximum power output of the battery packs. The given values are thus the peak cooling requirement, during the dredging operation. The average cooling capacity requirement is approximately 40-50% of the given function. The cooling of the systems are further discussed in paragraph 8.4.

Battery energy

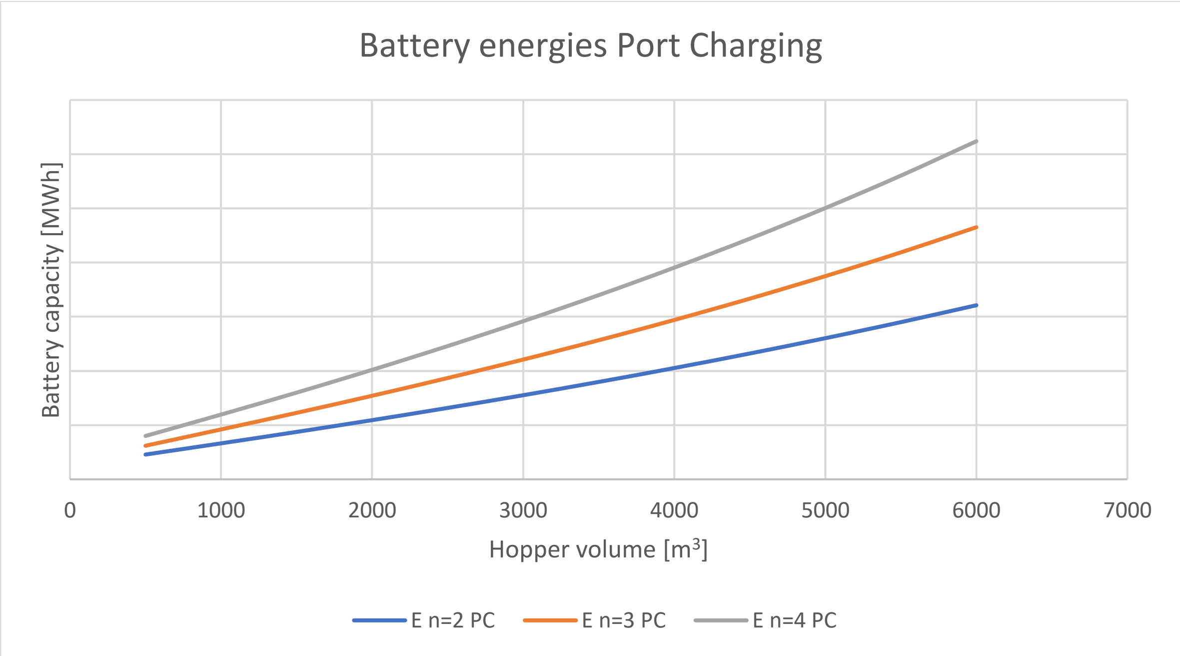


Figure 28 Energies battery ALERD

The battery capacities rise with a power function, which is a result of the linear increasing flow, geometric scaling of dredging equipment and increasing energy cycle time. The dredging, dumping and discharge time are dependent on the hopper volume, which takes longer for larger ships. Together, they primarily determine the required battery capacity for a given operational profile and hopper volume.

8.2.2 Hybrid ALERD

The hybrid powered ALERD is the most effective at 5-7 times dredging per energy cycle, port bunkering. For these profiles, the following relations can be set up, which is retrieved from the operational profile study:

Hybrid power

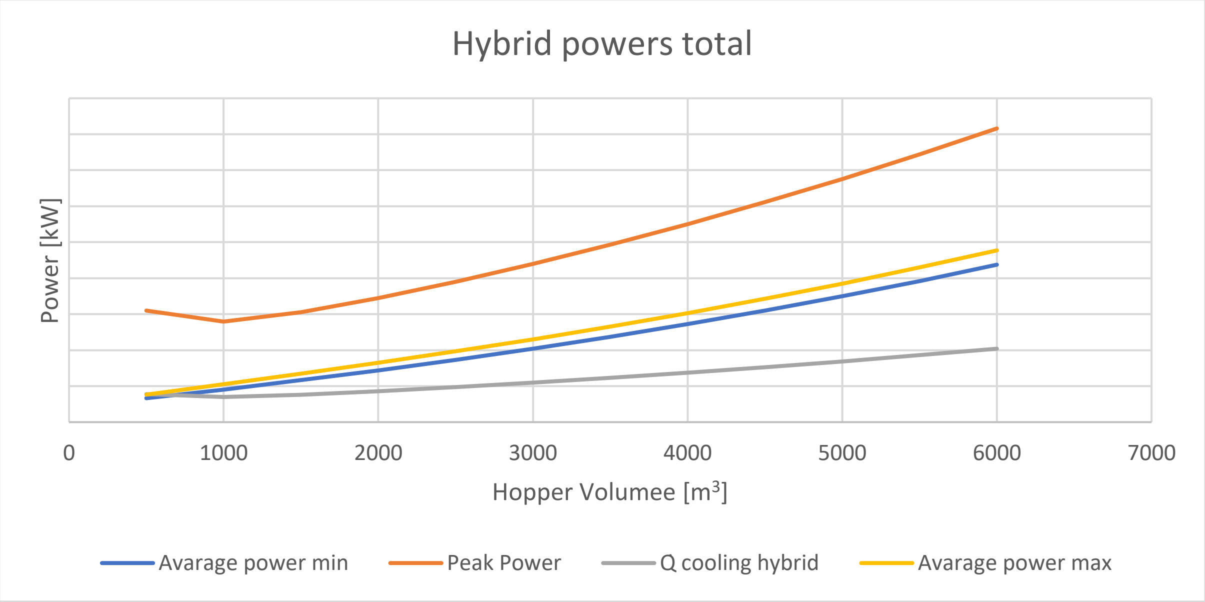


Figure 29 Powers hybrid ALERD

Similar to the battery system, the average power is slightly dependent on the profile and local/port bunkering. A range is given for the average power with an upper and lower limit to increase the readability of the graph. Again, the vessels with the lowest number of dredging cycles have the lowest average power, and the ships with the highest number of dredging cycles the highest average power. The difference between the upper and lower limit of the average powers are more constant for the hybrid powered ALERD. This comes from the variable transit speed, which is a function of the hopper volume and number of dredging cycles. The design specifications of an ALERD with relatively more transit time, the port charging variants, have more dredging cycles and thus a higher transit speed. The effects amplified with the combination of the increasing transit speed for larger hopper volumes. In short, the reduction of average power is decreased, due to a higher transit power.

The peak powers of the hybrid powered ALERD are slightly higher compared to the battery powered ALERD, due to the higher dredging flow. Together with a decreased overall energy system efficiency, a higher cooling capacity requirement is expected.

Fuel cell power

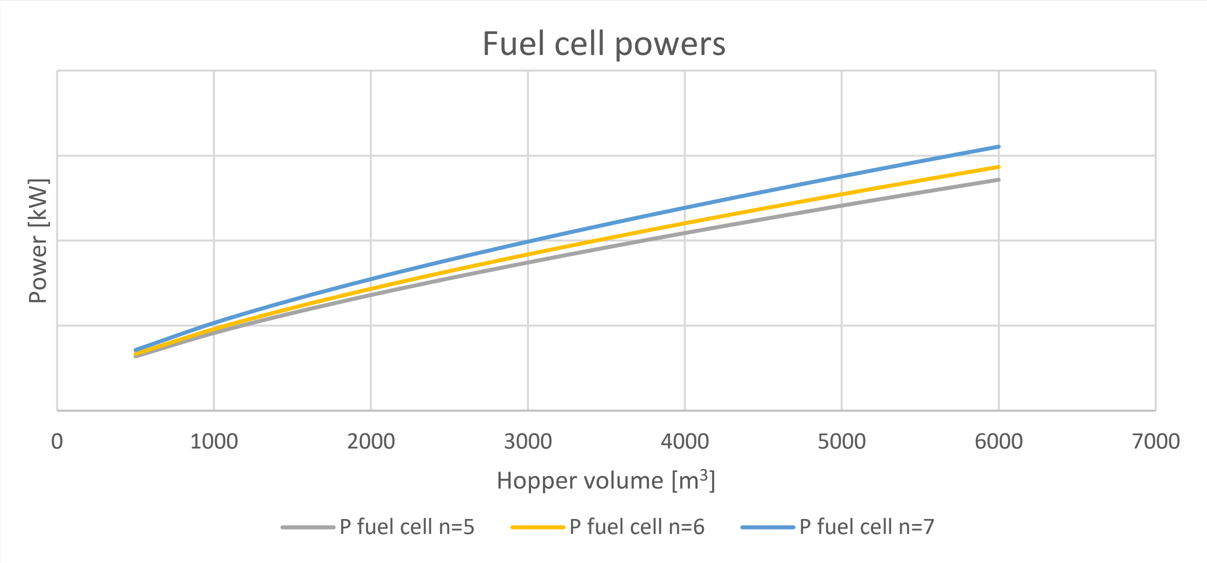


Figure 30 Powers hybrid fuel cell

Transit speed, and therefore the fuel cell power is only dependent on the number of dredging cycles and hopper volume. Therefore, the distinction between local and port bunkering is not included in the legenda.

The method of optimization, varying speed for the different operational profiles, is clearly visualized in this graph. By raising the transit speed for higher number of dredging cycles, the transit power and thus the fuel cell power is increased. Therefore, the fuel cell power designed for 7 dredging cycles has the highest output and the fuel cell power designed for 5 dredging cycles the lowest. Furthermore, the power of the fuel cell is increased by higher hopper volumes. This is affected by the increasing resistance coefficient and speed for larger ships. The following graph shows the battery peak powers of the ALERD, which is used during dredging.

Battery power

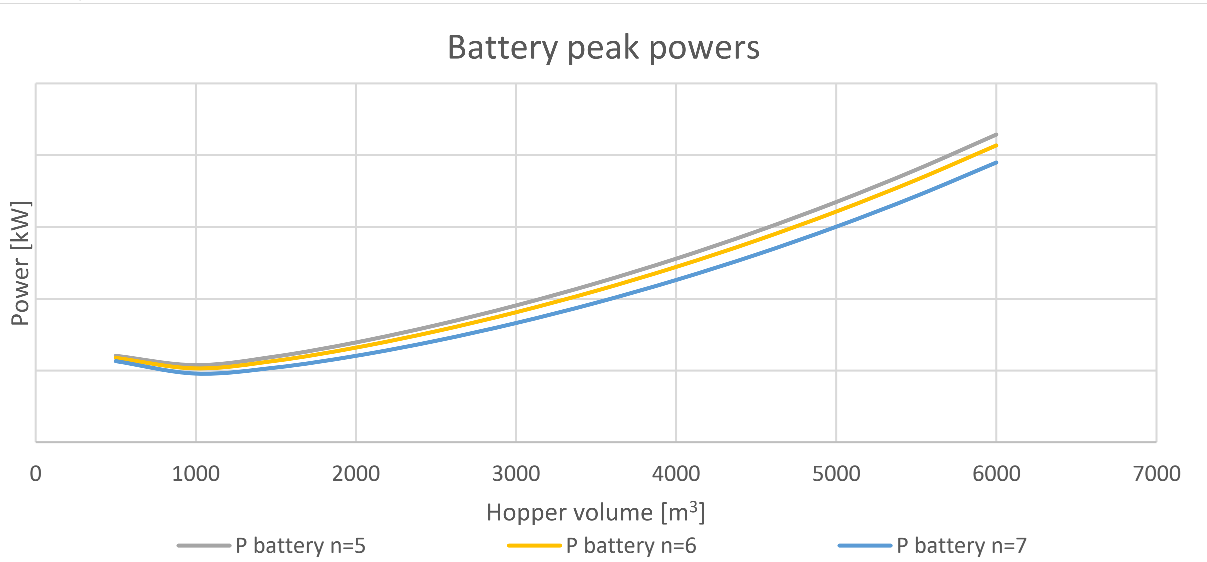


Figure 31 Powers hybrid battery

The goal of the hybrid optimization can be seen in this graph. Where the fuel cell power increases for more dredging cycles, the battery power decreases. As a result, the increment of required battery energy per dredging cycle is decreased as well.

Similarly as the battery powered ALERD, the power at 500 m^3 hopper volume is higher than at 1000 m^3, which comes from the decreasing dredging equipment dimensions.

Hydrogen energy

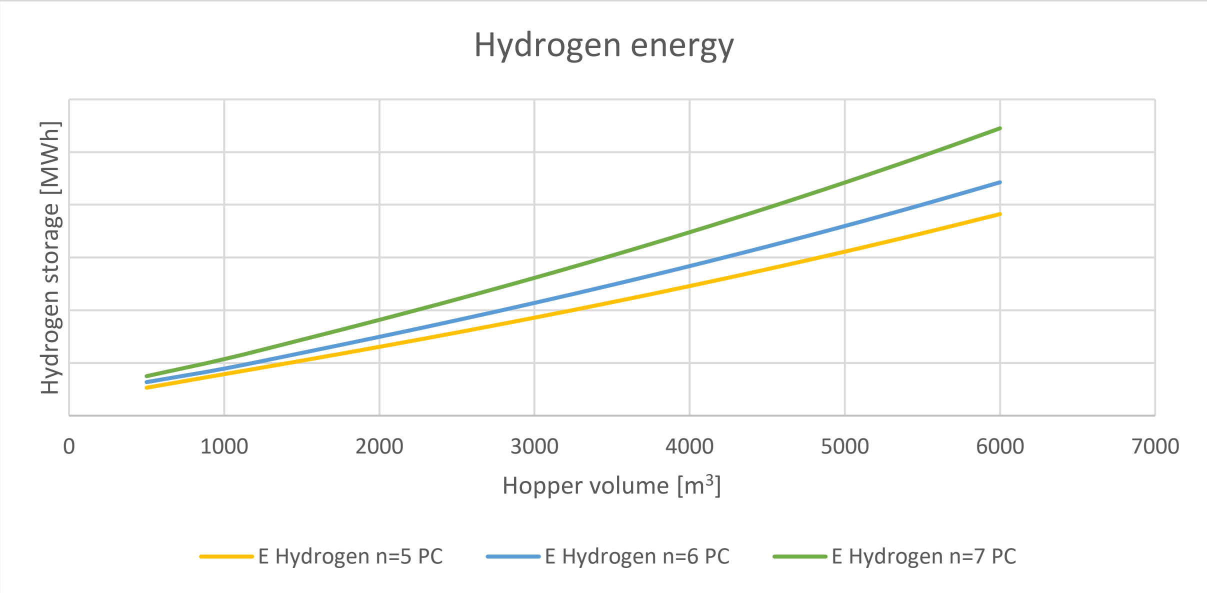


Figure 32 Energies hybrid hydrogen

The energy requirement of hydrogen is proportional to the fuel cell power. This comes from the assumption to run the fuel cell at constant load, to increase efficiency and lifetime. The energy requirement is also proportional to the energy cycle time, which is in its turn dependent on the hopper volume. The energy cycle time increases with hopper volume, which is a result of the increased dredging operation times.

Much similarities can be found between figure 32 and figure 28. A large distinction between these two is that the energy required from hydrogen is only a part of the total energy requirement, and the remaining energy comes from the batteries in the hybrid system. The capacity required from the batteries in the hybrid system is given in the following section.

To express the required energy from hydrogen in weight, every MWh of hydrogen energy equals 30 kg of hydrogen.

Battery energy

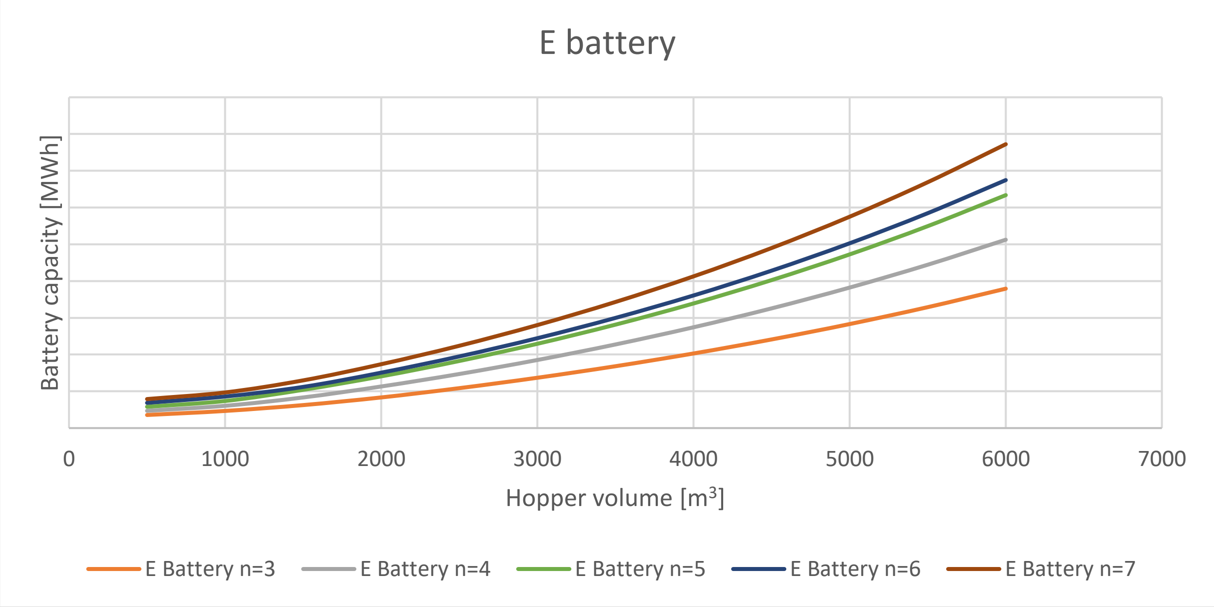


Figure 33 Energies hybrid battery

More design profiles are included in this graph to show the results of the speed optimization. The increment of battery capacity is reduced, by the variable transit speed and thus fuel cell power. Because the number of dredging-dumping cycles is not an integer multiple of the dredging-discharge cycle, some irregularities occur. The differences between n=3 and n=4, and n=6 and n=7 are larger, because relatively more dredging-dumping cycles are performed. The relative increment of dredging-dumping cycles increases the battery energy as well. When comparing the energies of different profiles, this should be taken into account. The results of the optimization can be directly obtained from the difference between n=3 and n=5, and n=5 and n=7, where the mentioned differences from dredging profiles is not present.

8.3 Placement, redundancy and reserve energy

8.3.1 Battery powered ALERD

Li-ion batteries have a density of approximately $2{,}5\frac{t}{m3}$. Because space is required for maintenance and inspections, additional space of up to 50% is expected. This decreases the battery room density to an average of $1{,}25\frac{t}{m3}$, which is still higher than seawater. Therefore the advised location is below the centre of buoyancy. Some submarines experiment with batteries placed in the double hull. This would require complex maintenance procedure, but it could eliminate the required void, increasing the total density of the battery room.

Furthermore, it is advised to place the batteries in multiple rooms for redundancy. When there are separate rooms in the front and aft with a separatable grid, maximum redundancy can be achieved. However, it must be taken into account that sufficient energy is left on both sides to bring the ship to safety. Therefore a calculation have been made for the minimum battery capacity, when they are separated.

For calamity combat, an intensive power consumption during 40 km of transit is taken into account. The distance is to bring the ALERD into safety and to receive help from the coastguard. The intensive power consumption consists of full transit power, including an additional assumed power. In total, equal to:

$$P_{emergency} = 125\%\ \mathrm{P}_{\mathrm{transit}} \tag{8.31}$$

The assumption is based on sailing the design transit speed and the use of emergency response equipment, such as firefighting pumps and additional ballast pumps.

Using the data from figure 28 and 125% transit power, the following graph has been created:

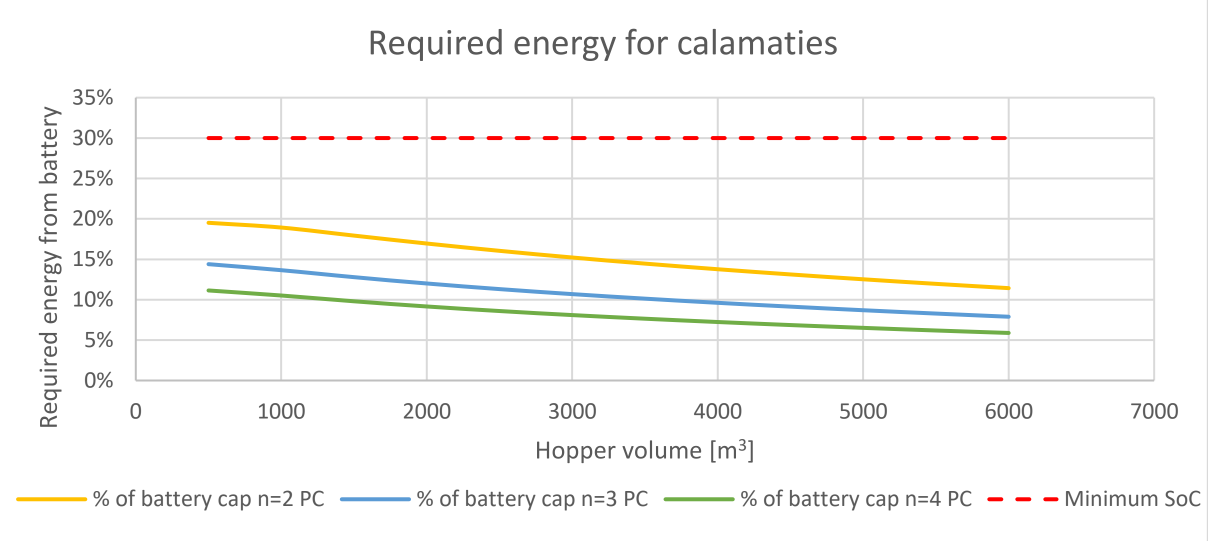


Figure 34 Energy calamity battery

The given values are relatively seen from the total battery capacity. When the required energy for calamities rises above 30%, it is more than the minimally available energy from the batteries. This comes from the assumption to run the batteries between 80-30% state of charge, of which the remaining 30% can be used for emergencies.

Using the assumption that 1 battery room may become unavailable, or causes the emergency, the number of separated battery rooms can be calculated. Using the 30% minimally remaining energy in normal operation, the data from figure 34 and equally divided battery capacity, the following number of battery rooms should be separated for redundancy;

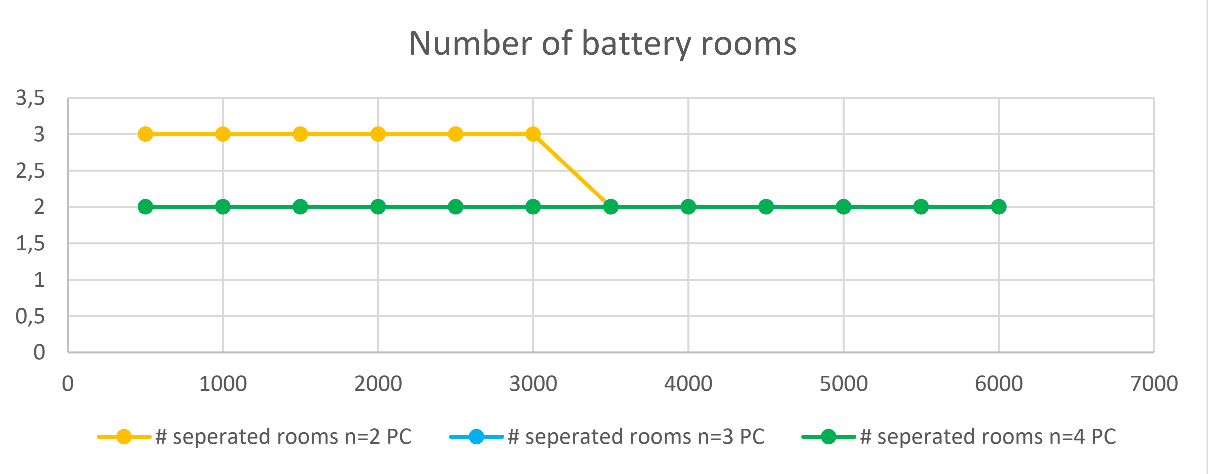


Figure 35 Amount of battery rooms for redundancy

Due to the minimum state of charge of 30%, the batteries only need to be placed in two or three rooms to maintain sufficient energy for redundancy. The design profiles n=3 and n=4 coincide and have to be placed in minimally 2 rooms to have sufficient energy available when one battery room becomes unavailable.

8.3.2 Hybrid powered ALERD

In contradiction with the Battery, the fuel cell system has insufficient density for positive stability. Even the highest dense component, the fuel cell itself, with a density of approximately 2 ton/m³ will have a density lower than seawater, when maintenance space is taken into account.

For the hydrogen storage, a high placement is inevitable. Due to its low density, a lot of net upward force is generated. A high placement will benefit the crucial stability.

Aside from the required energy for the emergency response, sufficient power should be available as well. Aside from the fuel cell, the battery can supply energy. It is assumed that the batteries are separated in three different rooms for redundancy. The remaining battery energy is now minimally equal to $\frac{2}{3}$ of the 30% SoC from figure 33. When this is extracted from the emergency power during the 40 km transit, equation (8.3.1), and using the fuel cell output from figure 30, the following graph is created:

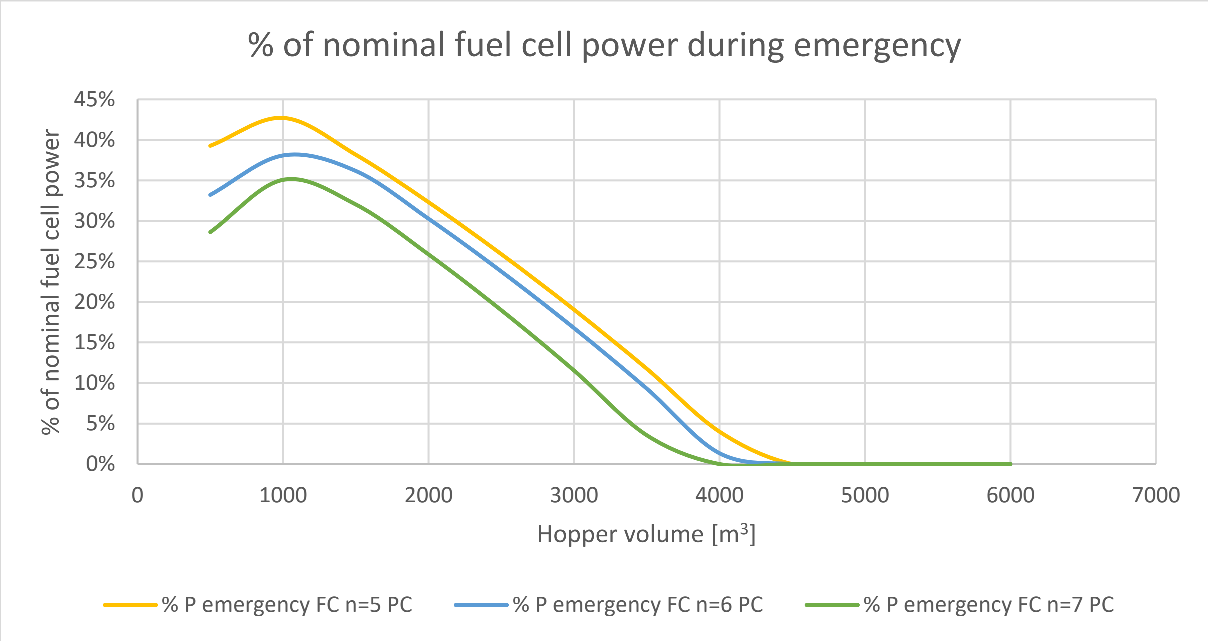


Figure 36 Powers calamity hybrid

The percentage of nominal fuel cell power is always below 43%. This comes from the assumption to run the fuel cells at 60% load in normal operation, in combination with the remaining battery energy, which is minimally $\frac{2}{3}$ of the minimal remaining 30% SoC.

Similarly, the fuel cell rooms can be separated for redundancy. Here, the remaining available power from the fuel cells should be sufficient when a fuel cell room becomes unavailable. With respect to 100% power output of the available fuel cells, the following has been concluded:

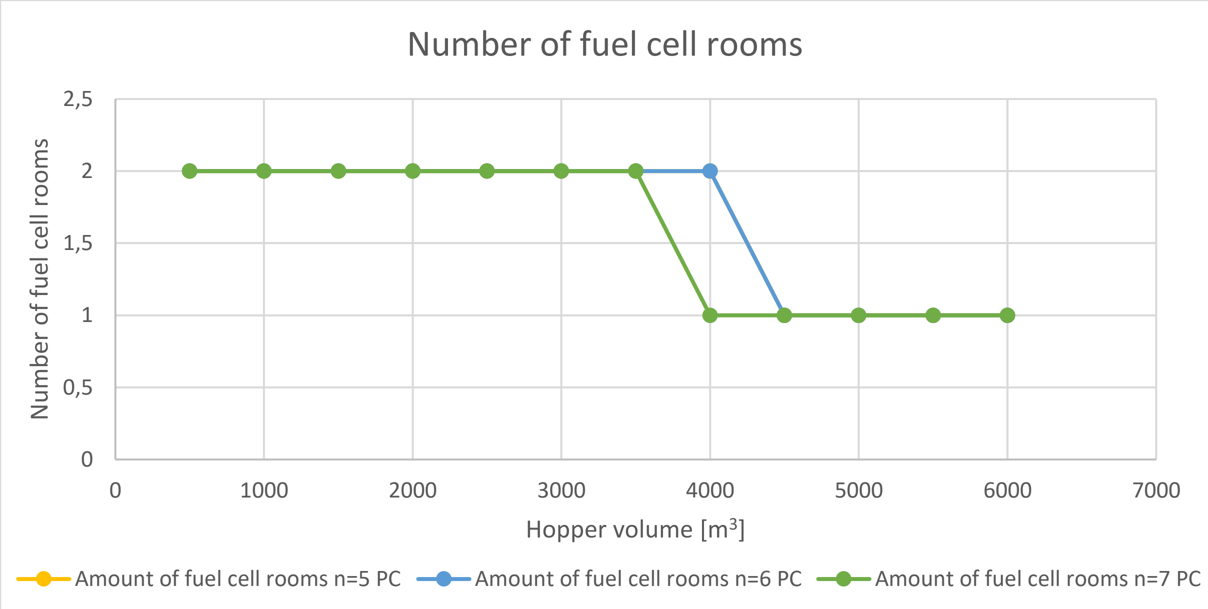


Figure 37 Amount of fuel cell rooms

The required power for the fuel cells reaches zero for some profiles and larger hopper capacities, because the stored energy in the batteries are sufficient for the operation during calamities. Therefore, the fuel cell does not have to be separated into different rooms for the purpose of redundancy for these ships.

The following graph shows the additional energy requirement from the fuel. Ideally, it should be zero, because that would mean no additional energy has to be taken on board for the case of emergencies. This differs from the batteries, where there is always energy remaining during normal operation.

Using the minimally remaining battery capacity, the following has been concluded:

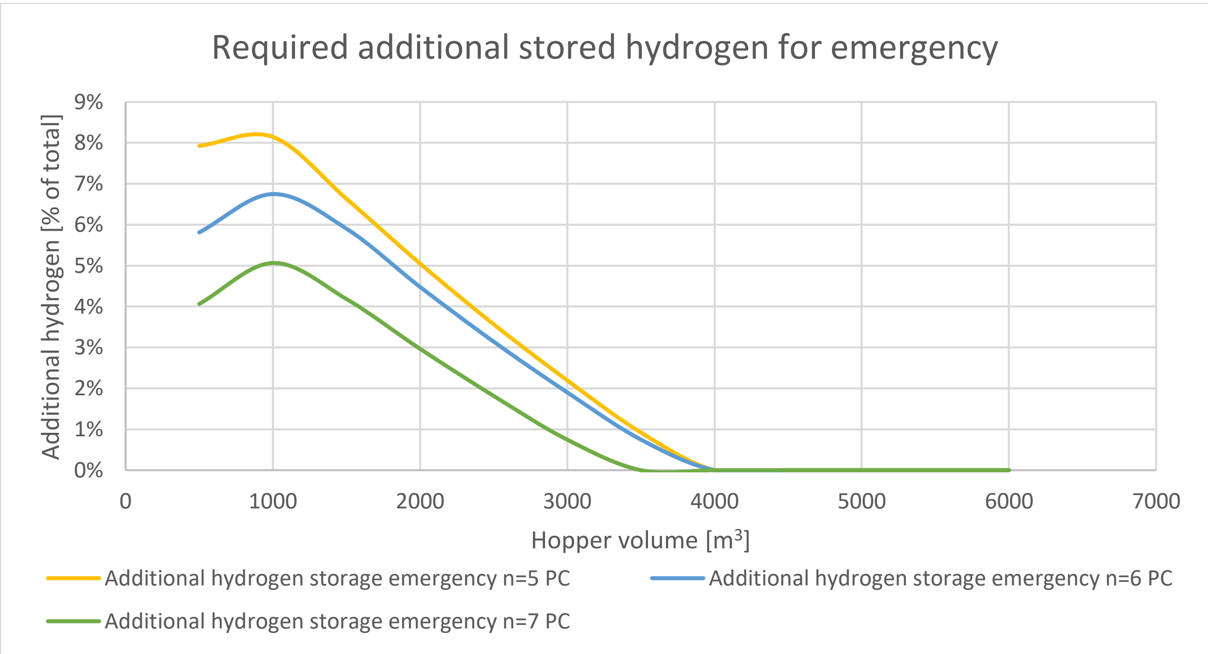


Figure 38 Additional hydrogen calamity

To guarantee that there is sufficient energy available during the event of calamity, additional hydrogen has to be taken on board for some ships and design profiles. The energy will be only available for this, and may not be used for regular operation. When a ship is designed that requires a low amount of hydrogen, relatively more energy is required for calamities.

Because for some profiles there is no power required from the fuel cell during calamities, there is no additional energy of hydrogen required as well.

To reduce the additional required energy of hydrogen, it is possible to separate the batteries in more different rooms. Furthermore, it is advised to store the hydrogen in safe and separate rooms when it is required for calamities. Otherwise, it might be possible that the fuel becomes unavailable.

8.4 Cooling

It had been concluded that a keel cooling system will be required for prolonged redundant and autonomous operation. Due to bottoming and surfacing, it was also concluded that the cooling surfaces must be placed on the side(s) of the ship.

A standard calculation for a keel cooler in a steel hull is: [93]

$$A_{keel\ coolers} = \frac{Engine\ kW}{32}\ [m^2] \tag{8.4.1}$$

Which is calculated for a diesel engine. For a Fuel cell this is an equivalent of $\frac{1}{64}$ square metres per kW if working temperature and efficiency is taken into account. For the battery system according to equation (7.45), this would be $\frac{1}{23}$ square metres per kW. Because the used data is for pleasure yachts, it is expected that these figures are estimated conservatively.

Using equations (4.61) and (8.41), the cooling requirement of the different systems and geometric scaling of the hull surface, the following graph with required cooling surface is acquired:

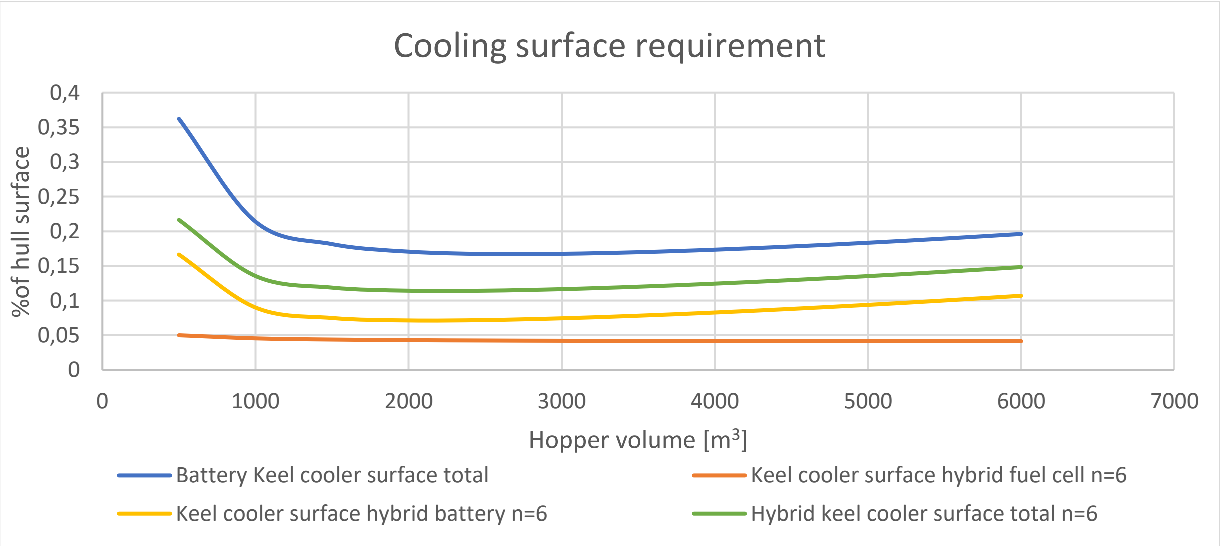


Figure 39 Cooling of systems

In the graph, the results are normalized to hull surface.

Regarding the placement of coolers to the sides of the hull, it can be assumed that cooling surfaces above approximately 20% of the hull surface are infeasible when it is applied directly on the hull. Some producers make stacked coolers. A disadvantage of this is that it has a serious effect on the resistance coefficient of the ship.

The hybrid variant has the best prospects, with a small advantage for larger number of dredging cycles per energy cycle. In the hybrid system, most cooling surface will be required for the batteries as well. More design profiles have been considered in the calculation, but it was noted that the differences between them are negligible.

Because the high loads during operation are limited in time, some overcapacity in the given numbers is expected. This, on the other hand, is absorbed by deposits/scaling on the keel coolers, which decreases the thermal conductivity coefficient.

8.4.1 Battery Powered ALERD

For the battery powered ALERD, 2 systems are proposed. The first system is a standard keel cooling system, which is applied in yachts and motorboats. There is one difference among the system in the ALERD, which is the operating temperature.

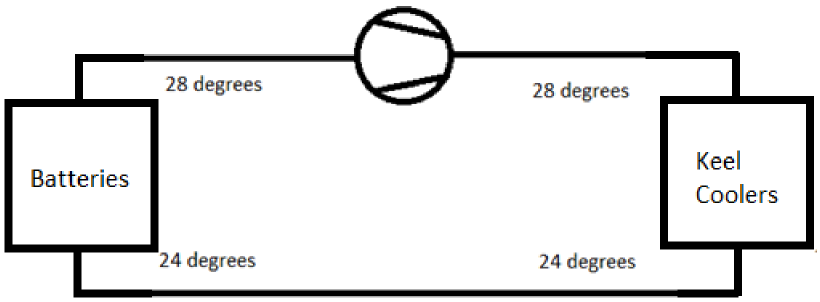


Figure 40 Battery direct cooling proposal

Above is a sketch of the proposed system. The sketched situation is in a hot summer, when the seawater temperature can reach 23 degrees Celsius. due to the low temperature differences, the cooling capacity may not be sufficient. A second system has been devised for this:

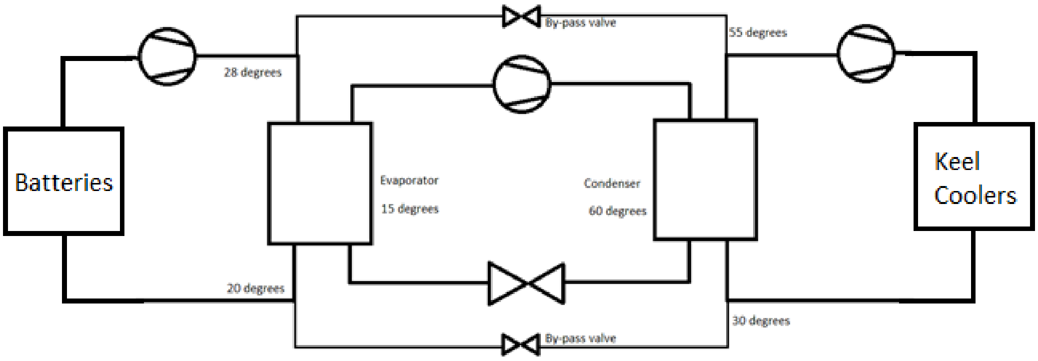


Figure 41 Battery indirect cooling proposal

The power requirement for the compressor can be estimated using the Coefficient Of Performance (COP)

Using: [94]

$$COP_{carnot} = \frac{T_{condenser}}{T_{condenser} - T_{evaporator}} - 1 \tag{8.4.2}$$

And: [94]

$$COP = COP_{carnot}\eta_{system} \tag{8.4.3}$$

And by using: [94]

$$\eta_{system} \approx 60\%$$

Gives:

$$COP \approx 3{,}8$$

With:

$$P_{compressor} = \frac{q_{cooling}}{COP} \tag{8.4.4}$$

Which is an acceptable power consumption for an alternative cooling method (compressor power is in the order of 10 to 100 kW). In combination with a by-pass, the cooling system has high efficiency when the seawater temperature is low, but keeps the required cooling capacity when the seawater temperature is high. Given the rising seawater temperatures (especially in coastal waters) and the future orientated plan, it is advisable to equip the system accordingly. It is also possible to implement the system in a later stadium, when the cooling appears insufficient in the summer.

8.4.2 Hybrid powered ALERD

The proposed system for the cooling is a closed, direct keel cooling system. This has been made possible by the better operating temperature of the PEMFC.

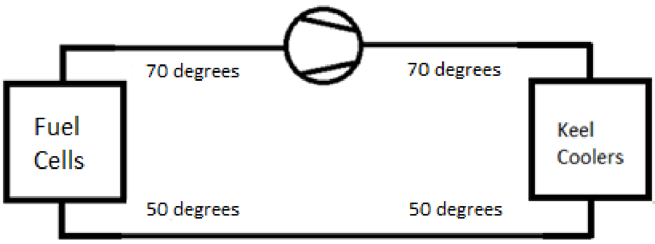


Figure 42 Fuel cell cooling proposal

Due to the high temperatures, this system cannot be used directly for the batteries. For this there will also be required a refrigerator system or a separate keel cooler system at low temperature.

Because the battery power and output durations are relatively low compared to the battery powered ALERD, fewer problems are expected with respect to the battery cooling.

8.5 Weight and volume estimation

To calculate the weight and volume estimation of the systems, a few assumptions were required. For the cylindrical storage tanks, cubical spaces around the tanks are calculated within the given values. The cubical spaces are given, because of the required foundations of the tanks and useful area. For the hydrogen storage, a 300 bar tank is chosen to determine if the storage density is sufficient for the ALERD. A 300 bar tank has the advantage over a 700 bar tank because it is cheaper and because it has less compression losses. When the storage volume, required for hydrogen, is too large, a 700 can provide a solution. For now, this does not seem to be the case and the proposal is kept at the 300 bar tanks. The following data are retrieved from the database of Marin and from a LOx tank of Linde:

Weight:

- Battery weight of 4 tons per MWh [64]
- Fuel cell of 22,5 tons per MW [64]
- 300 Bar hydrogen storage in cylinders at 1,1 tons per MWh [64]
- Liquid oxygen storage in tanks at 0,5 tons per MWh [95]

Volume:

- Battery volume of 2,5 m³ per MWh [64]
- Fuel cell volume of 15 m³ per MW [64]
- 300 Bar Hydrogen storage in cylinders at 2,5 m³ per MWh [64]
- Liquid oxygen storage in tanks at 0,75 m³/MWh [95]

The given weight and volume values are the contained energy densities, to represent the true storage densities.

The stability research of the ALERD has calculated a mass and volume for the energy system of representative 230 tons and 330 m³. The mass is extrapolated according to the assumption that it scales with the hopper volume to the power $\frac{3}{2}$, which is the inverse of the geometric hull mass which (at equal hull thickness), which scales at the power $\frac{2}{3}$. In this way, these weights are offset to maintain neutral buoyancy.

Resulting in:

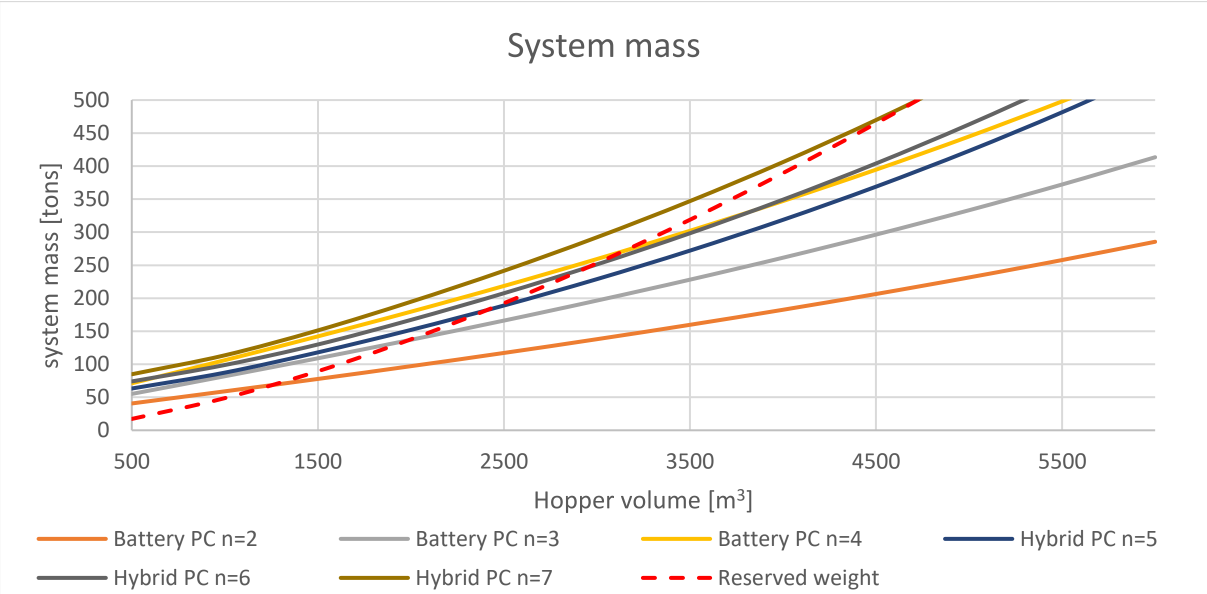


Figure 44 System mass estimation

The system weight has to be near the red curve to allow neutral buoyancy. When the system weight is higher, additional buoyancy has to be created. In contradiction, when the system weight is lower, additional weight has to be added. In the concept design, stationary ballast is used. Hence, additional weight for the energy system, especially in the form of batteries, is feasible. It is therefore quite possible that the hybrid PC n=7 system can be implemented in the submarine without any problems.

Because the red curve is the expected reserved weight for the energy system, the system mass should be near the given values. It is in this stage unclear if the system weight should be equal, more, or less than the given values.

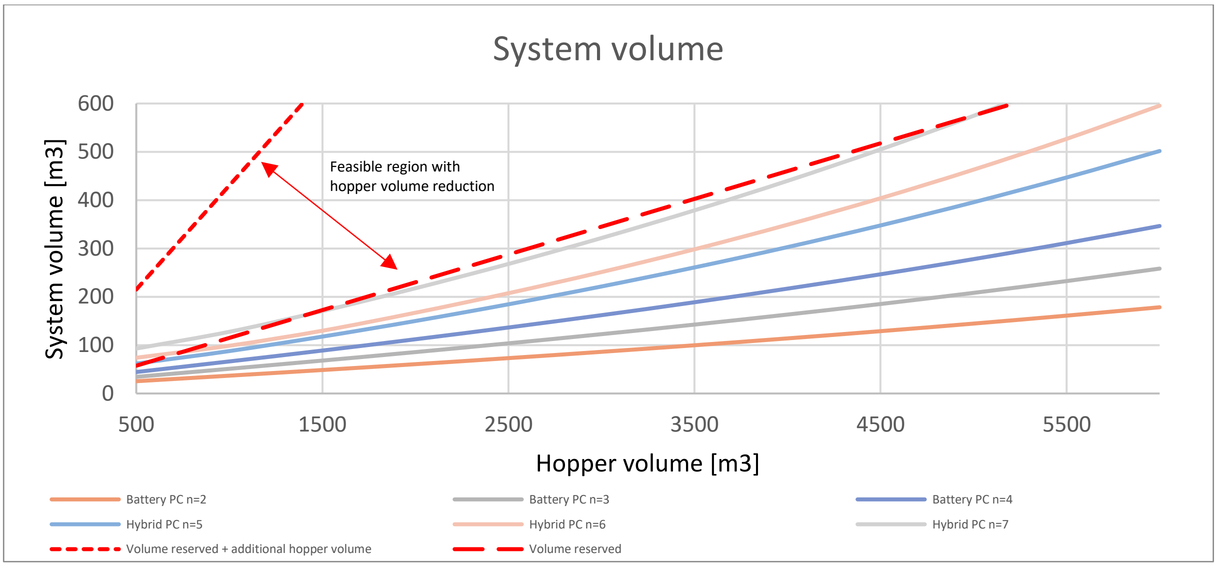


Figure 45 System volume estimation

The volumetric limit is a upper limit, because less required system volume can be converted into, for example, extra hopper volume or less displacement. If the system becomes too large, it is possible that the system does not fit or that the neutral buoyancy is affected. From the results it is likely that a 300 bar hydrogen storage is feasible for the purpose of the ALERD. When the relative hopper volume reduction from AUMD to ALERD (due to the change in hopper density) is taken into account, the system volume is no concern for the ALERD.

8.6 Initial investment

A important criteria for the ALERD are the initial costs. The initial costs are a large risk for the investors and could influence the economic feasibility of the ALERD. Using the simulation data, the following initial investment are expected, in millions of euros:

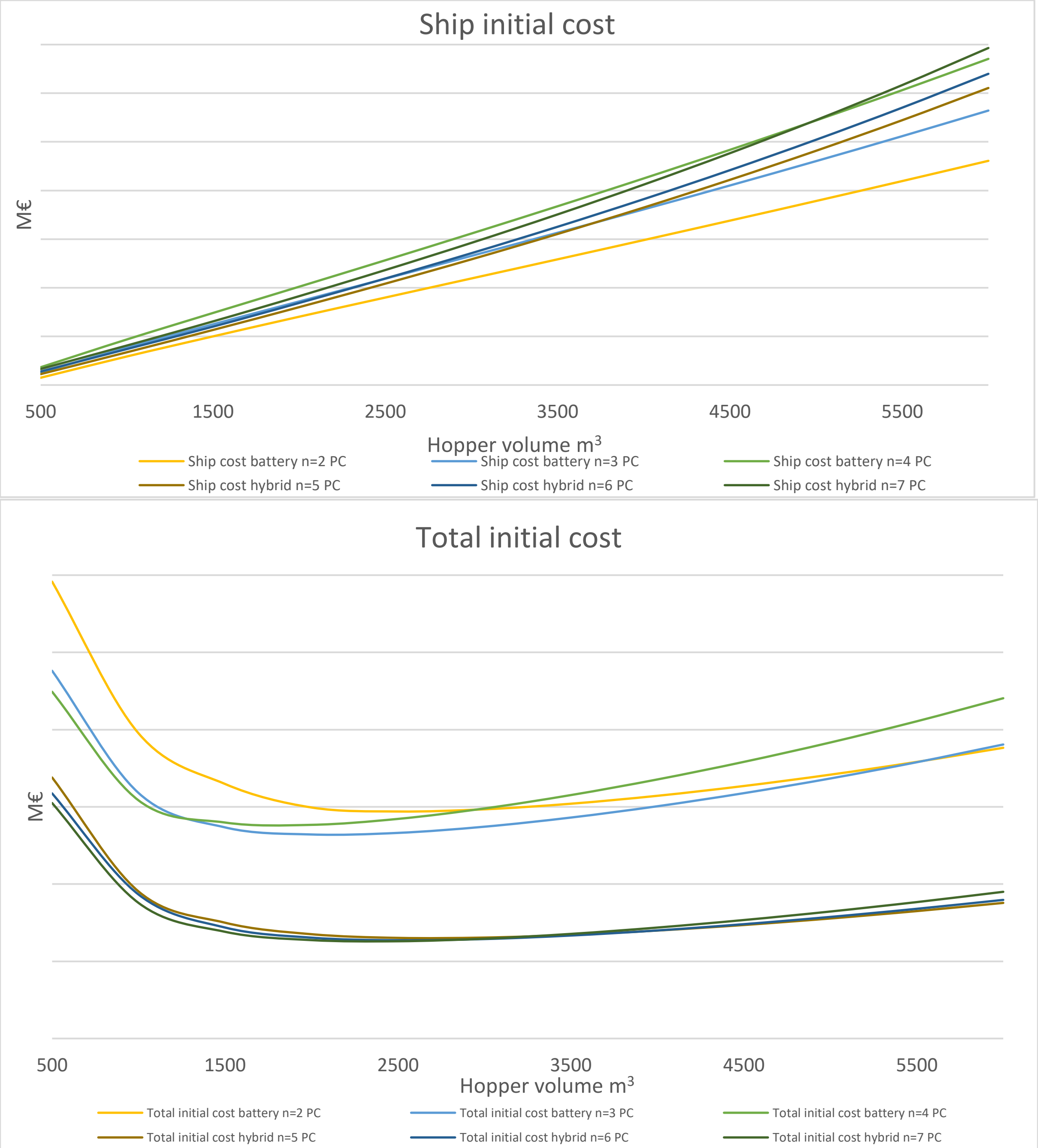


Figure 43 Ship and total initial cost

The results show that the cheapest ships are not the most cost efficient overall. This comes from the dredging capacity, which is primarily determined by the number of dredging cycles, hopper volume and Local/Port charging/bunkering. The lowest total investments are approximately at 1500-3500 m^3 hopper volume, which determine the optimal hopper volume for the lowest dredging costs. The hybrid powered ALERD has in this category the advantage over the battery powered ALERD. The graphs show how much influence the CAPEX has on the dredging costs, from the resemblance in shape.

9 Discussion

For each part of the research, separately, a discussion is given over the methods and results.

9.1 Discussion modelling

The model was created with the idea of a plausible situation in which the ship gets the most out of the given energy supply. This is a self-determining operational profile, based on the remaining energy on board. This makes the model stable and gives the best results for a given energy storage. The energy storage is calculated in advance, wherefore the requested number of dredging cycles can be achieved in the profile. This value can then be locked, to adjust input values, such as sailing distances. Together, this gives the possibility to apply variable situations to a static simulation.

Furthermore, these applications exclude that the ship can sail with negative energy status, which would cause the calculations to be erroneous.

During the research, input from the client was that the main goal of the ALERD is bottom door replenishment. The discharge of the sediment is not a hard requirement anymore, but the model is designed for both. Small changes in the optimal profile could result from this. Furthermore, less ships will be required for the project and thus the costs per cubic metre will decrease. The model is capable of simulating the bottom unloading profile.

The acceleration, deceleration and time between operation are not included in the simulation. The energy requirement of acceleration and deceleration cancel each other out mostly, but some additional time has to be taken into account. This can be found back in the assumed margin percentage.

9.2 Discussion optimization

The optimization uses the electric load balance and basic equation regarding the relation between sizing, speed, flow and power.

A first comment on this is scaling. In reality, geometric scaling is not possible for ships. This is clarified when ships become smaller. Theoretically, at a scale factor that goes to zero, all magnitudes also become zero. This is not possible, because systems have a minimum size. In addition, systems do not scale linearly and this also relates to the ship hull thicknesses and propulsion systems. Furthermore, the machinery rooms and energy storage will not directly depend on the scale of the ship, but on the installed power and required energy. In addition, the AUMD was designed with a battery as an energy carrier in mind, with the PEMFC hybrid being a major contender for the ALERD.

Because the scaling ratios are relatively close to 1 for both systems in the optimal region, it is expected that the outcome will not be influenced by these errors in assumptions.

The scaling influences the dredging equipment as well. There are assumptions that influence the results. In general, the size of the most important part, the drag head, is largely determined by this. Think of the forces and stability of the ship which must correspond to each other. However, this includes a bandwidth that is acceptable, which is not included in the calculation. This is also outside the focus of the research, because it no longer relates to the energy system. It is not expected that this will have much influence on the results of the energy system, because the optimization of both systems seeks a balance between battery energy demand and dredging yield.

The transit power of the ALERD is largely dependent on the propulsion power. The simulation uses the assumption that the ALERD can sail fully submerged. To allow for this as much as possible, some changes will be needed to the hull shape with regard to the AUMD and the ALERD. The ALERD will therefore become slightly flatter and in order to maintain the same hopper volume, it will become slightly more extended in length/width. As a result, the ideal "torpedo shape" is lost and the hull efficiency is slightly lower, resulting in a higher resistance. Due to the low sailing speed, the effects of this will be minor, so that the choice that has been made not to have to include this.

9.3 Discussion variable input data

The approach of a dynamic simulation uses static simulation results. This has been done with the use of varying input values and keeping the other input values constant. For example, the simulation of variable transit distances in a profile has been done with constant stored energy and varying the transit distance. For each given transit distance the simulation calculated the results, and these were stored in a table. All transit distances combined give a bandwidth of results. A counter argument for this approach is the effects of taking samples of transit distances. In order to obtain results, the choice has been made to include a limited number of sailing distances. Afterwards it was concluded that the effects of sailing distances on costs gave a predictable response. This further indicates that the use of samples has no influence on the dynamic situation. There could be however some small deviations due to the matching, but are not expected to have considerable influence on the results.

9.4 Discussion results

The results of the report are given for both systems, because when local charging/bunkering is possible, the systems are very competitive. In addition, the results of the weight and stability studies can rule out the feasibility of a system. But as it stands now, the PEMFC will be the best solution when using the results.

Because the results of the stability and weight studies are delayed, no conclusion could yet be drawn on these aspects of the systems. It is expected that this can influence the dredging profile, hopper volume and type of system. These are variables that have a lot of influence on the neutral buoyancy of the ALERD, and are therefore of great importance. A rough estimate has been made on these variables, using scaling of the reserved free space and weight in the AUMD.

The data are given for the full results of the simulation, hopper volumes 500 to 6000 m^3. However, as explained in chapter 7, the optimal cost results can be found around 2500 m^3. For the hybrid type of ship, there is a broad range where the optimal results can nearly be achieved, which is between 2000 and 4000 m^3. The battery powered ALERD is more specific and requires the ship to be around 2500 m^3. When using the data for design, this has to be taken into account.

The design data of the SOFC hybrid has not been included, because the system is still under development. However, it has the best promises with regards to cost efficiency and practical considerations. Furthermore, the energy storage has volumetric benefits over the PEMFC hybrid.

10 Conclusion

Through this research the following main research question has been answered:

Which sustainable system has the best capabilities to supply the ALERD with electrical energy, and what are the design data?

The answer to the main research question is:

"The PEMFC-Li-ion hybrid is at the moment the best sustainable electric energy supply system for the ALERD. The best results can be accomplished with a hopper volume of approximately m^3 and port bunkering. Due to rounding of the number of ships based on the dredging project, the best results will be achieved at a hopper volume of m^3, dredging cycles per energy cycle and port bunkering. The design data of this profile and hopper volume are as follows. For the energy supply, MWh or tons of hydrogen, and MWh of battery capacity storage is required per ship. A MW PEMFC fuel cell is required to operate constantly at a 60% nominal load of kW. The fuel cells have to be separated in two rooms and the batteries in three rooms for redundancy. A total of tons and a cubical volume of m3 has to be reserved for the complete energy supply system. Four ships will be required for the yearly replenishment capacity of 12 million cubic metres. Each ship has an expected investment of approximately million euros."

The decisions made in the report are based on costs, because they determine how much interest there is in developing the ship. By using this method, the simulation seeks an optimal balance between dredging capacity and costs. This is done by varying the input data: Dredging cycles, transit speed and pump flow (for a given hopper volume). Multiple cases have been applied, and overall the hybrid system has the greatest capabilities in terms of costs and practical implementation. The battery powered ALERD is remedied by the large investment costs of stored energy, which has the result of an optimum with fewer dredging cycles per energy cycle.

The direct ammonia fed SOFC-Li-ion hybrid has multiple advantages over the PEMFC-hybrid, which primarily is the better fuel characteristics. At the moment however, this system is not yet available on the market, but is highly expected in the near future. When this system becomes commercially available, it is highly recommended for the ALERD.

A counter argument for the ALERD is its high initial investment costs. Over the predicted lifetime, the ALERD is very competitive and even better than a conventional dredger. However, less soil can be replenished per ship per year, and in combination with the higher ship costs, the initial investment is approximately 4-5 times higher than with the use of conventional dredgers. Here, the hybrid powered ALERD has the lower initial investment compared to the battery powered ALERD. Due to the much lower operational costs, driven by the exclusion of personnel costs, the ALERD will return the investment. However, this depends on the expected cost developments, as calculated by the MARIN that were included in the calculation. This confirms that the emission free requirement, and thus the chosen system, is (economically) feasible.

Both systems have an optimal hopper volume, which was an additional open question during the research. The optimum hopper volume is determined on one side by the efficiency of the dredger profile and the other side by the corresponding stored battery capacity. Because the hybrid powered ALERD has the ability to reduce the dredging battery capacity by increasing the transit speed, there is a larger region of optimal hopper volume.

With a local charging/bunkering station, a sedimentation cost of €/m^3 is calculated. The best results are made at approximately m^3 hopper volume. When the ALERD is forced to enter the port for refilling the energy stock, this cost per m^3 sedimentation rises to €/m^3 for the hybrid solution. Over the lifetime of 25 years, this gives a maximum development cost of million Euro for local recharging stations. It had been concluded that the costs, and the corresponding development time are not sufficient for the first

ALERD’s. The hybrid solution has a larger range of hopper volume, where acceptable costs can be achieved. Equally, this applies to the amount of dredging cycles per energy cycles, where the hybrid solution has many possibilities to achieve the best cost results. The battery system is limited to one choice for the local and port charging variants. The hybrid ship can dredge efficiently 5-9 times per energy cycle. This benefits the operational freedom of the ship, has fewer port arrivals and mooring/bunkering, and more possibilities in the weight and volume determination of the system.

The battery powered ALERD has better prospects to charge autonomously, which reduces the labour costs. A secondary preference for this system is that it has sufficient reserve capacity in case of a calamity. At last, the battery powered has the best MKI, because it has the best energy efficiency and because of the losses in the production of hydrogen. The Hybrid powered ALERD has better cooling capacities, and has more operational freedom. In increased transit distances, it has better abilities because it has more stored energy. Both systems seem to be able to fit in the ALERD. However, research is still ongoing on this topic.

The answer of the research question is retrieved from the data from chapter 8 at the optimal rounded hopper volume of chapter 7. During the research it had been found out that multiple solution, with respect to hopper volume and dredging cycles, can suffice. It is therefore quite possible that the given optimal point is different from what is desired due to considerations that have not been included in the report. By means of the results in chapter 8, the correct data for the ALERD can be determined for the new specifications.

11 Recommendations

There is currently a lot of developments going on with regard to sustainable energy supplies. Even during the thesis, some additional systems became in the scope of the ALERD. Because many of these systems are often overestimated in the early stages of their developments, no reliable values could be adopted here. Because the development of the ALERD is aimed to be 5 years, it is advised to keep an eye on these developments. Notably, the direct ammonia fed SOFC and new types of batteries are expected to make a breakthrough. The simulation is able to implement these systems when reliable data is known. The new battery system is expected to be implemented according the Li-ion battery system. The SOFC has a very high operating temperature, which requires special handling. Because the operational profile is designed to operate stationary, start-up problems are of less importance. However, when the ship is unable to operate, it is possible that the fuel cell must shut down or deliver power to an outside source. The Ammonia fed SOFC has the ability to have more dredging cycles than the current hybrid ship, causing to operate much more efficient. Ammonia has the advantage that it behaves more like classic fuels and thus their advantages. The SOFC remains a very interesting option, provided it will be developed to commercial availability.

When hydrogen is chosen as a fuel, collaboration and/or interest is advised for the relevant developers of hydrogen production. This could increase the development speed and improve feasibility. Until then, the fuel can be delivered by trucks or with local storage points. Interesting locations for the project remain: Rotterdam, Flushing, Ijmuiden and Den Helder.

It is recommended to design the ALERD on the data as a result from the research. Furthermore it is advised to choose a larger number of dredging cycles, which is still feasible to implement in the ALERD with respect to volume and weight. This has multiple advantages, primarily less trips to the port. When another number of dredging cycles or hopper volume is chosen, it is important that both of these match. In Appendix B is the relation between hopper volume and dredging cycles visible. Increasing number of dredging cycles has the effect of decreasing the hopper volume for optimal results and contrariwise.

The hybrid powered ALERD has possibly some room for improvement, which is another power management that could decrease the costs per cubic metre. By charging the batteries during the operational profile, the battery size can be decreased and thus the costs. This is what the optimization for the hybrid ship does as well, by increasing the fuel cell output. Recharging is a more direct approach, but it has consequences on the lifetime of the batteries.

When the ALERD is designed, it is advised to run the simulations again to determine the requirements of the systems. It is believed that there will be some changes that can influence the outcome of the results, which are: Hull resistance, Hopper volume:displacement ratio, weight and volume limitations, and dredging/ballast equipment data. These changes can influence the power and energy requirements and the dredging capacities.

Because these results have also influence on the optimization and optimal hopper volume, it is advised to repeat the steps in chapter 6 and 8. It is not expected that the changes have influence on the dynamics, and therefore the steps in chapter 7 are not required.

As a recommendation for the ALERD, it is advised to go for the PEMFC hybrid ALERD. This is the best option because it is at the moment the cheapest solution that is commercially available. Developments directly affect the results by reducing fuel costs. It is expected that there will be many developments in batteries in the future. Instead of already developing a ship on batteries, with high development costs, it is advised to wait for this.

When the costs of batteries have fallen to such an extent, the ALERD, just like the hybrid ship, can sail a more efficient profile. This happens approximately, when the costs for the battery storage fall below 200 euros per kilowatt hour. Here, the optimal dredging profile n for the battery powered ALERD is five and for the hybrid is eight. The simulations were made at equal fuel cell costs.

12 Model validation

Model validation and increasing the reliability were a large part of the research and possibly even the most time consuming. The simulation is based on assumptions and not entirely available or known values, such as costs. During the research this was troublesome, because these values determine which system is the optimal solution for coastal maintenance in the Netherlands. Furthermore, the importance of this was reinforced by the, with a tight deadline.

In the first versions of the model, less data was applied under the guise less is better. However, this gave results which were not validable. Without a reference, the results were just numbers and a true comparison could not be made. Additionally, the first results were much better than the conventional dredger and target values of €/m³. By adding extra data and costs, retrieved from the THSD and ship building financial studies, the target values were reached. Furthermore, by applying the same source data to the conventional dredger, identical values were retrieved for the current dredging costs. This validated the resources and gave already an identification that plausible assumptions were made.

The made assumptions are based on representable systems or activities. The MARIN uses a certainty indication for all values in their database. For all components, the upper value with high certainty is chosen. By using and checking all values with the database, a consistent assumption is made. Because the determination is made relative between the battery and hybrid system, a constant conservative approximation among both systems does not influence the outcome.

By taking the upper limits of the sailing distances in the distance assumptions, a conservative high dredging cost/m³ is made. As a result, the ALERD is able to reach all distances or operate at higher cost efficiency than expected. Because these values were taken, the dynamics didn't change the outcome as well.

The costs calculation is not complete, and therefore some difference can be found when the ships are developed. The calculations does not take into account for example shore personnel and profits from the mooring station. Furthermore, the fixed charges for these locations and ship is not taken into account. There are so many other small costs that have not been included, but which are not expected to strongly influence the outcomes. Relatively speaking, these will also be approximately the same for both ships and will not change the result of the best solution. Ultimately, it would only affect the financial feasibility of the ALERD, which is actually out of the scope for this research.

For the validity of the systems, the comparison and implementation chapter has been added. These chapters function as a conformation that the systems will work in practice. Not everything has been worked out here, because a lot of it is available off the shelf. To confirm the validity of the given systems, the choice was made to go for the PEMFC and the Li-ion battery. Because it is expected that the SOFC and the modular diesels cannot be implemented without problems, these were not implemented in the simulation. The same applies to the modular batteries, in order to fill the energy supply for a shorter time. The modular batteries have however been considered by decreasing the charging time, but it could not compete with the hybrid variant, because the battery replacement is expected to be in the port and considerable replacing time should be taken into account.

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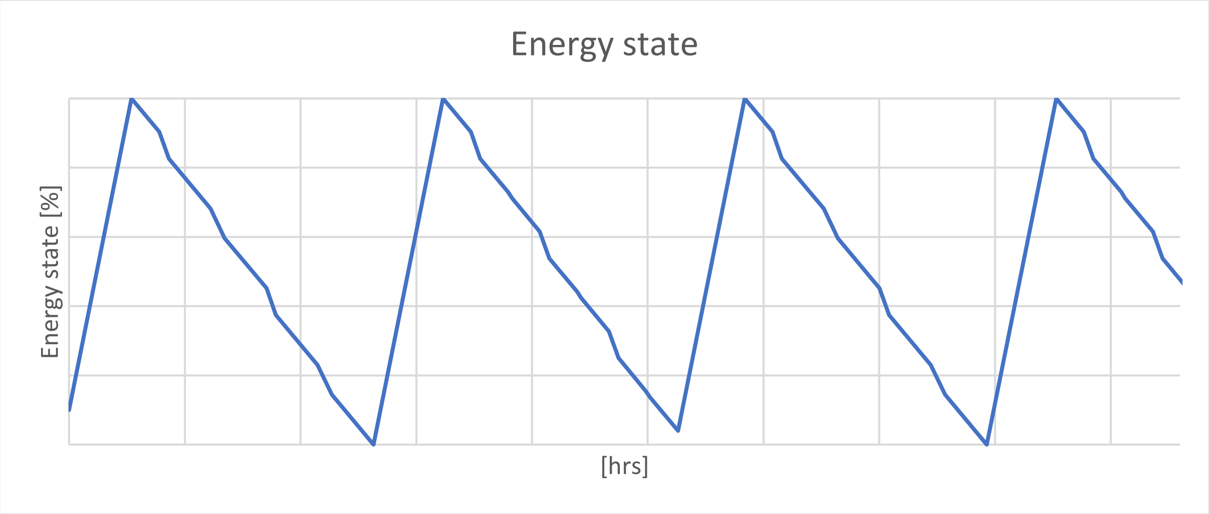
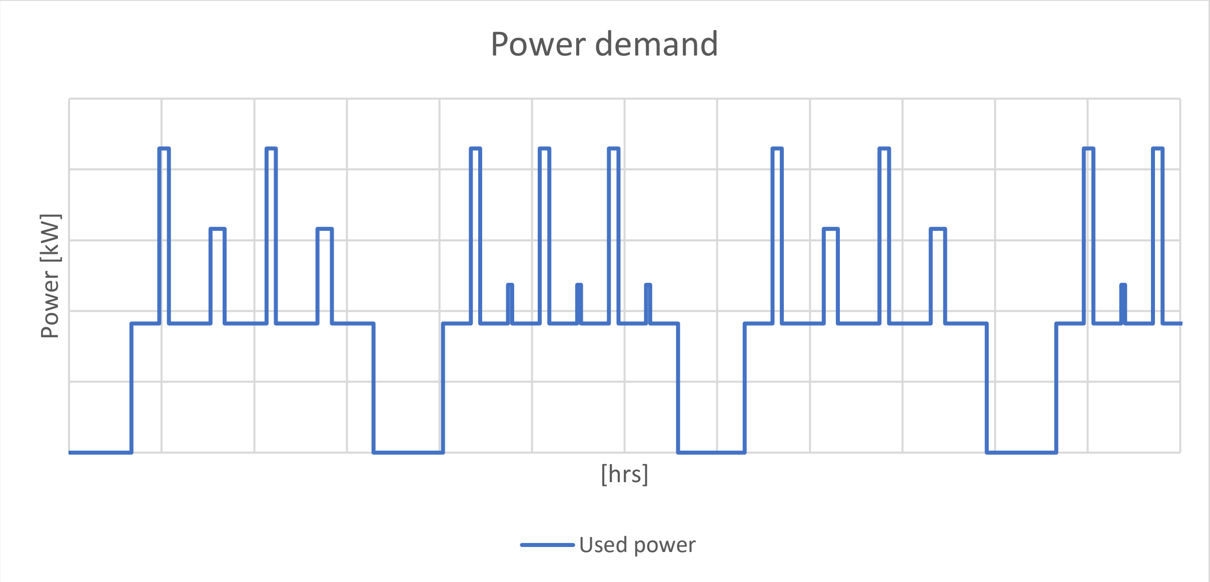
Appendix A

Operational profile of the ALERD

N=2 Local charging

Battery

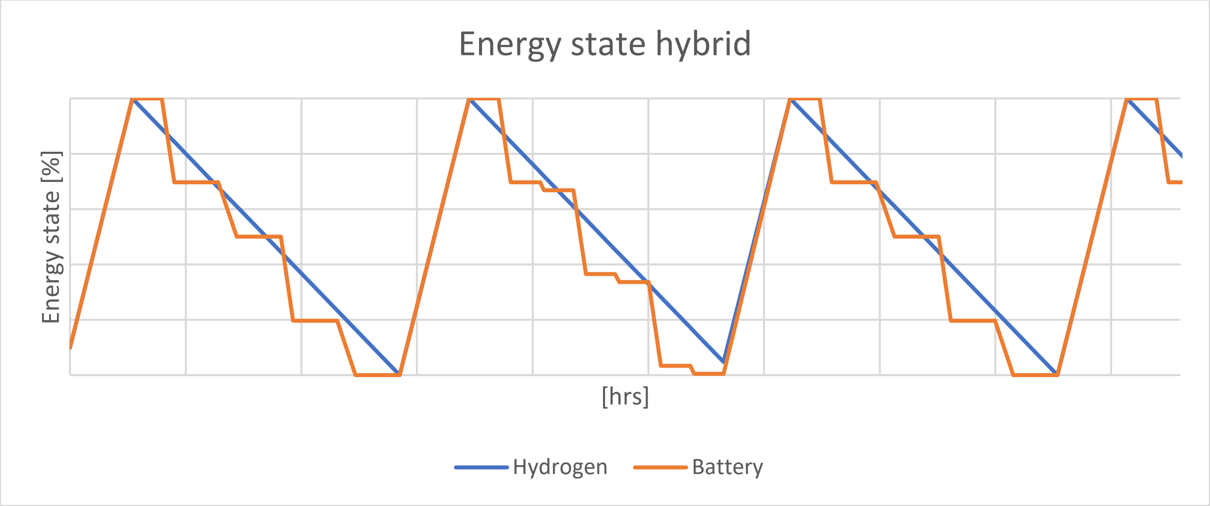


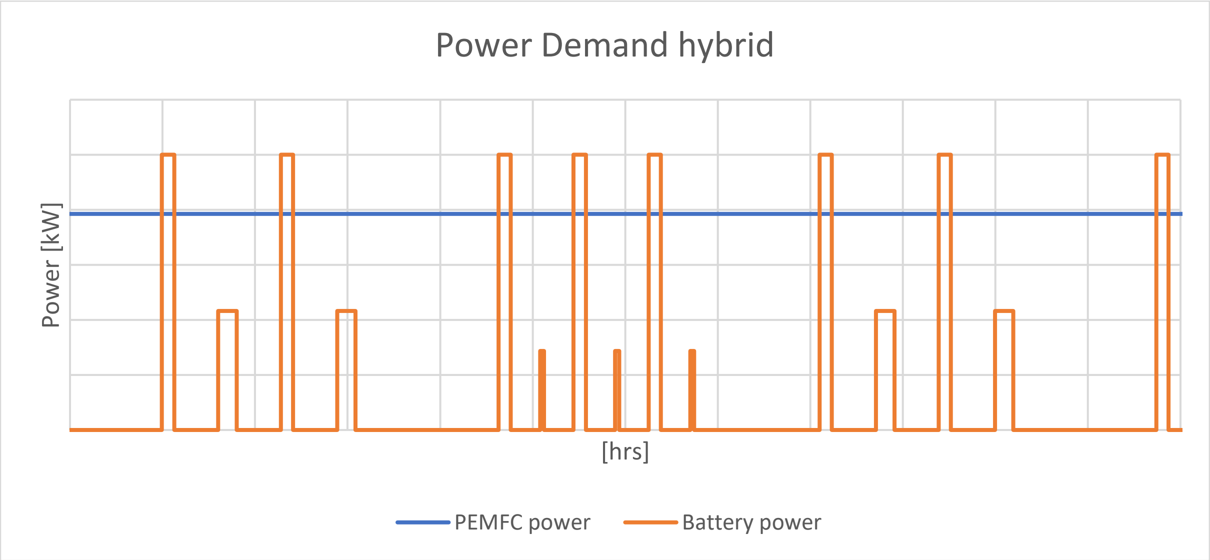


The Operational profile N=2 has the characteristic that it carries sufficient energy for 2 times dredging and discharging or 3 times dredging and dumping. To improve operational efficiency this has been applied in the simulation as well.

The ALERD starts at the mooring station with 10% energy capacity. When the ship is fully charged at hrs, it leaves the mooring station and starts transit. At, the dredger has arrived at the dredging location and starts the dredging operation. When this is finished a transit to the discharge location followed by the discharging operation is carried out. The energy state of the dredger is sufficient for a repetition of the dredging process before it returns to the mooring station. At hrs, the energy state of the dredger is 0% and it has arrived back at the mooring station where the ALERD is recharged. After recharging, the ALERD carries out 3 dredging operations together with mooring operations.

Hybrid



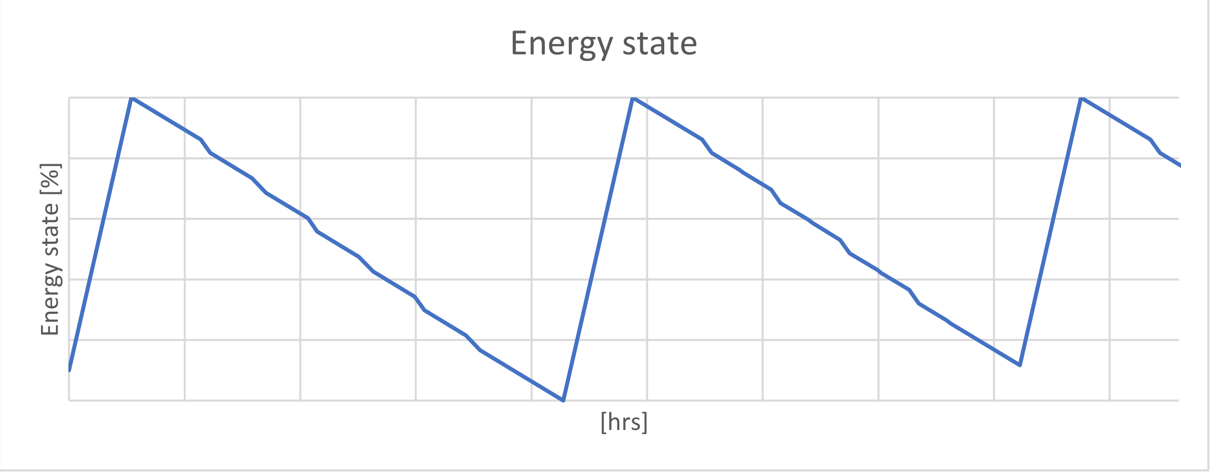


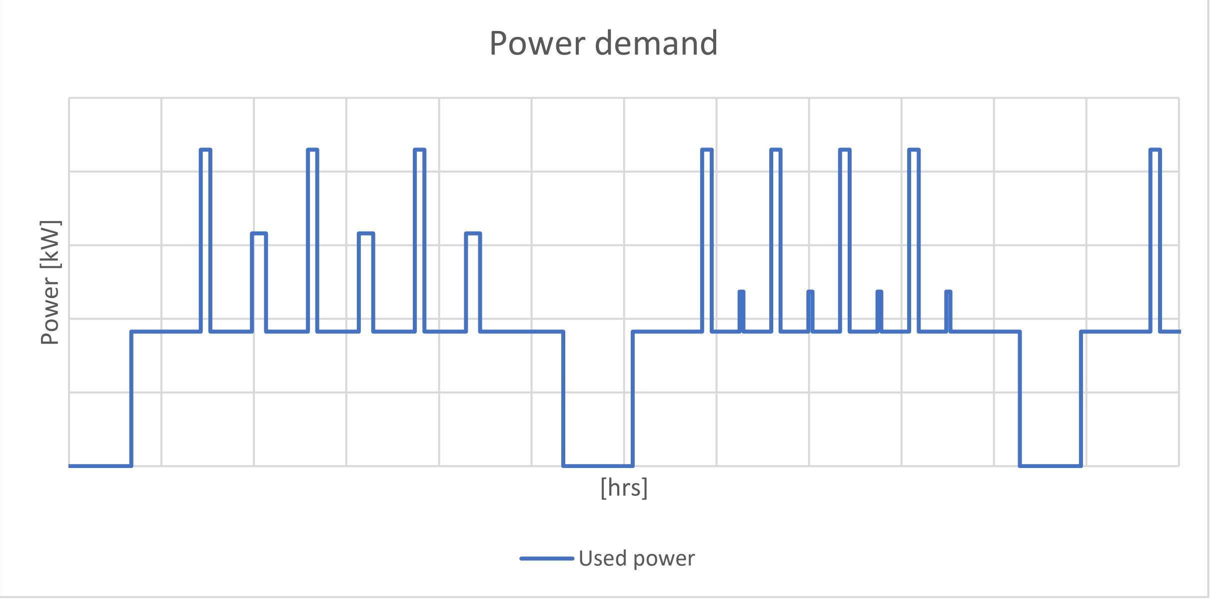
The operational profiles are equal but the hybrid energy supply system uses two components to deliver power. In blue is the energy state of hydrogen and the power from the PEMFC. Together these are the fuel cell system in the ALERD. Orange represents the Li-ion batteries inside the ALERD, which is used for peak shaving.

The PEMFC delivers a stationary power output for longevity and efficiency. During mooring, the power of the PEMFC can be used to charge the batteries. The batteries supply power during the dredging, discharge and dumping operation, where large powers are required for the dredging and ballast pumps.

N=3 Port Charging

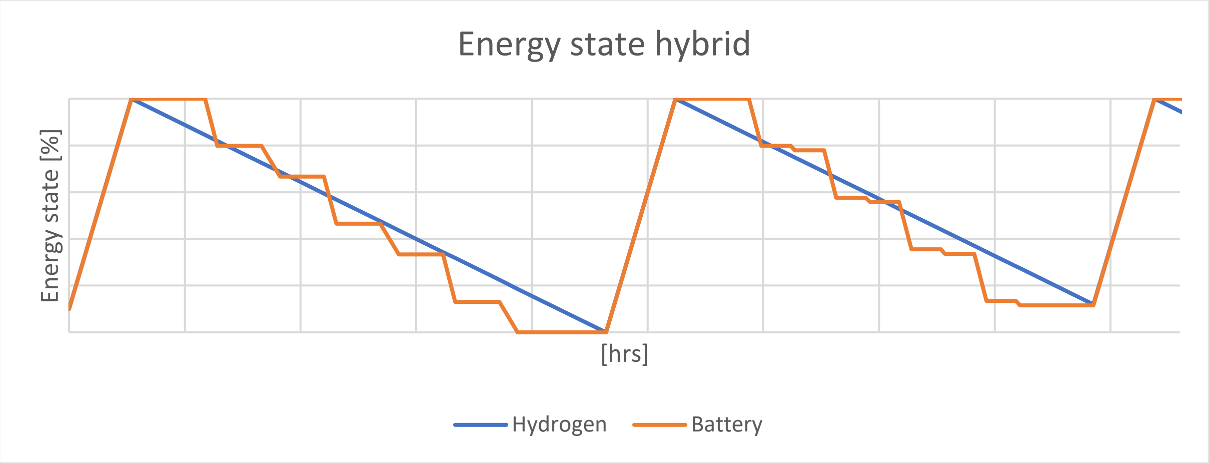
Battery



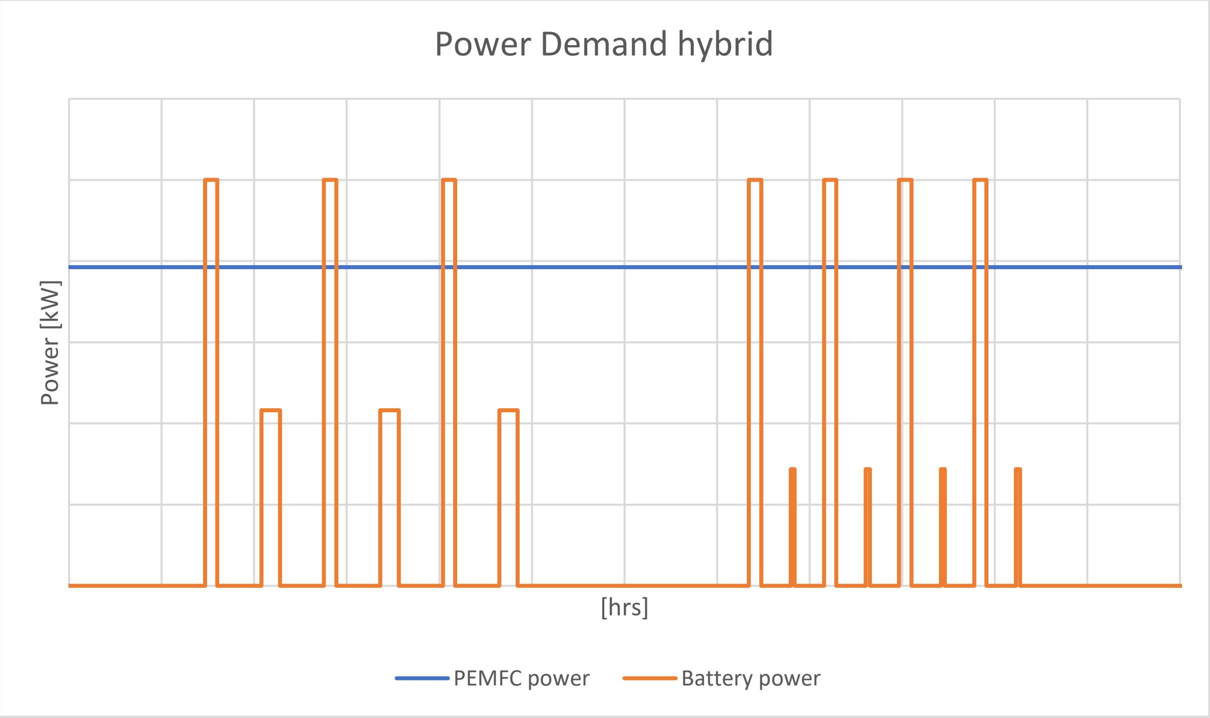


Equal to the previous operational profile, first the ALERD starts a dredging-discharge cycle followed by a dredging-dumping cycle. The difference is that the now N=3 dredging operations is minimum acquired during operation. It can be seen that the stored energy is less optimal, because there is still 12% energy left when the ALERD arrives in the port after the dredging-dumping energy cycle.

Hybrid



Energy state hybrid
Energy state [%]
[hrs]
Hydrogen
Battery



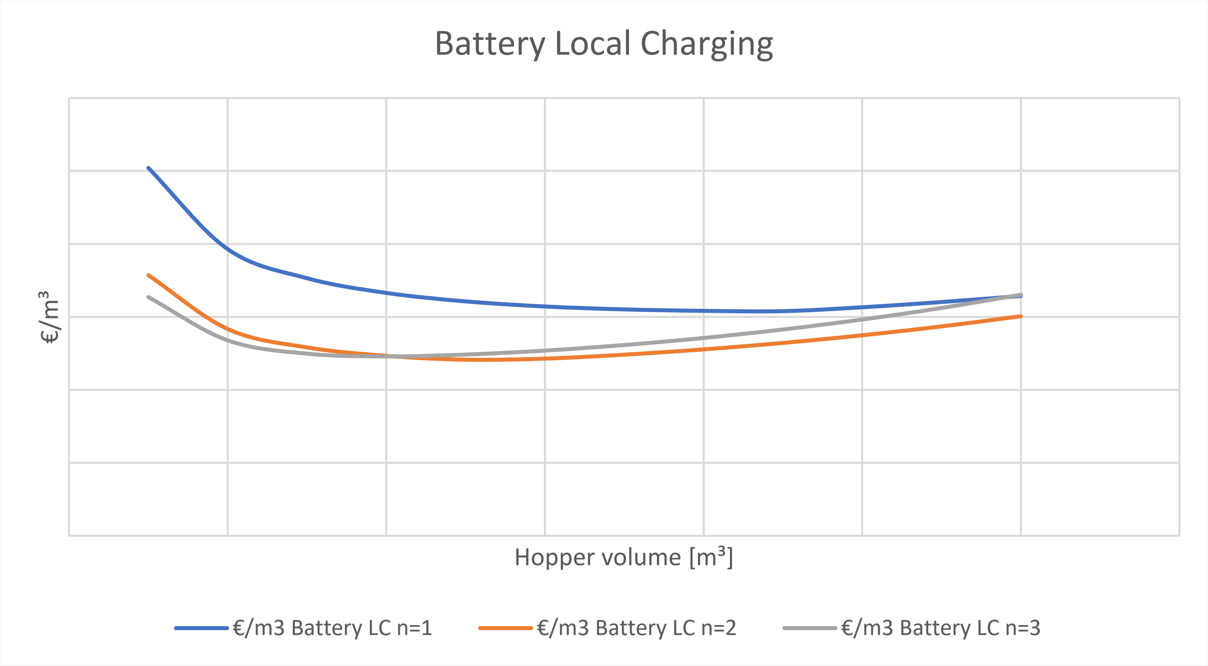
Power Demand hybrid
Power [kW]
[hrs]
PEMFC power
Battery power

Appendix B

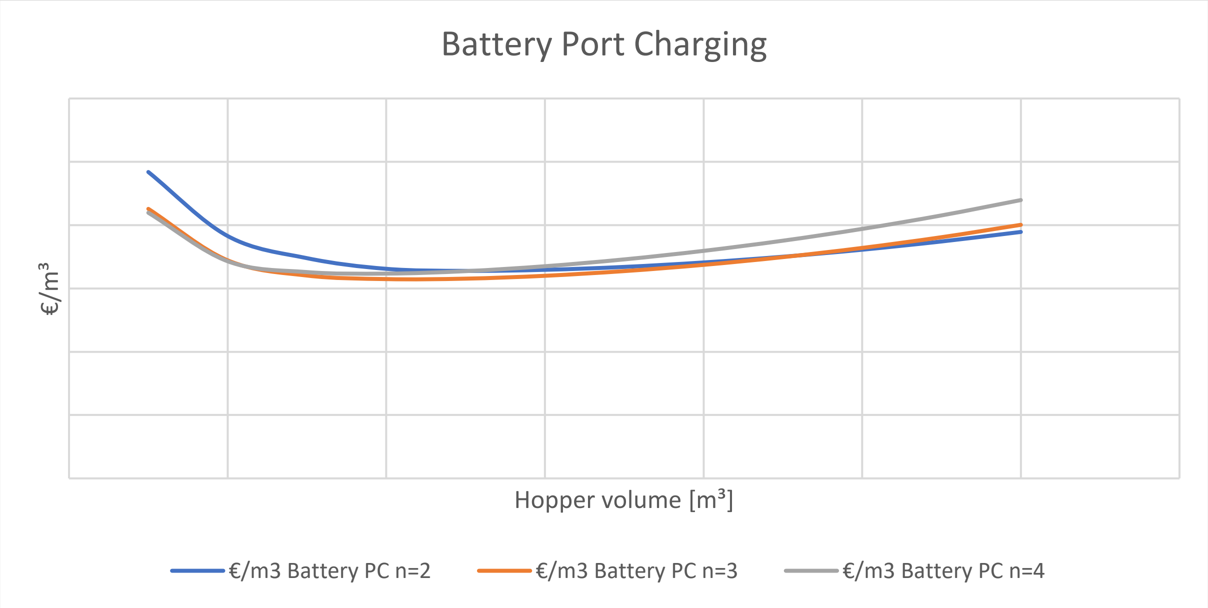
Results of the operational profile simulation

Cost estimation results

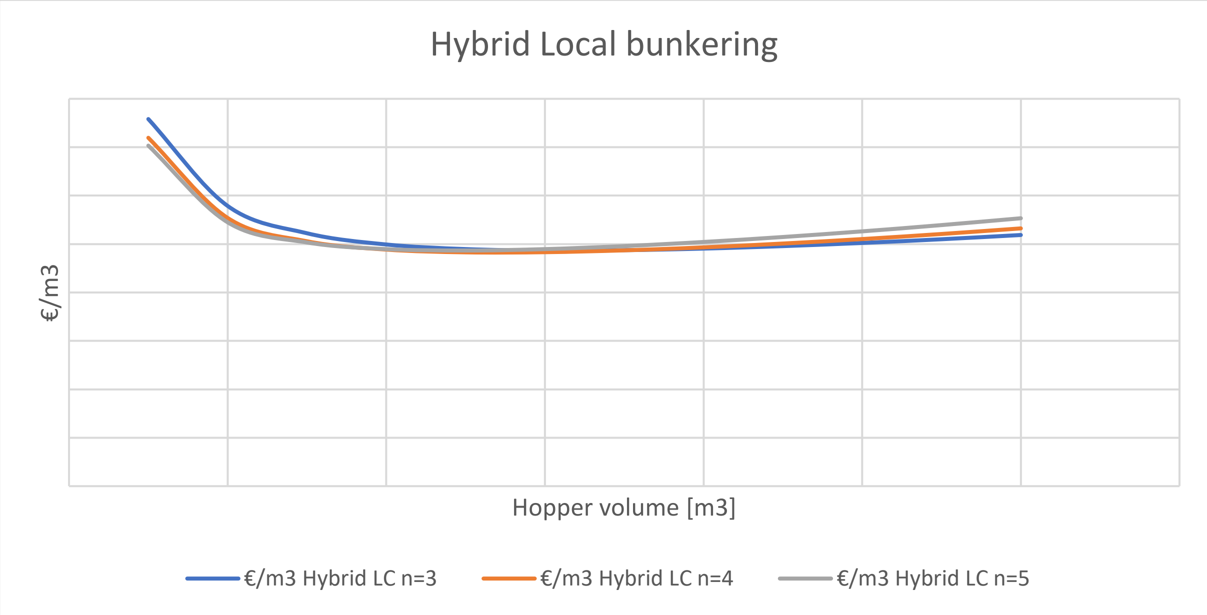
Following graphs show the costs per replenished m³ sand.



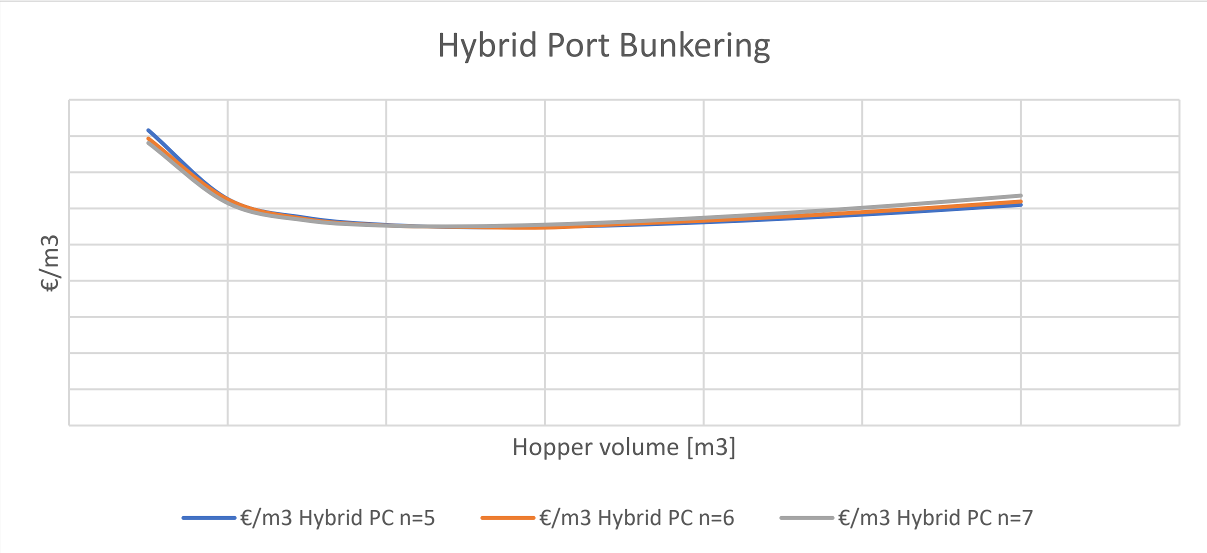
Because the costs of the battery powered ALERD are primarily determined by the stored energy, the this profile tends towards less dredging per cycle. However, due to the inefficiently of less dredging per cycle, the optimum is at n=2. The operational profile n=1 requires a significantly larger ship to reach it optimum. This is to reduce the loss of the less efficient profile, because a larger ship requires relatively less transits.



Port charging is costly for ALERD due to the extra amount of energy by the larger distances to the mooring station. As a result, large differences can be seen with local charging and more frequent dredging per cycle has less influence on the total costs. Because larger ships require in comparison less trips to the mooring station, there is a break-even point where the costs are equal among the profile types.



Between dredging repetitions n=2, n=3 and n=4, the costs per m³ sedimentation is almost equal. The explanation for this is that the profit of a more efficient profile is equivalent to the extra costs of carrying more fuel and battery capacity. It was chosen to focus on the profile n=4 because it has operational advantages over a ship requires to refuel more frequently.

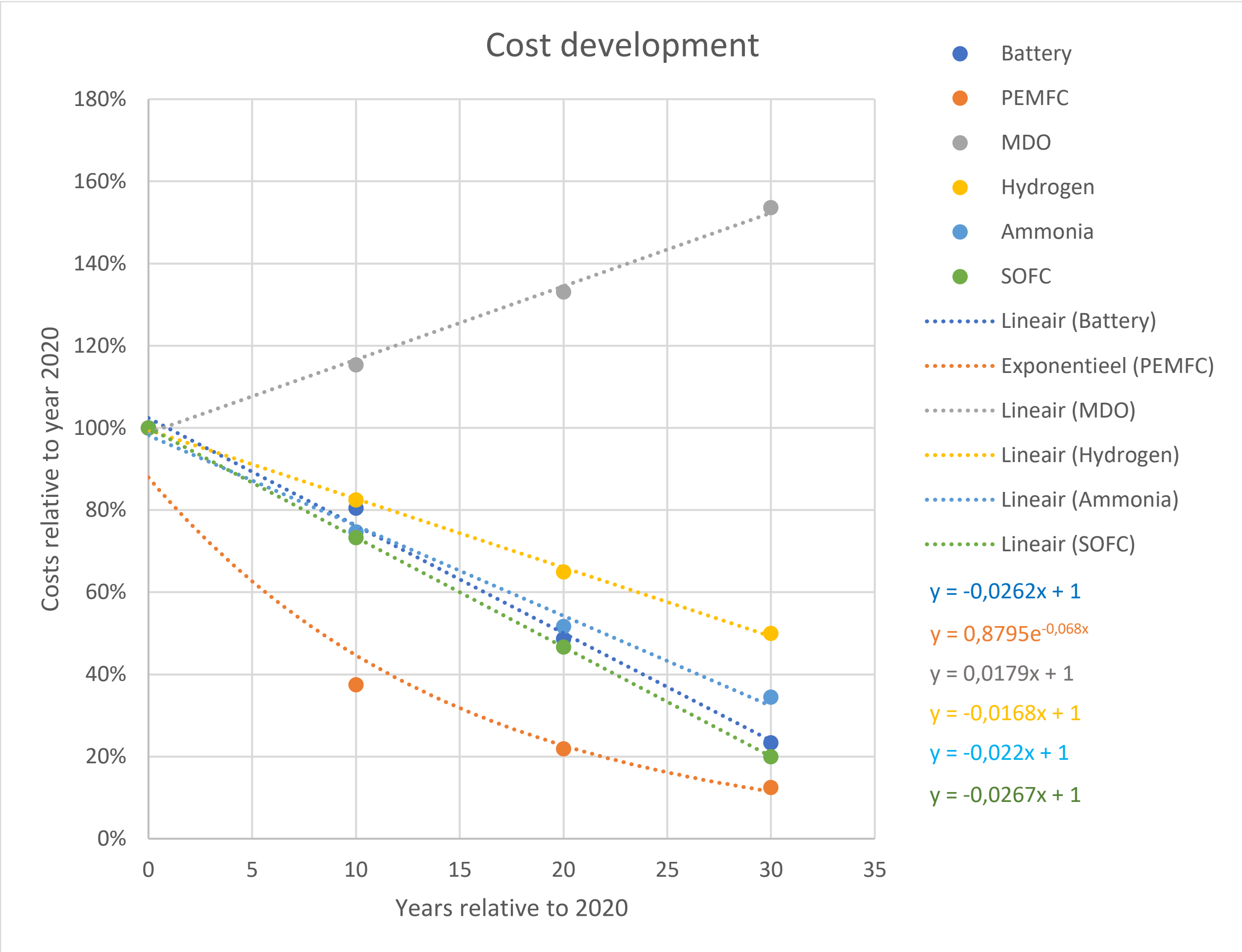


The influence of the profile becomes larger when the ALERD is substituted to port bunkering. The explanation for this is that the profit of a more efficient profile is now greater than with local charging.

Therefore an optimum profile can be found with more dredging cycles.

Cost development expectation

The following data is retrieved from Marin [64] and implemented in the cost expectation TCO. It is expected that the ALERD will be built in 2025 and has a lifetime of 25 years. Therefore, the data from 2025 until 2050 are used in the calculation. In the legenda, the equation of the trend lines that are used in the simulation are given. In the calculation is y the costs relative to year 0 (used in chapter 6), and is x the year relative to 2020.



Overview of system properties

Below is a summary of the found properties in the literature.

Portable energy storage technologies	Energy density Wh/kg	Energy density Wh/L	Power density W/kg	Power density (W/L)	Power Rating	Discharge time	Suitable storage duration	Stack efficiency	round trip efficiency	Life Time (Year)
Flywheel	10 -- 30	20-80	400-1500	1000-2000	0-250 kW	millisecs - 15 min	sec-mins	92-98	85-96	15
CAES	30-60	3--6			5-300 MW	1 - 24+ h	h-months		50-89	20 - 60
Nuclear	2*10^10	4*10^11	1900	2200	1-1000+ MW	h - months	h-months	25-38		20 - 60
Fuel cell	1000-33300	500-2000	500+	500+	0-50MW	sec - 24+ h	h -months	<75		5 -- 15
PEMFC	700-1000	530-900	2000-5000	1000-3000	1 W - 500 kW	sec - 24+ h	h -months	50-70	30-50	
SOFC	1000-33300	500-4000	500-2500	1500-7500	100 W - 2 MW	sec - 24+ h	h -months	60-65	55-60	
AFC	700-1000	530-900	50-200		100 - 200 kW	sec - 24+ h	h -months	60-75	62	
DMFC	1000-5000	530-4000	20-50		0.1 W - 1 kW	sec - 24+ h	h -months	20-30	10--25	
RMFC	1000-5000	530-4000	20-50		300 W - 8 MW	sec - 24+ h	h -months	50-60	25-40	
PAFC	1000-33300	500-2000	20-50		0 - 10 MW	sec - 24+ h	h -months	55	40	
MCFC	1000-33300	530-4000	15-40		100 MW	sec - 24+ h	h -months	55	47	
Reciporating engine	33300	530-2000	30-1000	15-500	0-80MW	sec - 24+ h	h -months	40-55	20-50	
Gas turbine	33300	530-2000	500-10000	200-4000	0-40MW	sec - 24+ h	h -months	10--50	8--40	
Super capacitor	2.5-15	500-5000	500-5000		0-300 kW	millisec - h	sec - h	95-97	90-95	
Lead-acid	40-50	150-160	180	500	0-200 kW	sec - h	h - months	90-95	80-90	
NaS	150-240	150-250	150-230		50 kW - 8 MW	sec - h		90-95	80-90	10--15
NaNiCl	100-120	150-180	150-200	220-300	0 - 300 kW	sec - h	sec - h	95-98	85-90	10--14
VRB	10--30		50-125		30 kW - 3 MW	sec - 10 h	h - months	95-98	85-90	5--10
FeCr	10--50		16-33		5 - 250 kW	sec - 12+ h	h - months	85-90	70-80	
ZnBr	30--50	30-60			50 kW - 2 MW	sec -10 h	h - months	85-90	70-80	5 -- 10
Zn-Air	150-3000	500-10000	100		0 - 10 kW	sec - 24+h	h - months	80-90	50-55	
Li-ion	100-265	250-670	500-2000	1250-5000	0-200 kW	min - h	min - days	95-98	85-90	
SMES	0.5 - 5	0.2-2.5	500-2000	1000-4000	100 kW - 10 MW	millisec - 8sec	min - h		95-98	20 +
LAES	97				350 kW - 5 MW	1-24+ h	h - months		50-70	20 +

[28] [31] [3] [38] [43] [47] [64]