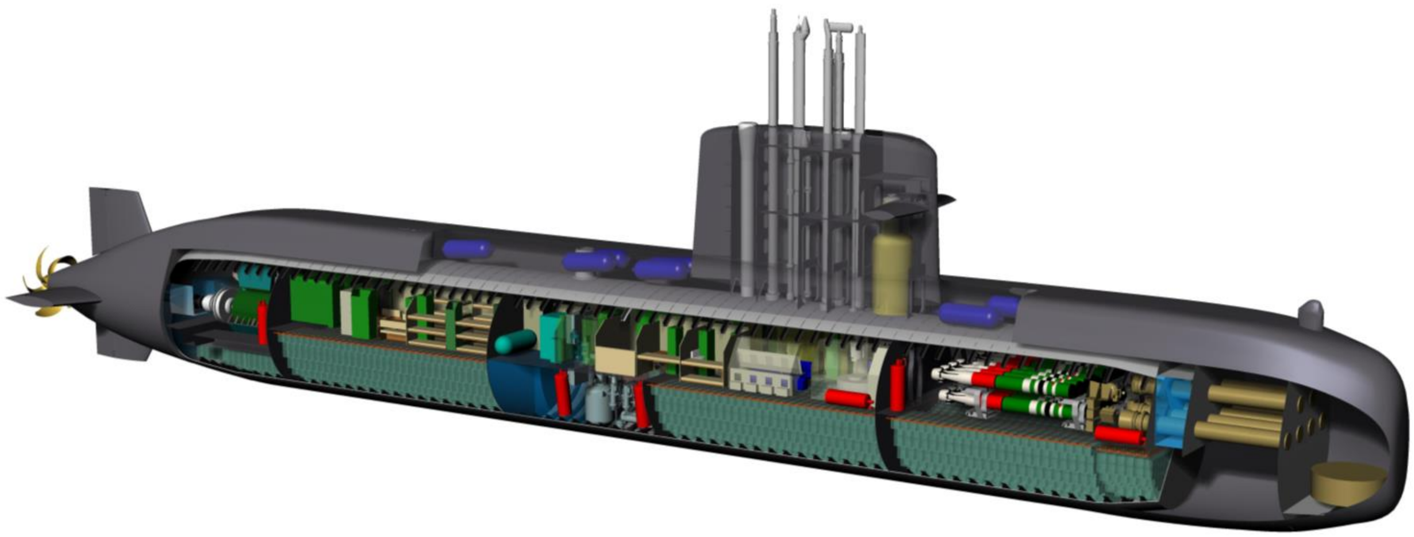
System design support tools in an early design stage for an entirely battery powered submarine

By

Jasper Valk

Thesis

September 21, 2020



Thesis for the degree of MSc in Marine Technology in the specialization of Marine Engineering

System design support tools in an early design stage for an entirely battery powered submarine

By

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Performed at

Nevesbu

This Thesis SDPO.20.032.m. is classified as confidential in accordance with the general conditions for projects performed by the TU Delft

September 21, 2020

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Preface

This master thesis on the development of system design support tools for submarine design is written to obtain the Master of Science degree in Marine Technology at the Delft University of Technology. With this thesis I conclude my six years of study at the TU Delft.

I would like to express my appreciation to Nevesbu. They provided me with an interesting and challenging assignment. I have learned a lot from all the interesting conversations I had with my colleagues.

I would like to express my gratitude to Ir. Klaas Visser, Dr. Ir. Peter de Vos, Dr. Ir. Geert H. Keetels and Ir. Sven A. Los for being part of my graduation committee, for their helpful feedback and insights during my research. My sincere appreciations go to Ir. Sven A. Los. Thank you for all the knowledge you shared and the feedback and the questions that pushed me to think in other directions.

I would like to thank my grandfather, Fokke Valk, for his enthusiasm about technology and sailing, my parents for their continuous support and interest in my study and the rest of my family who believed in me and gave me the motivation to complete this thesis. Furthermore, Melle thank you for proofreading the entire thesis while being busy with your own study.

I would like to thank my friends who made studying in Delft an unforgettable time. I have enjoyed the many study trips to Friesland, Belgium, Romania, China, South Korea and Japan and the hilarious skiing trips to the France Alpes.

I hope you all enjoy reading this thesis.

Jasper Valk

Delft, September 21, 2020

Abstract

Technical developments of the last decades have led to an increase in design space for non-nuclear submarines, especially regarding the increasing amount of feasible power plant configurations. To be able to select the most suitable power plant configuration, it is important to know the effect on the complete submarine design and all systems on board. In the last years, Nevesbu has developed power plant optimization and sizing models to be able to select the best power plant configuration for a certain design. However, these models do not take auxiliary systems into account. The common way used of estimating the main parameters of auxiliary systems in an early design stage, is scaling based on existing submarine designs as reference. When new technologies are applied and alternative power plant configurations are selected, such as totally lithium-ion battery powered designs, reference designs cannot be used any more to make an estimation of the required auxiliary systems. Therefore, new methods have to be developed.

The objective of this thesis is to gain knowledge about, and quantify the direct and indirect consequences for the auxiliary systems when lithium-ion batteries are implemented on a large scale in an entirely battery powered submarine. Design support tools will be developed to support the designer during the design of the battery and auxiliary systems. The associated main research question is:

How can a designer be supported, in an early design stage of an entirely lithium-ion battery powered submarine, when trying to determine the size, weight and energy consumption of systems that, among others, support the safe implementation of the new batteries?

For this thesis, the safe implementation of lithium-ion batteries in an entirely battery powered submarine is studied. This type of battery has the risk of thermal runaway, which is a cascading process in which the battery releases all its stored energy, generating a lot heat and toxic gases, causing an increased risk on an explosion. Research has shown that a foam injection system could be used to mitigate the risk on thermal runaway and such system is also capable of extinguishing other types of fires inside the submarine, creating a safer working environment for the crew members. A foam injection system requires pressurized air, but the amount does not have a significant impact on the pressurized air storage.

The increased endurance of the entirely lithium-ion battery powered submarine requires a reevaluation of the environmental control systems. The amount of chalkholders as CO_2 absorbers and oxygen candles to generate oxygen increases due to the increased endurance. The additional weight and volume of these consumables are undesirable. A regenerative CO_2 absorption system is introduced which is smaller and lighter, but requires a significant amount of the installed battery capacity, causing a reduction in endurance.

To support a designer in an early design stage, several design support tools are developed: for the lithium-ion battery system, the foam injection system and the pressurized air system. These tools estimate main parameters such as weight, volume and heat load based on system designs and input parameters such as size and weight of components and the pressure hull radius and length. The tools show the designer the consequences of design decisions and provides important information about knock-on effects on other systems. Furthermore, the tools can be used to optimize the weight and volume of the battery system and foam injection system.

A case study, based on a concept design of an entirely battery powered submarine showed the usability of the tools, quantified the effect of these systems on the overall concept design and the importance of the results in an early design stage. The number of crew members had to be reduced with seven to implement the regenerative CO_2 absorber and LOX tank. The required pressurized air storage did not change due to the implementation of the foam injection system, but the overall submarine became safer. After changing the concept design, the weight and stability still satisfied all requirements. Taking the output of the tools into account during an early design stage can prevent large design modifications.

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Abbreviations

MEM	Main Electric Motor
SWBS	Ship Work Break Down Structure
HVAC	Heating Ventilation
HP	High Pressure
LP	Low Pressure
MBT	Main Ballast Tank
HPU	Hydraulic Power Unit
SoC	State of Charge
EVOG	Emergency, Vital, Operational and General
NCA	Lithium-Nickel-Cobalt-Aluminum
NMC	Lithium-Nickel-Manganese-Cobalt
LFP	Lithium-Iron-Phosphate
BMS	Battery Management System
BCU	Battery Control Unit
SCU	String Control Unit
CAFS	Compressed Air Foam System
VCG	Vertical Center of Gravity
LCG	Longitudinal Center of Gravity
VOC	Volatile Organic Compounds
LOX	Liquid OXygen

1 Introduction

1.1 Background

“Submarine, any naval vessel that is capable of propelling itself beneath the water as well as on the water’s surface.” [1] This special type of vessel typically has four major tasks: to gather intelligence, to attack, to gain foreign stability by its deterrent presence and to drop of special forces.

Submarines are complex vessels. This platform has to carry out different types of missions in harsh conditions while being undetectable. It also has to carry people to control the submarine and to execute the missions. Since a submarine must be able to sail underwater, the weight balance is of utmost important. The weight of the submarine must be equal to the weight of the displaced water, otherwise it will either sink or will not be able to dive. So, the weight has a direct relation with the volume of the submarine. It is equally important during design to find the right balance between energy generation, storage and usage. Finding an optimal overall balance makes submarine design complex.

There are two main types of submarines: nuclear powered and diesel-electric powered. The first one is larger and more expensive than diesel-electric submarines but can stay underwater for a long time. The diesel-electric submarine is smaller, cheaper and quieter when sailing underwater. However, it cannot stay underwater for a long time. From the start of the diesel-electric submarines they use lead-acid batteries. The energy storage capacity of these batteries is limited. This makes the submarine vulnerable since it has to snort to recharge its batteries by using the diesel generator. A schematic illustration of a diesel-electric submarine is provided in Figure 1. Resent research has led to new types of batteries which have a higher energy density. These batteries, lithium based, can store more than five times the amount of energy per volume and weight unit [2]. This makes it possible to design different type of electric power plants than the common nuclear or diesel-electric power plants.

Two examples are the entirely battery powered submarine design and battery fuel cell powered submarines. Recent studies showed already the feasibility and potential of such a designs.

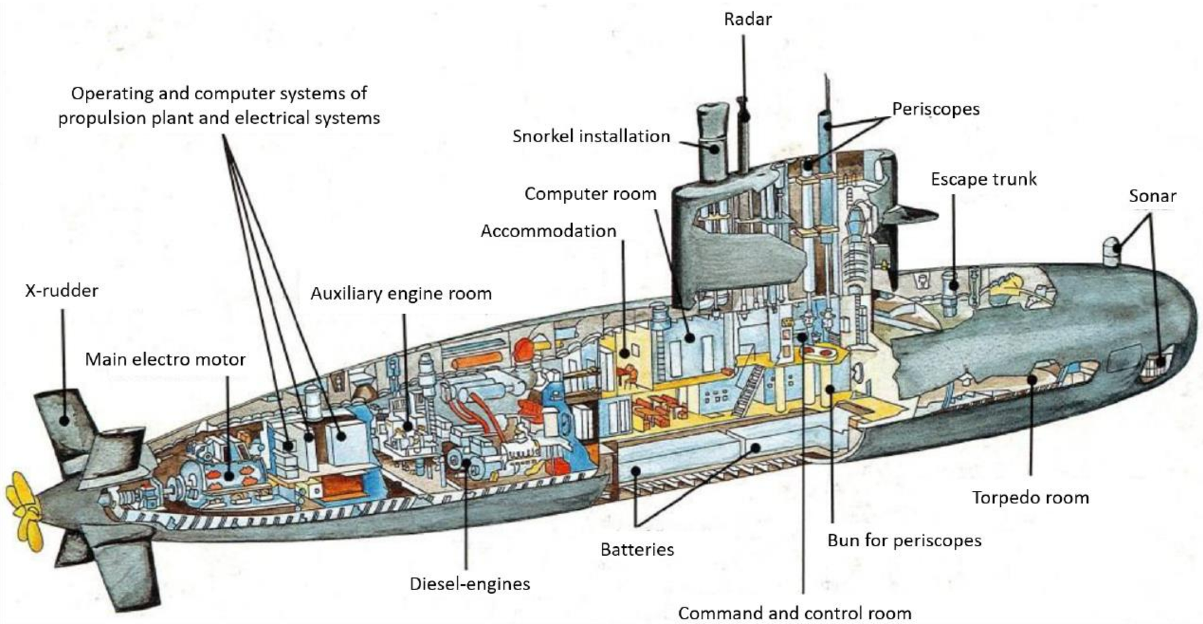

Figure 1: Artistic impression of a diesel-electric submarine [3].

1.2 Starting point

During submarine design it is important to identify the main parameters of all the systems in an early design stage, such as volume, weight heat and energy consumption, to prevent problems during later design stages. The last few years several students performed their graduation research at Nevesbu. L.P.W. Rietveld performed a research on a first principle model of the propulsion system of a diesel-electric submarine with lithium-ion or lead-acid batteries [4]. He developed a tool to determine the main parameters of a submarine's power plant based on a mission profile. This information can be used to create a preliminary design or just to check if certain options are feasible. S.A. Los performed a research on the feasibility of an entirely battery powered submarine and used the first principle model to make a concept design [2]. M. ten Hacken continued with the first principle model and implemented a PEM fuel cell and a PMSM [5]. M.E. Venema performed a feasibility study of a fully electric (battery/fuel cell) submarine based on the previous projects but on an increased level of detail [6]. None of these studies had a focus on auxiliary systems.

A common way of estimating the main parameters of auxiliary systems is looking at reference submarine designs. Unfortunately, this is more challenging when designing a submarine with a different type of power plant. The different power plant and capabilities requires different (quantities of) auxiliary systems. At this moment the knowledge and tools to determine the main parameters of the auxiliary systems of an entirely electric submarine in an early design stage are missing.

The studies that have already been performed used a diesel-electric submarine reference design. During this research the reference design will be available as well [7] [8].

The reference design is used by S.A. Los for the development of an entirely battery powered concept design. An impression of his concept design is provided in Figure 2 and the main parameters are listed in Table 1. The diesel electric reference submarine and the concept design of an entirely battery powered submarine will be used during this research.

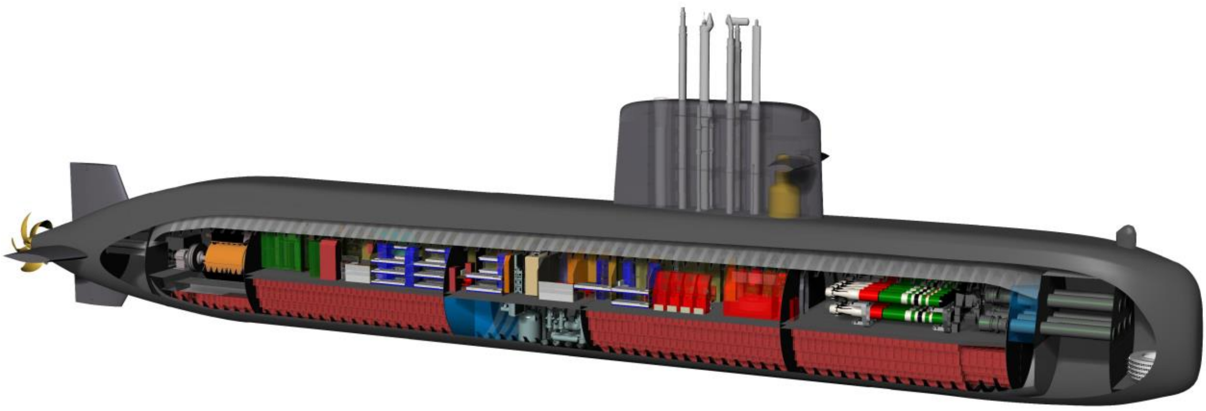

Figure 2: Concept design of an entirely battery powered submarine [2].

Table 1: Main characteristics total battery powered concept design [9].

Dimensions	Length	66.5	[m]
	Hull diameter	6.5	[m]
Displacement	Surfaced	1700	[ton]
	Submerged	1900	[ton]
Diving Depth	Max. operational	300	[m]
Combat	Launching tubes	6	[-]
	Weapons	20	[-]
Speed	Max for one hour	20	[kn]
	Burst	21.5	[kn]
Batteries	Installed capacity	88.5	[MWh]
	Number of strings	1476	[-]
Autonomy	Range @ 5 kn & nominal auxiliary load	1950	[Nm]
	Submerged endurance @ 2 kn	24	[days]
Accommodations	Crew & trainees	34 + 4	[-]

1.3 Problem

The problem this thesis addresses is the lack of a support tool for designing auxiliary systems of a battery powered submarine in an early design stage. This submarine has a power plant based on lithium-ion batteries as the only energy source. In comparison with a diesel-electric submarine, the absence of the diesel generators and its auxiliary systems and the integration of lithium-ion batteries, will require the introduction of new auxiliary systems and will have knock-on effects.

The problem is, that not only some of the effects are unknown, the exact consequences of all knock-on effects are unknown. An example of such effect could be the implementation of an extra safety system, which might have a knock-on effect on the weight of the submarine or causes an increase in demand of another system.

1.4 Objective and scope

The objective of this thesis is to gain knowledge about, and quantify the direct and indirect consequences for the auxiliary systems when lithium-ion batteries are implemented on a large scale in an entirely battery powered submarine. Design support tools will be developed to support the designer during the design of the battery and auxiliary systems. With these tools it should be possible to determine the main parameters of the auxiliary systems in an early stage submarine design. The end goal is to connect or integrate the separate tools. Before this is possible, design support tools for the separated systems will be developed. With the developed tools a better insight should be provided of the direct and indirect consequences of the integration of the lithium-ion batteries.

The objective of this report is to answer the main- and sub- research questions, which follow below.

1.5 Main research question

- How can a designer be supported, in an early design stage of an entirely lithium-ion battery powered submarine, when trying to determine the size, weight and energy consumption of systems that, among others, support the safe implementation of the new batteries?

1.6 Sub questions

1. What does literature say about sizing submarine auxiliary system components and the implementation of lithium-ion batteries?
   1.1. What are the relations between different auxiliary systems for conventional submarines, where have system boundaries typically been defined and can the system boundaries be similar in a battery powered submarine?

   1.2. Which auxiliary systems are needed for a safe, large-scale implementation of lithium-ion batteries in a submarine?
   1.3. Based on the criteria for weight, volume, energy consumption and importance for the safe implementation of the battery system, which auxiliary systems will be selected for implementation into the design support tools? Are there other alternatives in the industry to replace the component/system with?
2. What is a suitable method of modelling the systems and their components? What will be the input parameters for the designer support tools?
3. How do the auxiliary systems scale, when changing the input values? (Sensitivity analysis)
4. What are the consequences and knock-on, i.e. secondary, effects on auxiliary systems of implementing lithium-ion batteries, removing the diesel generator sets and the auxiliary systems for the diesel generator sets?

1.7 General report structure

This report consists of two parts. The first part consists of a literature study and is graded as part of the course code MT54010 accordingly. The topics discussed during this literature study are: submarine systems, submarine specific design requirements, the safe integration of lithium-ion batteries and the consequences for the submarine design when creating an entirely battery powered submarine. The literature study is completed with a selection of systems that are interesting to investigate further in the second part.

The second part of this report is the thesis and will be graded under the associated course code: MT54035. In this part design support tools are developed for the battery system, foam injection system and pressurized air system. Also, the environmental systems are reviewed and alternative systems are discussed. Finally a cases study is performed based on the entirely battery powered submarine concept design and the research questions are answered.

Part 1: Literature Study

2 Literature study introduction

The intention of the literature study is to gain knowledge required to answer some of the sub research questions. During the literature study different sources are reviewed. Sources are found on the Internet and also internal documents at the office of Nevesbu have been consulted. As mentioned in the section Starting point a diesel-electric submarine design will be used as a reference during this research.

2.1 General overview of the literature

A lot of research has already been performed into submarines in the past 100 years. However, a difficulty is that a lot of this research is classified and thus not publicly available. Nevesbu has a lot of experience and knowledge in the field of designing submarines. The last couple of years Nevesbu, together with the TU Delft, has performed research in different submarine subjects as mentioned in section Starting point.

Research into submarines, sizing of systems and lithium-ion batteries is also outside Nevesbu a popular field of interest. Recently, DNV-GL finished a study in cooperation with companies from the maritime industry about the safe implementation of large lithium-ion battery systems on board of civil ships. They focused on the thermal runaway process and the different possibilities of extinguishing and cooling the batteries [10]. Moreover, other companies have invested in research for the implementation of lithium-ion batteries for naval submarines. Kokam is one of them. They researched the whole process; from specialized lithium-ion cell chemistry to complete onboard systems. They even claim to have installed a lithium-ion battery system in a submarine [11]. Thyssenkrupp is also investigating the possibility of implementing lithium-ion batteries in a submarine [12] [13]. They outsourced the cell design and only focused on the integration of a large lithium-ion battery system.

Sizing of systems and components in an early design stage is an interesting topic for industry and scientists. Models and tools that can mitigate the risk of design complications in later design stages, may reduce time and costs of the whole design process. A research is performed into a method of sizing ship system components based on first principles. “This is done with the idea that the dimensions of a type of machinery can be estimated by sizing the core of that machine to the required power output using first principles” [14]. For this research the method has been successfully applied to diesel engines, gearboxes and electric machines. furthermore, other research focused on the development of a Cooling System Design Tool. This tool was “developed to enable naval architects and engineers to better illustrate, early in the design process, the requirements and characteristics for the chilled water system components” [15] [16].

These researches are only the top of the iceberg when considering submarines, sizing of systems and lithium-ion batteries. They do illustrate the interest in these topics as will further be explained in chapter.

A gap in the available literature is found in the safe implementation of the lithium-ion batteries in submarines and the design support tools for auxiliary systems. Systems such as the Heating, Ventilation and Air-Conditioning (HVAC), cooling systems or components such as pumps and compressors are already widely implemented into submarines [7] [8]. Literature about these (sub)systems are more available than literature about lithium-ion battery implementation into submarines. This is why in this literature study most existing systems are only superficially looked at in chapter Submarine systems. Information about the more common systems will be consulted when needed for the development of a design support tool in the second part of this report.

2.2 Literature study structure

During the literature study some of the sub questions are addressed. Chapter three gives information about submarine systems and their relations. Followed by chapter four in which some submarine specific requirements are discussed. The safe integration of lithium-ion batteries is treated in chapter five. Based on the knowledge gained in chapter three to five the consequences for the submarine design can be discussed in chapter six. The last chapter of the literature study consists of a selection of systems that are most interesting and relevant to investigate further and to include in the design support tool in the second part of this report.

3 Submarine systems

The volume and weight of a submarine are related by means of density. The overall density of the submarine must be the same as the density of the water, otherwise it will not be able to dive or surface. When in early design stage the main dimensions of the submarine are chosen, the maximum available volume inside the pressure hull and thus the maximum weight, are fixed. In general, most of the modern conventional submarines have a space driven design [17]. This means that not the weight is critical during design, but the volume is. Every cubic meter must be used as efficient as possible to meet the necessary density requirement. To pack all the required systems and components into the relatively small volume of the pressure hull, functionalities of different systems have to be combined. As an example, the air intake of the diesel engine and the equalizing ventilation help each other fulfilling their task by providing fresh air to both the submarine crew and the engine.

"A system is a combination of machinery, equipment and its connections (piping, cabling) which performs the task indicated by a (sub)function" [18]. A submarine has to operate in extreme water depths and must be silent and able to withstand shocks. These conditions and the high level of integration between systems make the submarine and her systems more complex than the systems would be on their own. This complexity makes it hard to identify every (sub)system and their properties. Furthermore, it makes it more complicated to make a good estimation of the weight, volume and energy consumption of a system in an early design stage.

To cope with this complexity, this chapter gives an overview of the systems and subsystems inside a diesel-electric reference submarine and to gain a better understanding about these systems and their relations. First the Ship Work Breakdown Structure will be introduced together with the most general groups of systems. Every general group will be superficially looked at. Also, arguments are given why to look further into certain groups. The section below explains the auxiliary group in more detail and in the last part of this chapter some of the important relations between the systems will be discussed.

3.1 Main system overview

In 1973 the US Navy introduced a Ship Work Breakdown Structure for their ships (SWBS). The SWBS is intended for the use in specification preparation, cost estimating, cost progressing, management, weight control, drawing numbering, shipyard job order coding and similar purposes [19] [20]. The SWBS groups are based on basic functions and are 3-digit coded. The seven groups, 100 until 700 are presented in Table 2. Users of this system can add a fourth digit to break down the structure even further into more detailed components.

Table 2: Weight percentage per general group of the SWBS of the reference submarine ([7]).

SWBS Group	Item name	Weight (% of total)	Weight (T)
1000	Hull-structure-general	30	580,78
2000	Propulsion-plant-general	22	427,33
3000	Electric-plant-general	1	20,73
4000	Command-and-surveillance	2	44,19
5000	Auxiliary-systems-general	6	106,31
6000	Outfit-and-furnishings	3	49,46
7000	Armament-general	4	67,58
F	Variable-loads	27	506,83
M	Margins-and-ballast-status	5	101,50
	Total	100	1904,699

The SWBS is a useful tool in order to define systems and subsystems, because it describes what is included and what is excluded per item [21]. In this way it is possible to attach the correct component data, such as mass, volume or energy consumption, to the related system. The SWBS is used for submarine design before. But, since the submarine in this research is entirely battery powered, the usability of the SWBS might be questioned. With the different propulsion configuration, compared with a conventional diesel-electric submarine, a different format/classification could be possible. The battery system is used as only power source which provide power to all consumers at all time. The Main Electric Motor (MEM) could be considered as just one of the consumers, which imply that the battery system is not necessarily part of the propulsion-plant-general group. Nevertheless, the SWBS divides and defines all the (sub)systems in a structured manner. For this research it is not needed to define another format/classification because the function of the systems remains practically the same. As long as all the systems are included in the SWBS it is a useful tool.

Table 2 shows the weight per SWBS group and the percentage distribution of the total weight of the reference submarine [7]. Looking at the lightweight, the hull structure and propulsion plant take up most weight of the submarine. More than half of the weight of the propulsion plant comes from the batteries. This means that the batteries and the auxiliary systems together are responsible for nearly 25% of the lightweight of the submarine. Besides the weight, the engine room and auxiliary system room take a significant amount of space. Within the pressure hull of the reference submarine, the engine room and auxiliary engine room take up approximately 22% of the volume. A schematic overview of the reference submarine is provided in Figure 3. Some of the main components are pointed out.

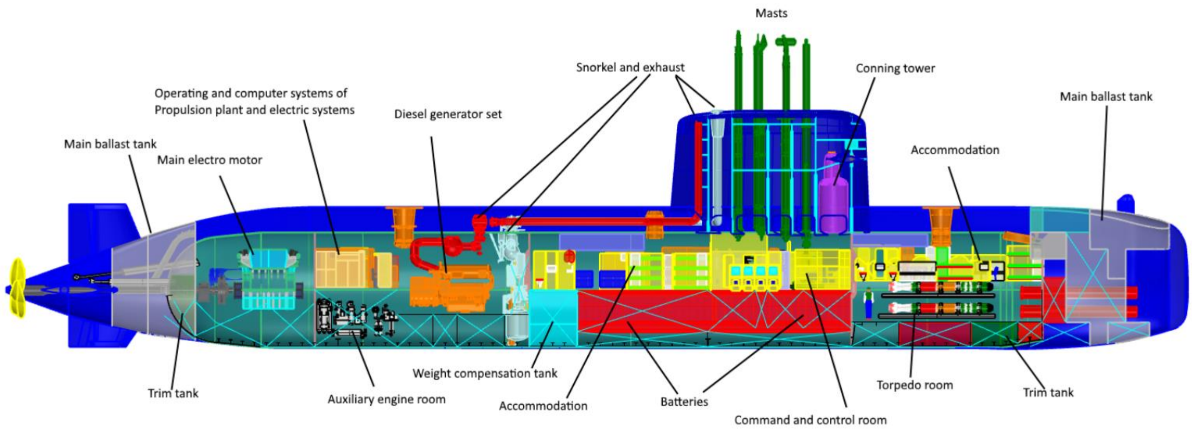

Figure 3: Schematic overview of the reference submarine design with some main components pointed out [6] [7].

As can be seen in Table 2, the hull structure of the reference submarine is the heaviest part of the submarine. The hull structure is heavy since it exists of thick steel plates that have to withstand high pressure and it has to carry all the other systems. The weight of the hull structure is mostly dependent on the size of the submarine and the maximum diving depth. Changing systems inside the submarine will change the hull structure, but only in a small amount. For this reason, the hull structure is left out of the scope of this research. Command and surveillance are left out of the scope as well. This is because the command and surveillance systems are highly specialized, require relatively little space and information about these systems is hard to gather.

The propulsion plant is an important part of the submarine. As described in chapter Starting point, Nevesbu and the TU Delft have done multiple researches about the optimizing of the submarine's power plant. Their focus was at the main components of the power plant and not yet at the auxiliary systems. These researches and the developed tools will be used as a starting point. Considering the propulsion plant, the main batteries are the most relevant sub-group of the propulsion-group for this research. An in-depth literature review about what is required for safe, large scale integration of lithium-ion batteries is provided in chapter Lithium-ion battery implementation. The literature review will help with the development of a design support tool. Besides that, the literature review will also focus on the knock-on, i.e. secondary effect on other systems and balances when implementing the lithium-ion batteries and when removing the diesel generator and its auxiliary systems.

The electric-plant group consists of: power conversion equipment, power distribution, switch-gear and the lighting system. From this group the power conversion and power distribution might be interesting auxiliary systems to look at. Even though the electric plant is only a small part of the weight of the submarine, it is still an important system since it distributes all the power. The power distribution system might change because of the different battery system and the absence of the diesel generators; a different layout of the switchboards might be necessary. Possible changes for the electrical system will be discussed in more detail in section Knock on effect on the overall submarine design. Whether one of the power distribution systems or components will be modelled will be discussed in chapter System selection.

When a submarine is in the patrol area it commonly sails very slow. During slow speed sailing the auxiliary systems use more power than the propulsion system. When the reference submarine sails at 4 knots the auxiliary systems use 62% of the total power [7]. For a different diesel electric submarine, an example of a possible mission profile with the corresponding propulsion power and auxiliary power is given in Figure 4. This to illustrate that the e-load of the auxiliary systems is significantly higher than the propulsive power during slow speed sailing. Because slow submerged sailing is often a large part of the mission profile, the auxiliary E-load has a large impact on the operational performance. For instance, when the auxiliary E-load is lower, the submarine's underwater endurance and range becomes larger which would be favorable; knowing the E-load of the auxiliary systems is therefore essential to design a power plant that can meet the requirements of the customer. The hypothesis that this is also applicable for an entirely battery powered submarine seems plausible. The peaks shown during covert transit will disappear however, the propulsive power does not change, and a diesel-electric submarine also only uses its batteries during slow, submerged sailing. A reduction in crew, caused by the change from diesel-electric to entirely battery powered, may cause a change in auxiliary e-load through a reduction of the hotel load. [2] [6]. Nevertheless, it is expected that the auxiliary e-load will remain a significant part of the total e-load during slow, submerged sailing.

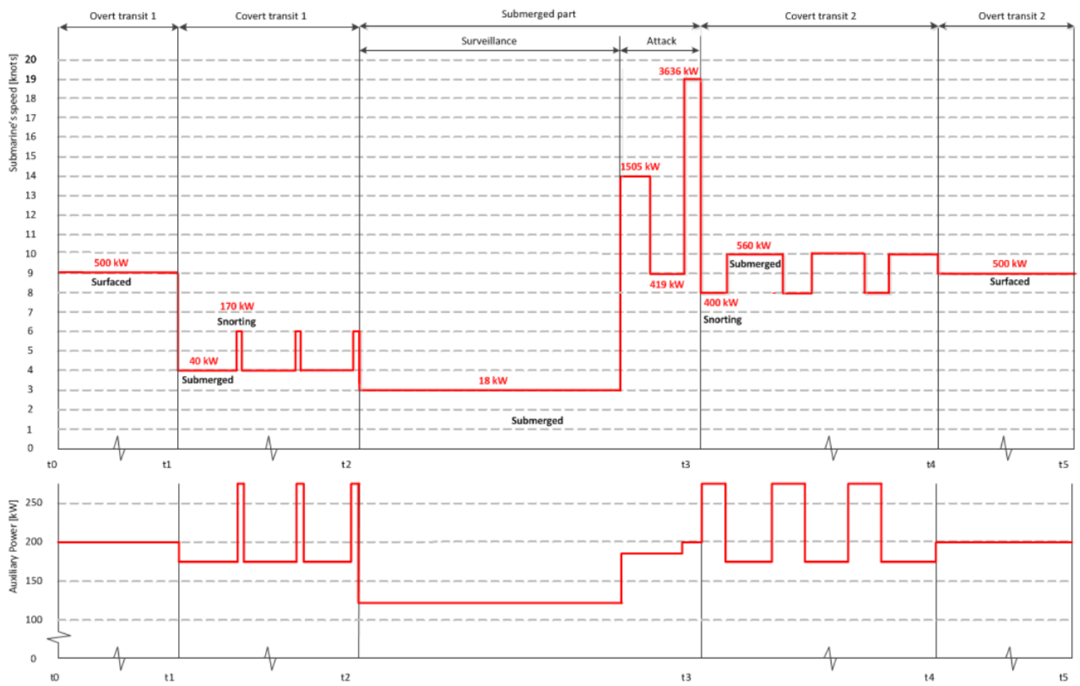

Figure 4: An example of a possible mission profile of a diesel-electric submarine with corresponding propulsion power and auxiliary power [5].

To make the weight distribution complete the variable loads are presented in Table 2 as well. All the consumables are placed in this group. During the missions the weight of this group will change because for instance fuel is burned and food is consumed. The margin and ballast group consist of a future growth margin and permanent lead ballast. The future growth margin compensates for possible future modifications and is located through the whole submarine, whereas the permanent lead ballast makes the submarine neutral buoyant and provides a low center of gravity.

3.2 Auxiliary systems

From the previous section can be concluded that for this research the most important part of the SWBS is the 5000 group. In this group most of the auxiliary systems are structured. Further, the 2000 group is relevant since this group includes the main batteries. In Table 3 the main categories of the auxiliary system groups are given together with the weight of these groups of the reference submarine. Later in this section the different categories are clarified and some of the more unknown subsystems are explained.

Table 3: Weight percentage per general auxiliary group of the SWBS of the reference submarine ([7])

5000	**Auxiliary systems, general**	**Weight (% of total)**	**Weight (T)**
5100	Climate control	14.5	15.4
5200	Seawater systems	6.1	6.5
5300	Freshwater systems	1.5	1.6
5400	Fuels and lubricants, handling and storage	2.1	2.2
5500	Air, gas, and miscellaneous fluid systems	35.5	37.6
5600	Ship control systems	24.2	25.7
5800	Mechanical handling systems	5.9	6.3
5900	Special purpose systems	10.3	11

3.2.1 Climate control

The climate control group consists of:

- Compartment heating system
- Equalizing ventilation
- Battery compartment ventilation
- Air conditioning system
- Chiller plant
- Chilled water circulation system
- CO_2 absorption system
- H_2 elimination system
- O_2 generation system
- Domestic cool and cold stores

These subsystems ensure the quality of the air through the whole submarine. An Important part of this is the Heating Ventilation and Air Conditioning (HVAC) system. This consists of temperature and humidity control, ventilation, CO_2 absorption and O_2 generation. The battery compartment ventilation system ventilates the battery compartments to prevent the build-up of too high concentrations of H_2 gases and transports the ventilated gases to the engine room. Spread through the submarine the H_2 elimination systems eliminates the hydrogen gases generated by the lead-acid batteries. The CO_2 absorption system and the O_2 generation system make sure the concentration of CO_2 and O_2 are at the required levels during submerged periods. The chiller plant together with the chilled water circulation system transports the chilled water over the water coolers of the air-conditioning units and the direct water-cooled equipment.

Removing the lead-acid batteries makes the H_2 elimination system superfluous because the new lithium-ion batteries do not generate H_2 gases. This is an obvious consequence of the different propulsion plant configuration. The other consequences are discussed in more depth in chapter Knock-on effects.

3.2.2 Seawater systems

The seawater systems consist of:

- Sanitary flushing system
- Seawater cooling system
- Bilge system

The sanitary flushing systems provide low pressure sea water to flush toilets or for general cleaning. The seawater cooling system transports the waste heat produced by various equipment, to outboard and supplies seawater to the consumers. The bilge system transports bilge water via the settling tank to outboard or to the weight compensation system.

3.2.3 Freshwater systems

The freshwater system consists of a freshwater generating system and a domestic fresh and hot water system. The first one produces freshwater from seawater and distilled water from freshwater. The second one stores freshwater and supplies domestic fresh and hot water to several consumers.

3.2.4 Fuels and lubricants, handling and storage

The fuel and lubricants, handling and storage system consists of a fuel oil transfer and compensation system and a lube oil transfer system. The first one is to enable the filling of the fuel oil tanks from shore, transfer fuel oil from the fuel oil tanks to both the service and conditioning system and compensates the weight reduction due to fuel consumption by transferring seawater to the fuel tanks. The second one transfers and stores lubricating oil and dirty oil.

3.2.5 Air, gas, and miscellaneous fluid systems

The air, gas, and miscellaneous fluid system consists of:

- High Pressure (HP) air plant
- HP air distribution system
- HP air blowing system
- Low Pressure (LP) air system
- Gas generator system
- Nitrogen storage
- Ballasting and de-ballasting system Main Ballast Tanks (MBT’s)
- Halon fire extinguishing system
- Portable fire extinguishers
- Hydraulic fluid plant
- Hydraulic oil distribution system

The HP air plant, HP air distribution and LP air system generates and provide HP air and LP air to several consumers. One of these consumers is the HP air blowing system that de-ballasts the submarine by blowing air into the main ballast tanks. The gas generator system rapid de-ballasts the main ballast tanks in an emergency situation by decomposing pressurized hydrazine into a gas mixture.

The hydraulic fluid plant and the hydraulic oil distribution system filter, store, pressurize and distribute the oil to the different consumers.

With the implementation of the lithium-ion batteries a different firefighting system is required that is able to extinguish lithium-ion battery fires. This firefighting system requires HP air, and thus the new battery system causes an increase in the amount of required HP air. In chapter Knock-on effects more is explained about the new firefighting system.

3.2.6 Ship control systems

The ship control systems consist of:

- Steering/diving actuators
- Automatic course/depth control system
- Trim system
- Weight compensation system
- Rudder/diving planes
- Rudder/diving planes lubricating equipment

The steering/diving actuators, the automatic course/depth control system, rudder/diving planes are responsible for the steering of the submarine. The weight compensation system makes sure that the submarine is naturally buoyant during different loading conditions and the trim systems keeps the center of gravity beneath the center of buoyancy to ensure the stability of the submarine.

3.2.7 Mechanical handling systems

The Mechanical handling group consists of anchor handling and stowage system, mooring and towing system and elevating and retracting gear of masts system. The first one handles and stores the anchor. The second one moors the submarine under surfaced conditions and assists in the embarkation of weapons for the torpedo system. The third one controls the positions of several hydraulically operated masts.

3.2.8 Special purpose systems

The special purpose systems consist of:

- Sewage system
- Garbage ejector
- Torpedo fuel pollution control system
- BIBS/HIS system
- Marker buoy system
- Beacon set DSRV system
- Lifesaving appliances
- Underwater signal ejector system

The sewage system collects and drains the sewage from toilets, wash basins, showers, sinks etc. and removes it to sea or shore. The garbage ejector removes garbage in special bags to outboard. The torpedo fuel pollution control system transfers dangerous and toxic torpedo fuel gases from the torpedo room to the air inlet of the diesel engine or bilge system. The BIBS/HIS system supplies, in case of an emergency, unpolluted air. The marker buoy system releases the marker buoys for emitting emergency signals to mark the position of the disabled submarine. The beacon set DSRV systems marks the location of the DSRV landing platform and the lifesaving appliances system optimizes the facilities for the escape and rescue of the crew. The underwater signal ejector system ejects underwater signal rockets or decoys.

3.3 Relations

As mentioned before, there are relations between the different systems and subsystems of a submarine. Research into diesel-electric reference submarines resulted in a general overview of the relations between the systems on board [7] [8]. These relations are graphically displayed in Figure 5 and Figure 6. Not all relations between the systems are shown in the figures. The weight, volume and heat balances are not displayed, since all systems have a relation to these balances. Making these relations visible would not add value to the figures. There are certainly more systems and relations, but the level of detail is considered sufficient for now. During further research more relations might be found, these will be discussed later.

Figure 5 shows the relations with the electrical systems, hydraulic systems, pressurized air system and seawater cooling system. For simplification reasons all the consumers are connected to the HP air system. For most consumers there is a pressure reduction valve to reduce the pressure to the required operational pressure. In some cases, the pressure is reduced gradually with the use of the LP air system in between the HP air system and the consumer. This is not displayed because this strongly differs per submarine.

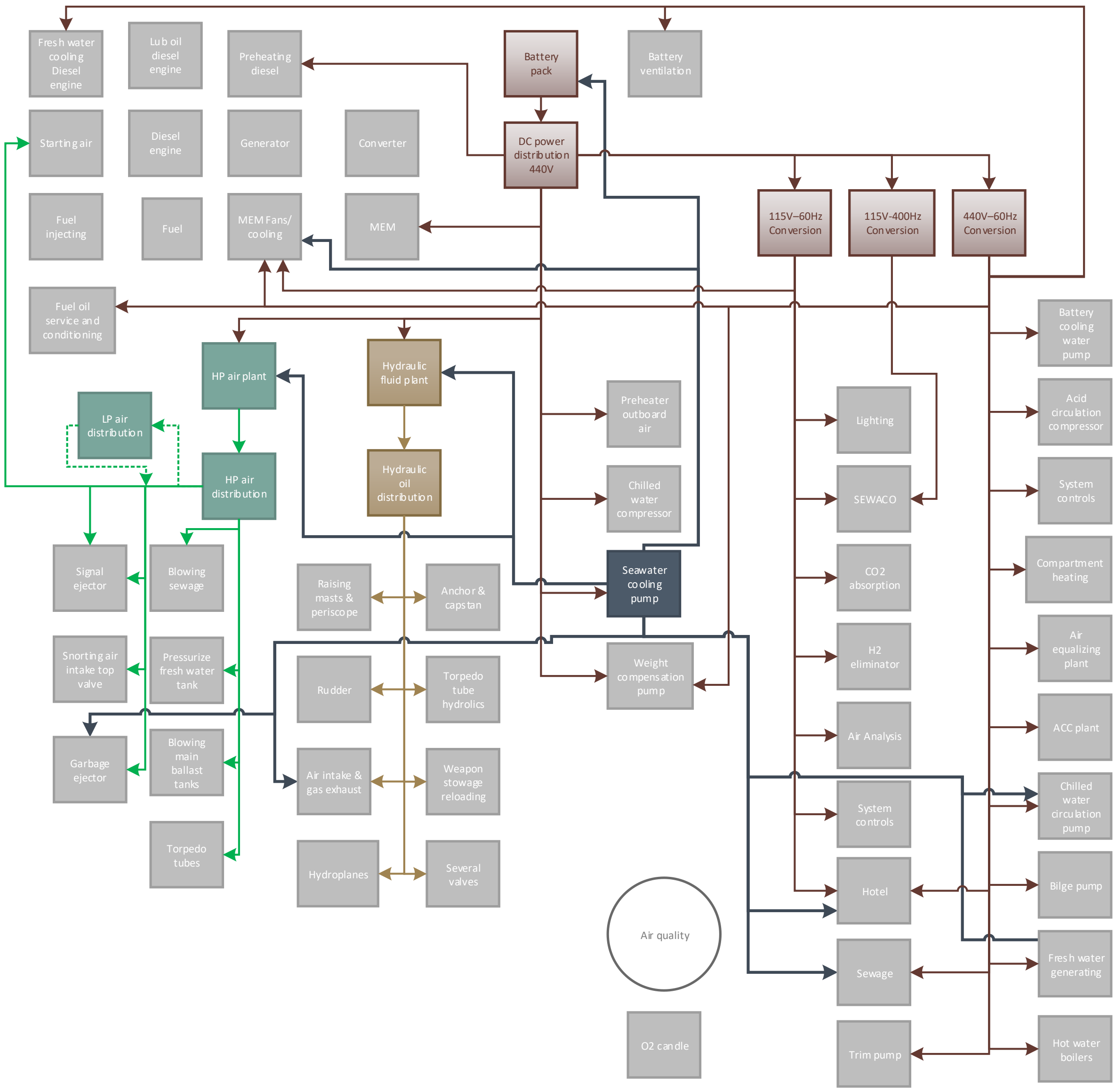

Figure 5: Global relations between systems: electrical, pressurized air, hydraulics and seawater cooling. (Diesel-electric reference submarine)

Figure 6 shows the more general relations and systems that contribute to the air quality inside the submarine. Part of this overview illustrates the clear relations between systems that are entrusted with the air quality. The air quality is of utmost importance for the crew's wellbeing. Consequently, these systems have to be well balanced.

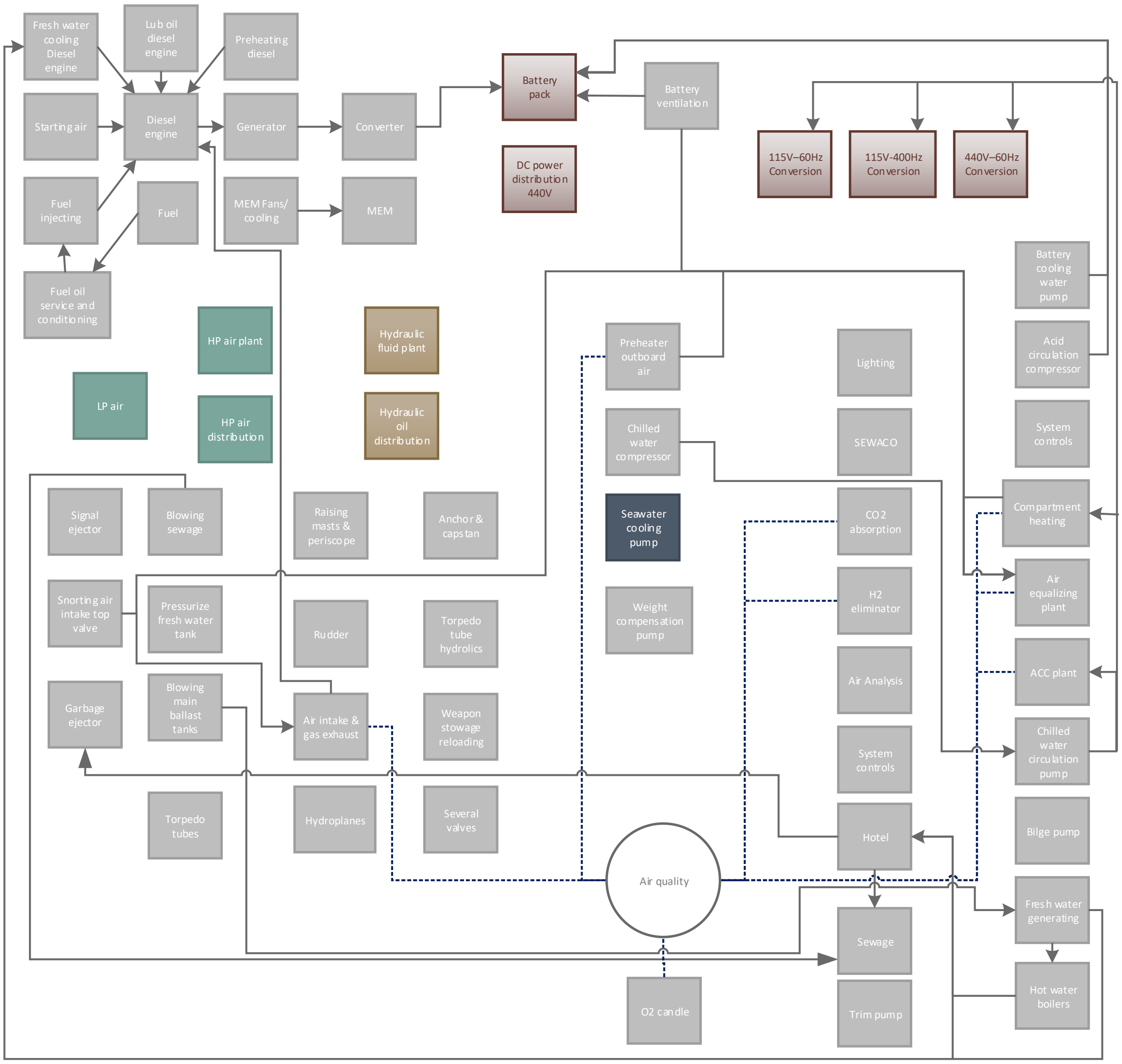

Figure 6: Global relations between systems: Air quality and general relations. (Diesel-electric reference submarine)

At this point information is given about the general groups of systems based on the SWBS; what they include and what the relations are between different (sub)systems. In the next chapter some submarine specific requirements are discussed. This will show why systems inside a submarine are more complex than the same systems on a surface ship.

4 Design requirements and philosophy

Knowing which systems are inside the submarine and their relations, gives an idea of the complexity. In this chapter some submarine specific requirements are explained [8]. The requirements show even more why systems inside a submarine are complex. Knowing these special requirements is necessary for the development of the design support tools.

4.1 Requirements

The design requirements and philosophy are used to design systems, subsystems and components. Some requirements are valid for every system and component, but some systems have their own (stricter) requirements. During design, these requirements must be considered.

4.1.1 Weight, volume and energy consumption

As already mentioned, weight, volume and energy consumption are important design parameters. Because there are limitations in the mentioned design parameters, systems and components must be as light, small and energy efficient as possible.

For example, on some surface ships hydraulic powered systems have their own dedicated Hydraulic Power Unit (HPU). This is an easy solution because it does not require a hydraulic distribution system, which would be complex and requires a lot of maintenance. In a submarine there would not be room for dedicated HPU's. This makes a hydraulic distribution system necessary which is exactly sized for its consumers.

4.1.2 Water pressure

Since the submarine must be capable of diving deep underwater, it must resist high hydrostatic pressures. Not only the pressure hull will experience hydrostatic pressure, but other systems as well. An example of such system is the seawater cooling system. The requirement of handling high hydrostatic pressures makes a system more heavy, complex and space consuming since the structures and components must be reinforced. Also, some tanks inside and outside the pressure hull must withstand high hydrostatic pressures. These tanks are called hard tanks and can handle the water pressure at maximum diving depth. Tanks inside the pressure hull that do not have to cope with the high pressure, are called soft tanks. For weight, volume and complexity reasons it is preferable to have as little as possible hard tanks and systems that have to withstand high hydrostatic pressures.

4.1.3 Shock

Submarines have to withstand shocks due to underwater explosions. The pressure wave of an underwater explosion causes a force on the pressure hull, which causes high accelerations both on the hull structure and equipment attached to it. Most systems and components inside the submarine are designed with the requirement to withstand these shock loads. They are reinforced and often have flexible mountings to move freely from each other.

4.1.4 Vibrations

Vibrations/noise coming from the submarine is something that can reveal the presence of the submarine. Every component inside the submarine is designed to produce the least possible amount of noise. Flexible mountings are used, additionally to shock absorption, also for absorbing vibrations caused by components or other sources.

4.2 Philosophy

If a system has to meet certain requirements depends on the design philosophy of the designer. A philosophy can dictate certain reliability, redundancy or other requirements per system. The EVOG (Emergency, Vital, Operational and General) classification method could be a part of a design philosophy and will be explained in this section.

4.2.1 Reliability

The reliability of a system describes if it can perform its intended function, without failure, for the required time duration in different situations. In the design of the reference submarine the reliability requirements for the different systems are coupled to the classification of a system [7]. Systems can be classified into four different levels: Emergency systems, Vital systems, Operational systems and General systems; abbreviated: EVOG. Table 4 explains the EVOG and provides examples of systems.

Table 4: Explanation EVOG

EVOG	Meaning	Example of systems
Emergency systems	survive, needed to rescue the crew from the submarine	Escape trunks, Emergency lightning
Vital systems	surface, needed to bring the submarine back to the sea surface	HP air blowing, Steering/diving actuators
Operational systems	operate, perform the operational task, for the total mission time	Freshwater generating
General systems	functions that are not strictly necessary to fulfil the mission	Mooring and towing

Emergency and vital systems have the highest reliability requirements to provide safety for the crew and rescue when necessary. This is achieved by partial and full redundancy, fail-safe design and/or early failure warning. This to ensure availability during extreme and emergency situations. Operational systems will have less strict reliability requirements. Systems in this group can meet the requirements with commercial technologies, supported by redundancy if needed. The general systems do not have specific reliability requirements.

4.2.2 Redundancy

Redundancy is applied as a design principle to increase the availability and reliability of the systems and components. The level of redundancy is dictated by the classification of the system as mentioned in Reliability. Redundancy can be functional or spatial. Spatial redundancy can be achieved by separating the redundant systems and components in different compartments. In case of a damage to the compartment, the other system can continue. There are different methods to achieve certain levels of functional redundancy [22] [8]:

- Full-backup ensures 100% capacity and functionality. This is achieved by installing two systems, subsystems or components, each having a capacity equal to the design capacity. In case of a cold spare, the backup system must be started when the running system fails. This can take some time. In case of a hot spare, the second system can take over immediately. Full-backup is mostly required for systems with the classification of emergency and vital.
- Multiple systems or components are designed to do the same task. The two systems or components are only needed in case of extreme operational circumstances. When one fails the other can continue on a lower capacity. This type of redundancy will be more common for systems with the operational classification.
- It is also possible to have redundancy with two systems which have different working principles. If one working principle fails, the other can continue or take over.

For distribution networks different setups are possible. These systems consist of one or more suppliers, distribution lines with valves and one or more consumers. A rather simple distribution network is shown in Figure 7. This system consists of two suppliers connected to one distribution line, feeding multiple consumers in the same section. Weak spots in this typical system are the single supply line, no valves to close certain parts and the concentration in just one room.

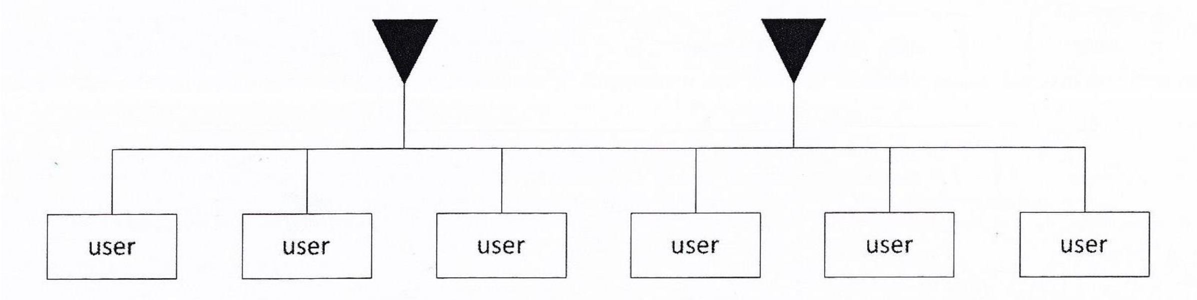

Figure 7: Single distribution (tree) [22].

A more advanced distribution network is shown in Figure 8. This system is devided in multiple zones. Each zones consists of one or more suppliers, a ring distribution and multiple consumers. All zones are connected with extra valves and some some vital users have two conections to the ring distribution. Advantages of this system are the many different configurations that are possible, vital users have multiple supply lines and each zone can operate on its own or can support other zones. Disadvatages of such system are the weight and volume necessary for the implementation, the complexity and higher maintenance requirements. Examples of systems that often use this type of configuration are electrical distribution systems and firefighting systems.

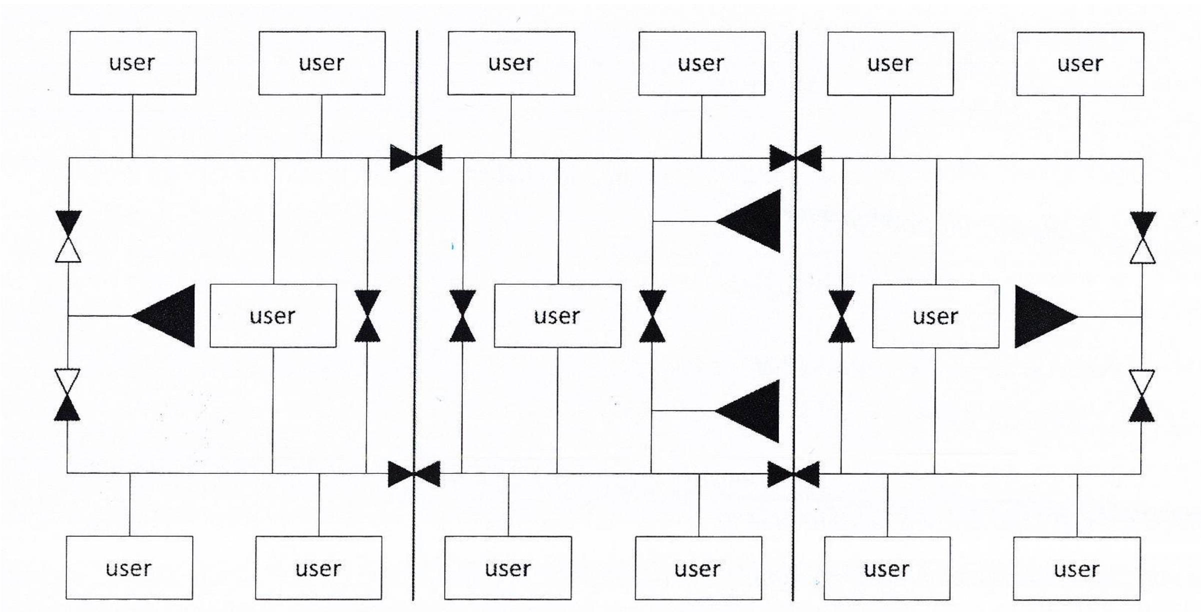

Figure 8: Zonal distribution [22].

5 Lithium-ion battery implementation

Lithium-ion batteries have improved properties in comparison with lead-acid batteries. They have a higher specific energy, 5 times, and higher energy density, 5 times, as can be seen in Figure 9. Since the volume and weight are critical in submarine design, these properties are important because more energy can be stored in the same amount (volume and weight) of batteries. Besides, other characteristics of the lithium-ion batteries are more favorable than the lead acid batteries as stated in Table 5. All these developments in the field of lithium-ion batteries has already led to the implementation of the batteries into submarines, as is claimed by Kokam [11]. However, Table 5 describes only positive properties, the lithium-ion batteries do have a higher risk of igniting. This is a serious safety issue which requires an appropriate solution.

In this chapter a literature study is performed into the Lithium-ion battery. The working principle will be explained shortly, possible risks and solutions will be discussed and the implementation into submarines and knock-on effects will be researched.

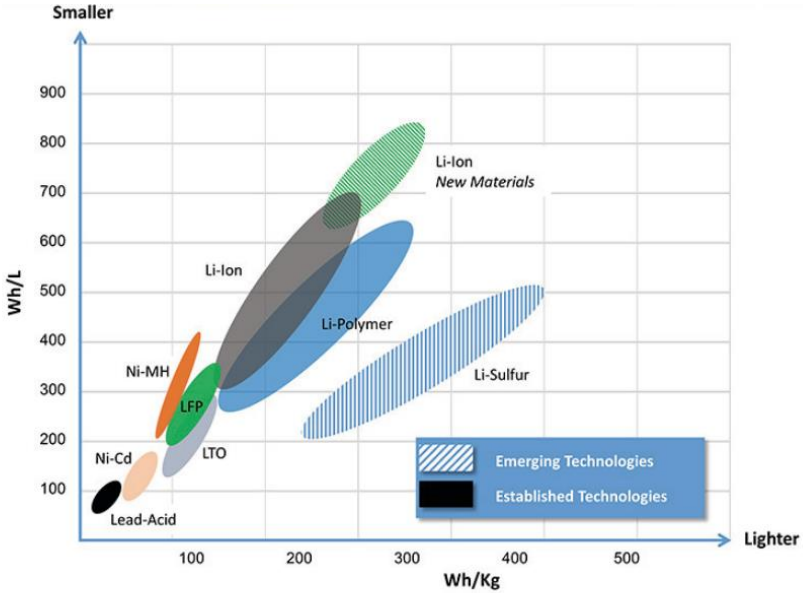

Figure 9: Specific energy and energy density of established and emerging technologies [23]

Table 5: Performance characteristics of the lithium-ion battery technology [24]

	Lead acid battery	**Lithium-ion battery**
Maintenance	High	Low
Specific lifetime	5 years	10 years.
Battery acid	Acid circulation system. Acid level inspection/re-filling. Battery washing.	No
Gas formation from battery	H_2 emission.	No
Availability	Full power only possible above 80 % State of Charge. Limited boat's availability due to maintenance charging. Need for external charging station and no crew on board during 3rd charging stage.	Full power independent of State of Charge (SoC). Suitable for multiple crew concepts.
Diesel/generator unit	Partial load at 2nd and 3rd charging stage.	Full load Optimal operating point (fuel oil consumption). Reduction of operation hours

5.1 Working principle of a lithium-ion battery

Batteries in general convert chemical energy into electric energy. A battery consists of an anode, cathode, electrolyte and a separator. During the electrochemical reaction the anode oxidizes and gives electrons, through an external circuit, to the cathode. The electrolyte provides the transfer of the ions between the anode and cathode and a separator prevents electrons from flowing freely from the anode to the cathode. A schematic representation of a lithium-ion battery can be seen in Figure 10. When recharging the battery this process is reversed.

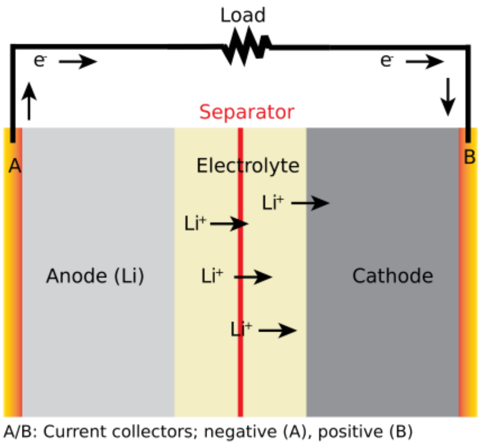

Figure 10: Working principle of a lithium-ion battery [25]

The lithium-ion battery is a relatively new type of battery that exists of lithium together with other metals. The different types of metal provide different properties as can be seen in Figure 11. Currently popular compositions of metals for commercial use are the lithium-nickel-cobalt-aluminum (NCA) or lithium-nickel-manganese-cobalt (NMC). This is because of the high specific energy, high specific power and cycle life [26]. Lithium-iron-phosphate (LFP) is regularly used as well in the maritime applications [10]. A lithium-ion battery typically has a nominal voltage of 3.6 volts, higher voltage can be obtained by switching the batteries in series. Other properties of the lithium-ion batteries are the high capacity at high discharge rates, a relatively flat voltage discharge rate and a low self-discharge rate. Causing that the available power is less influenced by the state of charge [2].

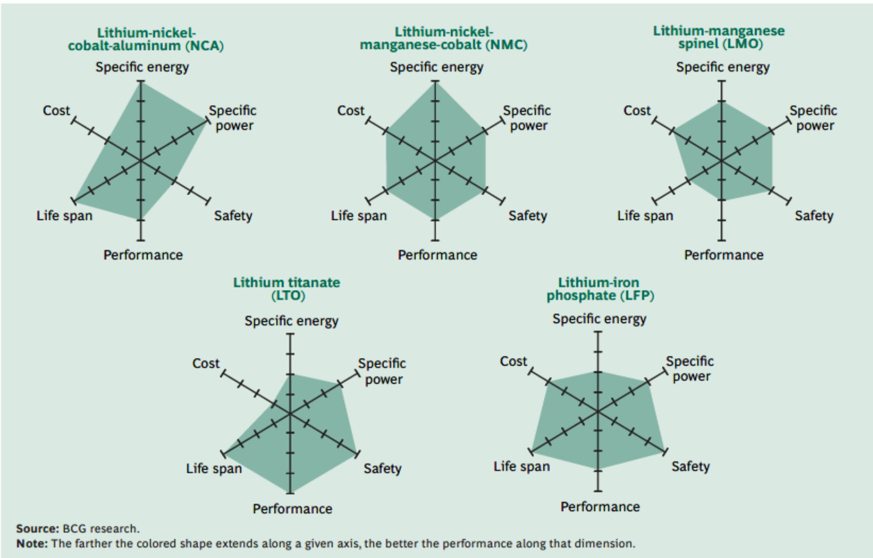

Figure 11: Different compositions of metals for lithium-ion batteries [27].

5.2 Lithium-ion battery system

Since lithium-ion battery cells cannot be produced in large size, a lithium-ion battery consists of multiple cells in series and parallel. Because of the high energy demand of a submarine, a lot of cells are required to deliver enough energy. An example of a submarine battery system, is the system designed by Kokam [11]:

- Single cells are stacked in series in submodules.
- Modules are created by switching four submodules parallel or in series.
- Strings are a set of modules that are connected serially to obtain the demanded voltage.
- Multiple strings are switched parallel to create a bank which can deliver the demanded power.
- The complete battery system exists of multiple banks.

The layout of a battery system is important. A good design ensures a level of redundancy and prevents high discharge currents. Redundancy comes from the different parallel banks and strings. When a faulty cell/module is detected, the string is disconnected and the other strings and banks can still deliver the required power.

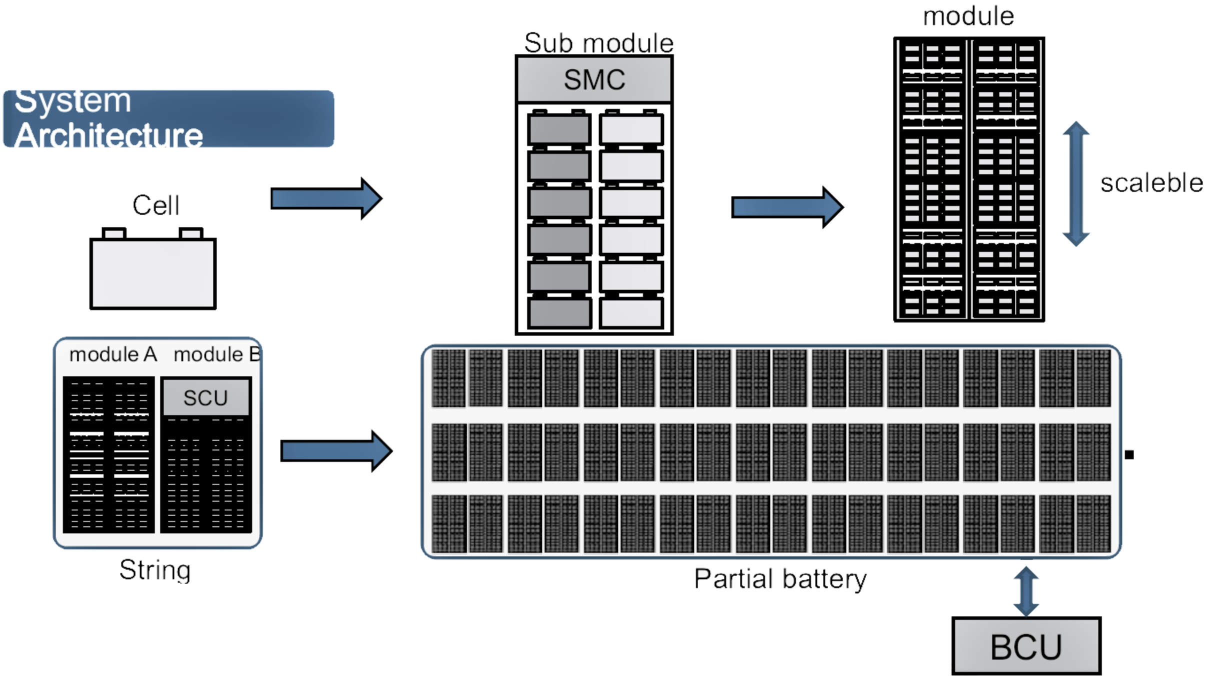

Figure 12: An example of a battery pack layout [24].

To monitor the cells, submodules, modules, strings and banks each layer has its own Battery Management System (BMS). A BMS controls its subsystem and tells the higher level BMS the corresponding status. In this way the top level BMS can control the discharge and charge of the battery system. In case something is wrong, a cell, submodule, module or string is disconnected to prevent more damage.

The energy density of the lithium-ion battery system is less than the energy density of a cell alone. This due to the presence of the BMS's and the buildup of the complete system. Figure 13 shows the decrease in energy density in a schematic way. The energy density of a modern lithium-ion cell alone could be 350 to 400 Wh/L, while the energy density of a whole battery system is much lower: 150 to 225 Wh/L [4]. These numbers are three years old. There are estimations that future lithium-ion batteries could have an energy density of more than 750 Wh/L and battery packs up to 500 Wh/L [28]. This is a significant increase and would make the batteries even more interesting to implement.

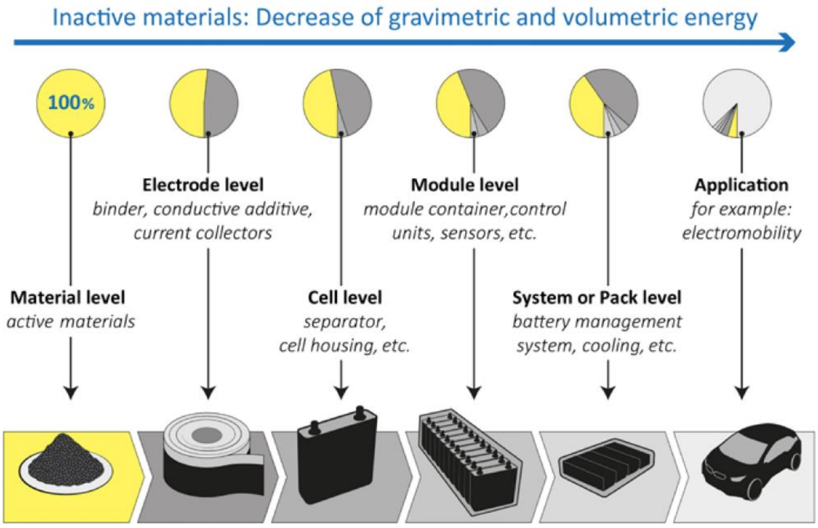

Figure 13: "Schematic illustration of a battery's production chain, from the material level via the battery cell, to the battery system level. In each step, inactive components are added and assembled into a key 'building block' for the battery system, which 'dilute' the energy provided by the active materials." [29]

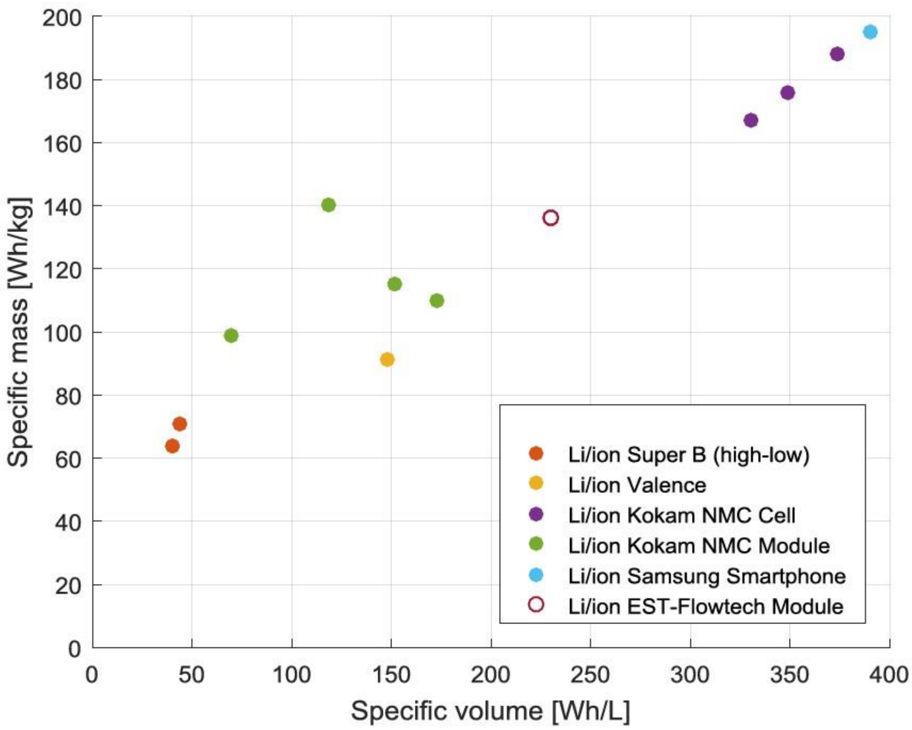

Figure 14: Energy density and specific energy of different lithium-ion batteries and battery packs [4].

5.3 Risks

Lithium-ion batteries have different risks than the commonly used lead-acid batteries. The worst that can happen with a lithium-ion battery is thermal runaway. During this process the battery releases all its stored energy by means of an exothermic reaction. When the battery is in thermal runaway its temperature rises, it starts venting toxic gases and there is an increased chance of fire or in the worst case an explosion. The most common cause of thermal runaway is internal short circuit of the battery [30]. This can happen due to thermal abuse, electric abuse or mechanical abuse. A schematic overview of the causes of thermal runaway is presented in Figure 15. Mechanical abuse can be caused by a shock, explosion or other incident. Overcharging or overdischarging can be a source of electrical abuse. Thermal abuse means that the surrounding temperature is too high, which causes the battery to heat up. All three types of abuses will eventually damage the separator of the battery. When the separator is damaged, electrons can move freely from the anode to the cathode: internal short circuit.

Beside the above-mentioned types of abuse, also the quality of the battery can be a source of risk. During the production of the lithium-ion battery cell a lot could go wrong, resulting in manufacturing errors. These errors can make a battery cell immediately unstable and this will probably be noticed. Unfortunately, it could also happen that a small imperfection in the battery cell will not be noticed. This cell will behave normal in the beginning of its lifetime, but the small imperfection can cause degradation of the cell. When the complete battery system is in use, the small manufacturing error can become more critical. Eventually causing a short circuit and even thermal runaway.

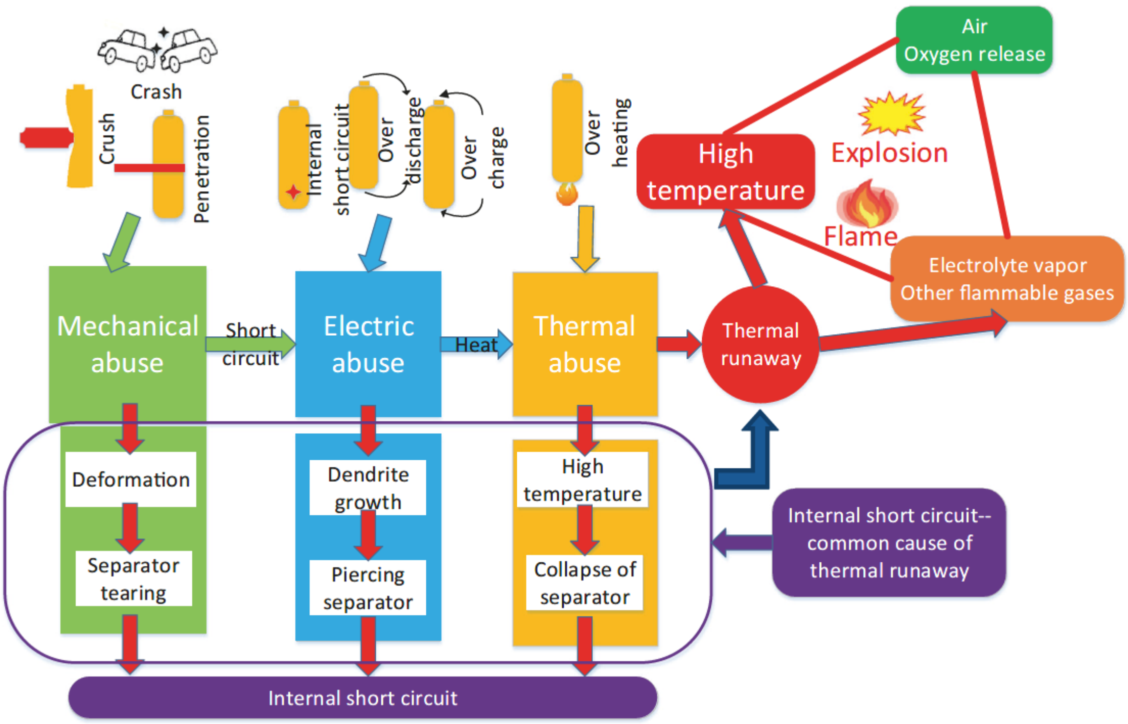

Figure 15: Schematic of the causes of Lithium-ion battery fire accidents [31]

5.4 Preventive measures

There are different ways to reduce the risks of a lithium-ion battery system. Some methods to improve the safety are mentioned shortly in this section.

Since there are different types of lithium-ion batteries with different properties, the risks will not be the same for all of them. An important different is the temperature that triggers the thermal runaway. The choice of the chemistry composition of the battery is important to build battery cells with high thermodynamically stability. Research is done to look into new materials to use as anode, cathode or separator [32]. The developments of these new materials look promising and will possibly improve the safety of the lithium-ion battery cells in the future. Despite this, the improvement of the battery composition is not within the scope of this research and will not be investigated any further.

Different companies have used different methods when designing a lithium-ion battery pack for a submarine. In all cases the battery pack is designed specifically for a submarine, but the battery cell can be used from existing consumer batteries [12] or can be designed especially for a submarine battery system [11]. Both methods have their advantages and disadvantages. The existing cell might have proven itself to be reliable and safe. Also, mass production and less R&D work might reduce the costs. When designing a completely new cell, the properties of it might be more beneficial; such as a higher thermal runaway temperature. Even if a cell is designed specifically for the submarine there will always be the risk of thermal runaway. Designers of a battery system have to look into the different possibilities and decide which option is the most beneficial.

To ensure the safe use of a lithium-ion battery, a BMS controls the battery system. “It provides protection against overcharging, overdischarging, high temperatures, low temperatures, short circuiting, and other failure modes” [33]. On every level of the battery system, battery cell, submodule, module, string or bank a BMS monitors the component. It uses sensors to know the current, voltage and temperature and communicates this with its higher level BMS. In this structured way the master BMS can decide how to switch the battery system for optimal and safe use. An important task for the lower level BMS’s is the balancing of the cells. This means that the cells are all closer to the same State of Charge (SoC). This is necessary to maximize the capacity of the battery [34]. Improving the BMS can make the Lithium-ion battery safer. Optimizing the BMS is beyond the scope of this research. The size of the BMS will be looked into in the next part of the research.

Controlling the temperature of the battery pack is important to reduce the chance of thermal runaway and to optimize the performance and lifetime. For temperature control there are different methods. Air-cooling/heating can be done with ventilation, and liquid cooling/heating can be done with different types of liquid. The layout of the liquid temperature control system plays also an important role in the effectiveness of the system [35]. The disadvantage of such liquid temperature control system would be the lower energy density and the power consumption of the system. Moreover, it is the question if it is necessary to implement a cooling system for an entirely battery powered submarine. The operating temperatures of the battery pack during slow and normal sailing speeds will not be high. The temperatures will only rise to unfavorable highs at high charge and discharge rates. Charging a entirely battery powered submarine will probably be performed inside a harbor, making extreme high charging currents not a common practice. Besides that, high discharge rates will only happen during a short sprint and is limited at the maximum powered of the main electric motor and is thus an exceptional occurrence. The operational profile, different temperature control methods, advantages and disadvantages have to be evaluated to decide if such a system is necessary to implement.

5.5 Damage Mitigation

With the previously mentioned technologies, the chance of thermal runaway is already low. In the rare case a lithium-ion battery cell experiences thermal runaway, every effort should be made to prevent spreading. The heat generated by the cell, which is in thermal runaway, will heat up other neighbor cells, forcing them into thermal runaway as well. This chain reaction can cause catastrophic events and thus cooling the battery system is of great importance. Also, when putting out a lithium-ion battery fire the flames have to be extinguished and the battery have to be cooled down. “If the battery temperature is high enough after the open flams are extinguished, there is still a possibility that the battery will reignite” [36]. This means that cooling down the battery cell long enough is of utmost importance.

“Lithium-ion battery fire tests have shown that applying liberal quantities of water or by submerging in water, a lithium-ion battery fire can be extinguished and the cell cooled inhibiting ongoing combustion or cascading to adjacent batteries” [37]. Unfortunately, using normal water inside a submarine is not convenient since it can damage other neighbor cells/modules and there is a risk of short circuit and corrosion. Further, it will affect the neutral buoyancy which can create a dangerous situation in which the submarine is not able to surface anymore. An alternative of water could be high pressure water mist. This method has high cooling capabilities, reduces the chance of an explosion, can extinguish small flames and has lower water volume requirements than normal water sprinklers [37] [38]. But again, water mist increases the risk of a short circuit. It can also not ensure the complete elimination of thermal runaway since it cannot cool inside the battery module. Furthermore, in a high SoC the thermal runaway cannot be stopped by water mist [39].

An extensive research from DNV-GL tested, besides water and high-pressure water mist, other methods to cool down and extinguish the lithium-ion battery [10]. The results of these tests showed that direct injection of a fire suppression media into a battery module is more effective than flooding the complete battery system. When using direct injection, other modules are not affected by the fire suppression media and the battery system can continue delivering power. Direct water injection did a good job extinguishing and cooling the battery, but is not recommended because of the risk of short circuit and hydrogen production. Another tested direct injection media is foam. This has the best heat mitigation performance and requires less volume of water compared to the direct water injection system. “Additionally, the foam-based system is deployed using de-ionized water to limit conductivity and corrosive effects” [10]. The system used during the test is the Compressed Air Foam System (CAFS) from FIFI4Marine. This is a promising system and will thus be investigated further in the thesis part of the report.

When a lithium-ion battery becomes too hot, it starts venting toxic and flammable gases [31]. It must be prevented that the gases leak into the rest of the submarine and poison the crew. This can be done by closing off all the openings to the battery compartment. In case the battery systems start venting, the pressure will rise and this could be a potential threat. A solution should be found to prevent extreme pressure build up. An adapted ventilation system might help ventilating the battery compartment when the submarine is surfaced. Additionally, when submerged an overboard pressure release option might be a solution to release some gas into the seawater [2]. These possible solutions need further research to assess the feasibility.

6 Knock-on effects

In the previous chapters information is provided about the systems on board of a submarine, submarine specific design requirements and lithium-ion batteries. With this information the consequences for the overall submarine design can be investigated. This chapter will first discuss the lead-acid battery removal and the direct and indirect effects. Secondly, it will discuss the same for the diesel generator sets removal. Subsequently, the required systems for a safe implementation of the lithium-ion batteries are discussed. Eventually, the overall knock-on effects for the overall submarine design will be looked at.

6.1 Lead-acid batteries removal

The replacement of the lead-acid batteries with the lithium-ion batteries results in a demand for other auxiliary systems. Support systems for the lead-acid batteries are not required anymore and are listed in Table 6.

Table 6: System reduction due to the implementation of lithium-ion batteries and knock-on effects on other systems [2].

SWBS	Auxiliary battery systems	Consequence
2232	Battery cooling water deionizing water	Lower demand for seawater cooling system
2233	Distilled water system	Lower demand freshwater generation system Lower demand LP air system
2234	Battery agitation system	

Removing these systems and the lead-acid batteries result in knock-on (secondary) effects for other systems inside the submarine [7]. As can be seen in the table there is less demand for the seawater cooling system, LP air and freshwater system. This could mean that a smaller system might be enough to fulfil the task. Before such conclusion can be made, the consequences of the fully battery powered submarine must be reviewed.

6.2 Diesel generator sets removal

The diesel generators need several auxiliary systems to operate. Removing the diesel generators means that the support systems are not needed anymore and that they can be removed as well. A list of the auxiliary systems that are not required anymore is shown in Table 7 together with the consequences for the other systems inside the submarine.

Table 7: System reduction due to the removal of the diesel engines and knock-on effects on other systems [2].

SWBS	Diesel engine and auxiliary systems	Consequence
2331	Diesel engines	
2332	Generator	
2333	Lubrication oil system diesel engines	
2334	Freshwater cooling system diesel engine	Lower demand LP air system
2335	Starting air system diesel engine	Lower demand HP air system
2336	Fuel oil inject system diesel engine	
2511	Air intake system	No air suction into the submarine
2522	Diesel engine start – stop system	
2561	Diesel sea water cooling system	
2591	Exhaust gas system	
2611	Fuel oil service and conditioning system	Lower demand freshwater and LP air
5411	Fuel oil transfer and compensation system	Lower demand seawater and LP air

As can be seen in the table the demand for HP air and LP air will decrease. Remarkable is the consequence for the air intake system removal. In case of a diesel electric submarine this system sucks fresh air into the submarine when the diesel generators are recharging the batteries. Without the diesel generators and the air intake system, another system must take over this task.

Even more important is the reduction in weight and volume due to the removal of the diesel generators and its auxiliary systems. As described in the research of S.A. Los, this weight and volume reduction will be used for the implementation of lithium-ion batteries and other required systems [2].

6.3 Required systems for safe lithium-ion battery integration

For the safe implementation of lithium-ion batteries several auxiliary systems are required:

- Battery Management System on multiple levels of the battery system
- Firefighting system
- Ventilation
- Overboard pressure release option
- Short-circuit protection

The BMS will be implemented on different levels of the battery pack. It controls the charging and discharging of the battery cells and disconnects faulty battery strings. A disadvantage of this system is the packing factor which will increase, resulting in a lower energy density. In addition to the BMS inside the battery pack there is a Battery Control Unit (BCU) needed outside the battery compartment. The BCU displays the status of the battery system and can be used to control the system.

Inside the battery compartment a firefighting system must be installed to mitigate thermal runaway. For this system a direct foam injection system is chosen to be the most promising for civil applications [10]. It must be researched if this is also the case for the submarine application. This system injects foam into the battery submodule to cool down the battery cells directly. It is possible to do this multiple time per submodule if necessary. More details of the mass and volume required and other information about the system will be discussed in the next part of this research. A system design, designed by FiFi4Marine, will be used as reference.

If deemed necessary to control the temperature inside the battery compartment, temperature control could be done with isolation and ventilation. This could be desirable to provide the battery an optimal operational temperature. The isolation must ensure that the battery compartment does not lose too much heat to the surrounding and the ventilation might cool or heat the pack if necessary. Additionally, a form of ventilation is required inside the battery compartment to prevent the local buildup of dangerous gases. Another potential risk is the increase of pressure inside the battery compartment due to venting batteries [2]. This risk must be evaluated and a suited solution should be found.

The total short-circuit current of a lead-acid battery pack is approximately 20 – 30 kA, whereas the total short-circuit current of a lithium-ion battery pack is approximately 400 – 500 kA [40]. The large short-circuit currents of the lithium-ion battery pack cannot be controlled. Neither electrically, nor mechanically. Consequently, short-circuit protection on a lower level in the battery pack, where the short-circuit currents are lower, could be an appropriate solution [2].

6.4 Knock on effect on the overall submarine design

Changing batteries and removing systems has consequences for the overall submarine design. In this section these consequences are discussed. Focus will not be on the quantitative part of the consequences, since this is not possible in this part of the research. In the next part of the research some consequences might be discussed quantitatively.

6.4.1 Weight balance and stability

Removing the diesel generators, lead-acid batteries and the auxiliary systems reduces the weight of the submarine. Implementing the lithium-ion batteries and necessary auxiliary systems will cause a shift in the Vertical Center of Gravity (VCG) and the Longitudinal Center of Gravity (LCG) and will change the trim polygon of the submarine. These changes have to be taken into account during design. The absence of fuel oil will have consequences on the trim polygon as well: less or no compensation is needed for the weight change due to fuel consumption.

6.4.2 Crew size

The entirely battery powered submarine concept design consists of less systems. Less systems could cause a reduction in operational duties and maintenance requirements. Moreover, M.E. Venema made a manning analysis for a fully electric (battery/fuel cell) submarine [6]. Assuming less maintenance at sea and a higher level of automation, a significant lower number of crew members would be needed. Resulting in a smaller accommodation, less required consumables and a reduction in heat load.

6.4.3 HVAC and heat load

With the lithium-ion batteries the submarine has an increased underwater range and endurance. Without the need of recharging during the mission the submarine can stay submerged for a longer period. During these underwater periods the air quality will be a critical parameter. Consequently, the systems of the climate control group must be redesigned: more CO_2 must be absorbed and more O_2 must be generated. In the reference submarine CO_2 absorption is done by several chalk holders and the O_2 is generated with O_2 candles. When being underwater for a longer period, more chalk holders and O_2 candles are needed. The amount of chalk holders and O_2 candles increase linearly with the submerges time, which will cause an undesirable amount [2]. There are systems that require less space and mass, but unfortunately use a significant amount of power. Further research is needed to find a feasible solution.

The ventilation system will change due to the absence of the air intake system. A new/adapted system has to be implemented to ventilate fresh air into the submarine when surfaced. A possible solution could be duct through the sail with a ventilator. The rest of the ventilation system will probably not change a lot because during submerged operation the diesel generators are turned off anyway [2].

Due to the different systems and different amount of crew on board, the heat balance will change. This means that systems that provide heating and cooling inside the submarine must be dimensioned accordingly. The removal of the diesel generator will cause a lower demand for seawater cooling and a reduction in heat load in general. Additionally, a reduction in crew will cause a reduction in humidity and heat. This might lead to a smaller demand for the seawater cooling, chilled water circulation and freshwater generation systems. More details are needed to determine the significance of the change in heat load.

6.4.4 Electrical systems

The electrical load balance will change when different systems are installed. The diesel engine control systems and those of its auxiliary systems will be removed, which results in a decrease in e-load. The BMS and extra ventilation systems on its turn will increase the e-load. S. A. Los made an estimation for an entirely battery powered submarine: the e-load was only significantly reduced during submerged operations.

Due to the absence of the diesel generators the maneuvering switchboard configuration will change. This will probably have a limited effect on the size and weight. The lithium-ion battery pack will have more strings and thus requires more switches. But since the short-circuit protection is removed from the battery switchboard, the size and weight of the battery switchboard will approximately stay the same [2].

Another notable consequence of the lithium-ion battery pack is the amount of parallel-switched battery strings. These could impose high currents in the cables running from the battery pack to the switchboard.

Because of the high currents, thick cables are required which are heavier. The presence of the lower level short-circuit protection and the thick power cables reduce the specific energy and energy density of the total battery pack.

6.4.5 Pressurized air

Consumers of the pressurized air system (HP and LP) are:

- Starting air diesel engine
- Signal ejector
- Snorting air intake
- Garbage ejection
- Pressurize freshwater tank
- Blowing main ballast tank
- Blowing torpedo tubes
- Pressurize several other tanks and other small systems

With the diesel generators and its auxiliary systems removed, the amount of pressurized air consumers reduces. The starting air for the diesel generators and pressurizing the lubrication oil tank are examples of reductions on the pressurized air system. Also, less air is needed for the snorting air intake system since snorting is not necessary anymore during the mission. Despite these reductions, the amount of high-pressure air bottles will probably increase due to the longer submerged time. Additionally, pressurized air is required for the direct foam injection system. There should always be enough air available to activate the system at any given time. This might also cause an increase in pressurized air storage.

7 System selection

After this literature study several design support tools will be developed. With the information from the previous chapters an insight is provided into the auxiliary systems of a diesel-electric reference submarine, their relations, some submarine specific requirements and lithium-ion batteries. In this chapter several auxiliary systems are selected to include in the next part of this research. Focus will be at the auxiliary systems that change significantly due to the different powerplant setup (entirely battery powered). Additionally, as mentioned in the section Sub questions, the other criteria are weight, volume, energy consumption, heat and safety.

7.1 Selection

For two different diesel-electric reference submarines an overview has been made of some relevant auxiliary systems. Only a selection of the systems is made and they are ranked on the influence on volume, volume distribution, weight and demanded power and importance of the system, as is presented in Figure 16 and Figure 17 [7] [41]. These two figures show that the relative weight and energy of these auxiliary systems do not differ much between the different submarines. The information in these two figures are useful to determine the influence of the different systems on the overall submarine design.

As discussed in the Objective and scope, this research is mainly focused on the auxiliary systems and the new batteries. The propulsion plant has already been researched and modeled before. Other than the lithium-ion batteries, the propulsion plant will not be investigated further in this research. Besides that, the electric plant will not be modeled. Although, the battery type changes, the electric system is not expected to change much as discussed in section Electrical systems. Where necessary some electrical components, such as cables and small electronics, might be implemented in the support tools.

The (sub)systems that will be investigated and will be implemented in the design support tool in the next part of the research are listed in Table 8. On the right side of the table the SWBS numbers of the mentioned systems are listed.

Table 8: (Sub)systems that will be modeled in the next research part.

System	Including SWBS numbers
Battery system	2230, (223X)
Firefighting system	5550
HVAC	2511, 5110, 5121, 5122, 5141
Chilled water system & seawater cooling system	5142, 5143, 5241
Air quality	5151, 5152, 5153
Hydraulic system & pressurized air system	5511, 5512, 5561, 5562

7.1.1 Battery system

The battery system changes a lot due to the new lithium-ion batteries. Not only changes the type of battery, the amount of batteries will increase significantly. The battery system is a large volume and mass to take into account during design, and thus important to size correctly. Because the battery system will consist of a new type of battery, new support systems are necessary for safe implementation. Part of the battery system are the multi-level BMS (including a short-circuit protection) and the cables inside the battery compartment.

7.1.2 Firefighting system

The existing firefighting system takes a relatively low amount of space, weight and energy as can be seen in Figure 16 and Figure 17. Nevertheless, due to the implementation of the lithium-ion batteries, the requirements for the firefighting system on board of the submarine change completely. The new requirement of extinguishing lithium-ion battery fires and cooling down the battery cells require a new type of system. As described in section Damage Mitigation a foam injection system will be implemented into the submarine. This system may also be useful in the rest of the submarine. This possibility will be further looked into in next part of this research.

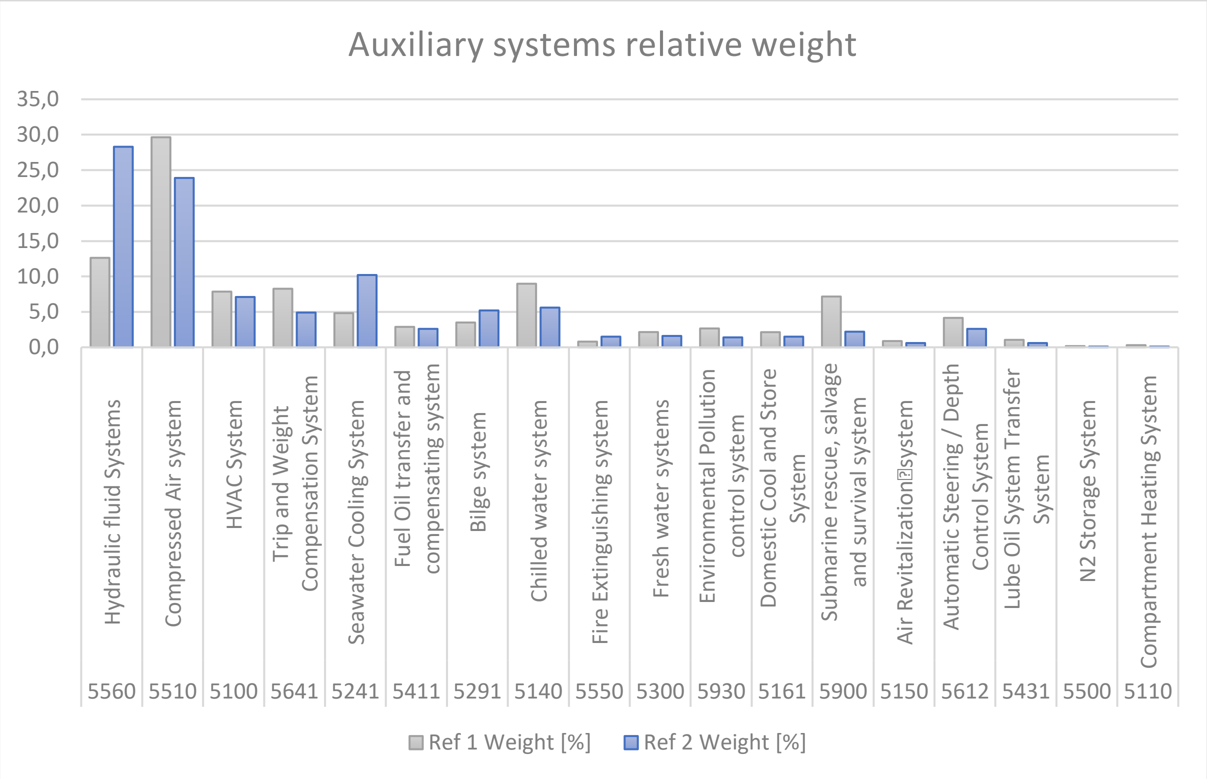

Figure 16: a selection of auxiliary systems and their relative weight for two different diesel-electric submarines [7].

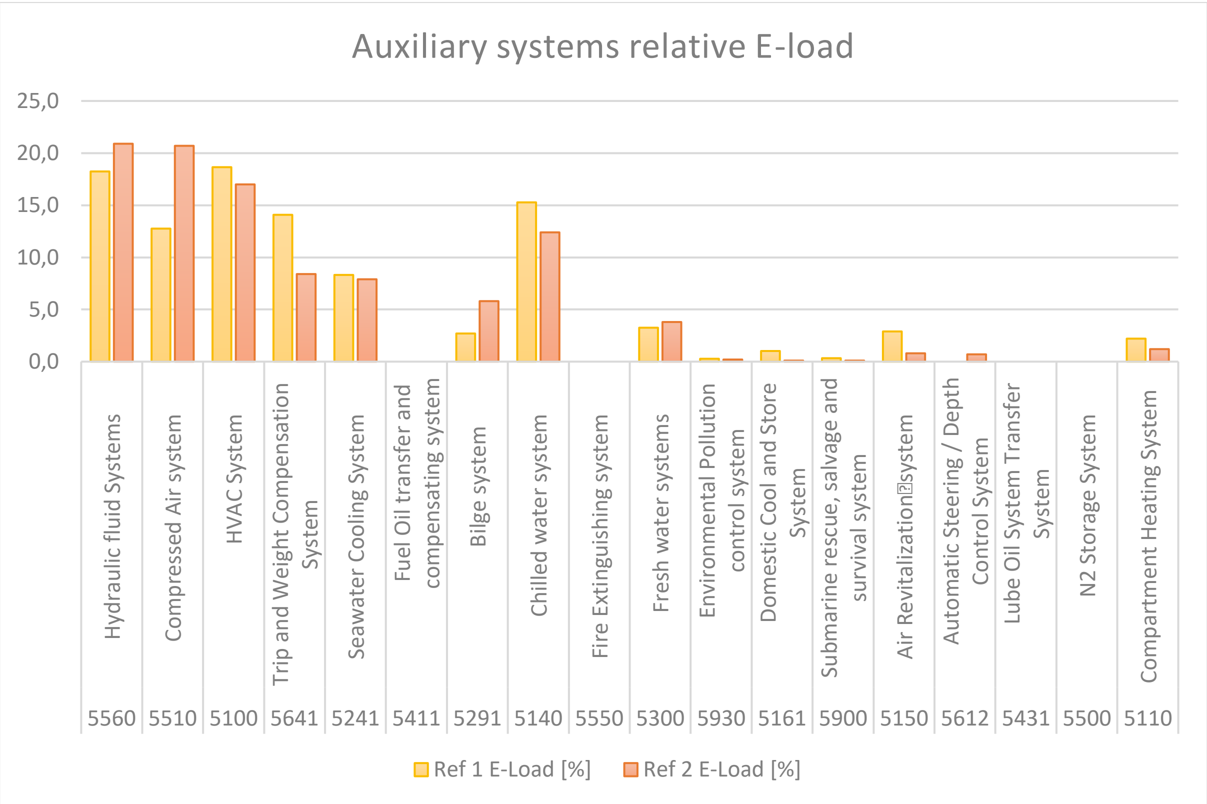

Figure 17: a selection of auxiliary systems and their relative power consumption for two different diesel-electric submarines [7].

7.1.3 HVAC

Figure 17 shows that the HVAC system has a significant e-load. Moreover, the change in the heat balance due to the removal of certain systems and the different amount of crew, will cause a change in the requirements for the HVAC system. The HVAC consists of subsystems which control temperature, humidity and ventilation.

7.1.4 Chilled water system & seawater cooling system

The removal of the diesel generator, the change of batteries and the change in the HVAC system cause different requirements for the chilled water system and seawater cooling system. Moreover, the chilled water system and seawater cooling system use a significant amount of energy as can be seen in Figure 17.

7.1.5 Air quality

With the lithium-ion batteries the submarine can stay underwater for a longer time. This causes an increase in the amount of chalk holders and O_2 candles needed to ensure the required air quality. The storage of these consumables reaches large numbers. So, a feasibility study into different systems to ensure the air quality must be performed.

7.1.6 Hydraulic system & Pressurized air system

Both the hydraulic and pressurized air system are a significant weight and uses a significant amount of energy as can be seen in Figure 16 and Figure 17. The new firefighting system requires HP air to operate, and some other systems will be removed. This will probably change in demand for both systems.

It might also be interesting to investigate the possibility to electrify some of the consumers to reduce the demand of the hydraulic system and pressurized air system even further.

Part 2: Thesis

8 Thesis introduction

In the literature study knowledge is gained about submarine systems, design requirements, lithium-ion batteries and the consequences of changing the diesel-electric reference design into an entirely battery powered submarine. Furthermore, a selection is made of the systems that are interesting to investigate further during the thesis and to implement in a design support tool.

A dot on the horizon is the development of one large high level design support tool that should assist the designer during an early stage design. The tool should include multiple systems for which it can make a substantiated estimation of the main parameters, such as weight, volume and energy consumption. During this thesis, design support tools are developed for the systems separately. They will be the building blocks for the larger design support tool, which is the ultimate goal.

The chilled water, seawater cooling and hydraulic systems are part of the selected systems. During the thesis, insufficient time was available to implement these systems into a design support tool. They are treated in this chapter, but won't be discussed in the rest of this report. Including these systems into a design support tool is still interesting and can be done in follow-up research.

8.1 Thesis report structure

The second part of this report, the thesis, consists of the development of several tools and a case study. In this chapter, chapter eight, an overview is provided of the systems inside the concept design and their relations. Also, system boundaries are defined for the systems that are included in the design support tools.

Chapter nine begins with the design of the lithium-ion battery system and subsequently a design support tool is developed for this system. The same set-up is used in chapter ten for the foam injection system and in chapter eleven for the pressurized air system.

Chapter twelve has a different setup. It consists of the challenges that has to be coped with when designing the environmental control systems, especially for the entirely battery powered submarine. Additionally, different new technologies are explored to replace the existing air quality systems.

Chapter thirteen contains a case study to show the usability of the developed tools and to find out what the consequences are for the concept design. The report is finished with a conclusion in which the main- and sub- research questions are answered, followed by the recommendation, discussion, bibliography and appendix.

8.2 Defining system Boundaries

Before the design support tools can be made, the system boundaries have to be defined. Many auxiliary systems are connected inside a submarine, either as a supplier, a consumer or they work together. This makes the boundaries of these systems often vague and makes the design process of a system a challenging process. Defining the system boundaries in an early stage helps with the design of the different design support tools. The tools will be made stand-alone so they can be used individually. For this purpose, it is important to know how the systems relate with each other to get a clear overview of the inputs and outputs required for each sizing tool. Also, if the design support tools are merged together in a later stage, it is important to have all the outputs required as input for other systems. Determining the system boundaries also helps getting a better understanding of the total picture.

In the literature study an overview is made of the relations between the systems of the diesel-electric reference submarine: Figure 5 and Figure 6. This overview is used as starting point and adjusted for the entirely battery powered concept design as can be seen in Figure 18 and Figure 19. Systems that were no longer required are removed, new systems are added and the relations between the systems received an update.

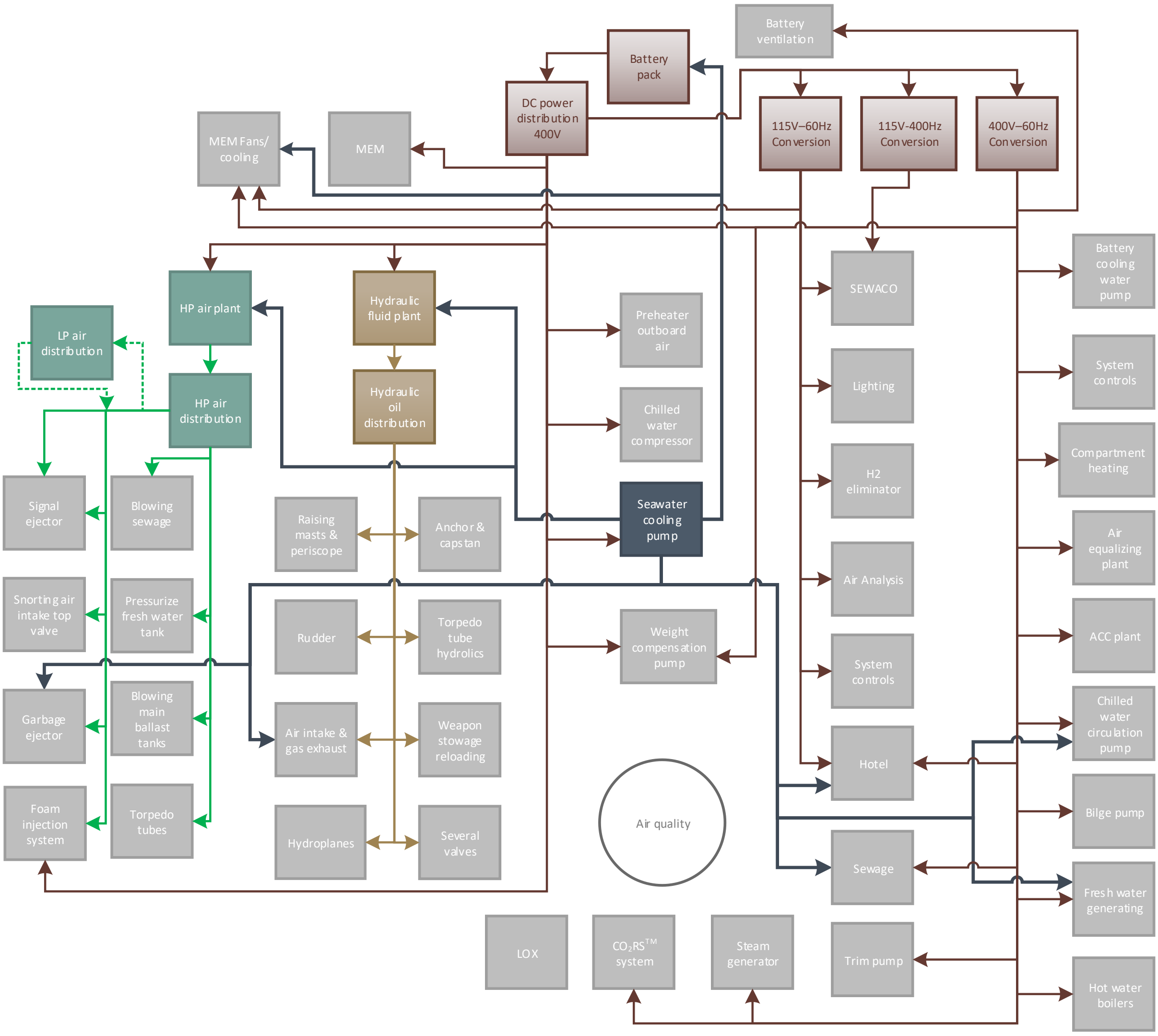

Figure 18: Global relations between systems: electrical, pressurized air, hydraulics and seawater cooling. Starting point from Figure 5, updated for the concept design (new systems included).

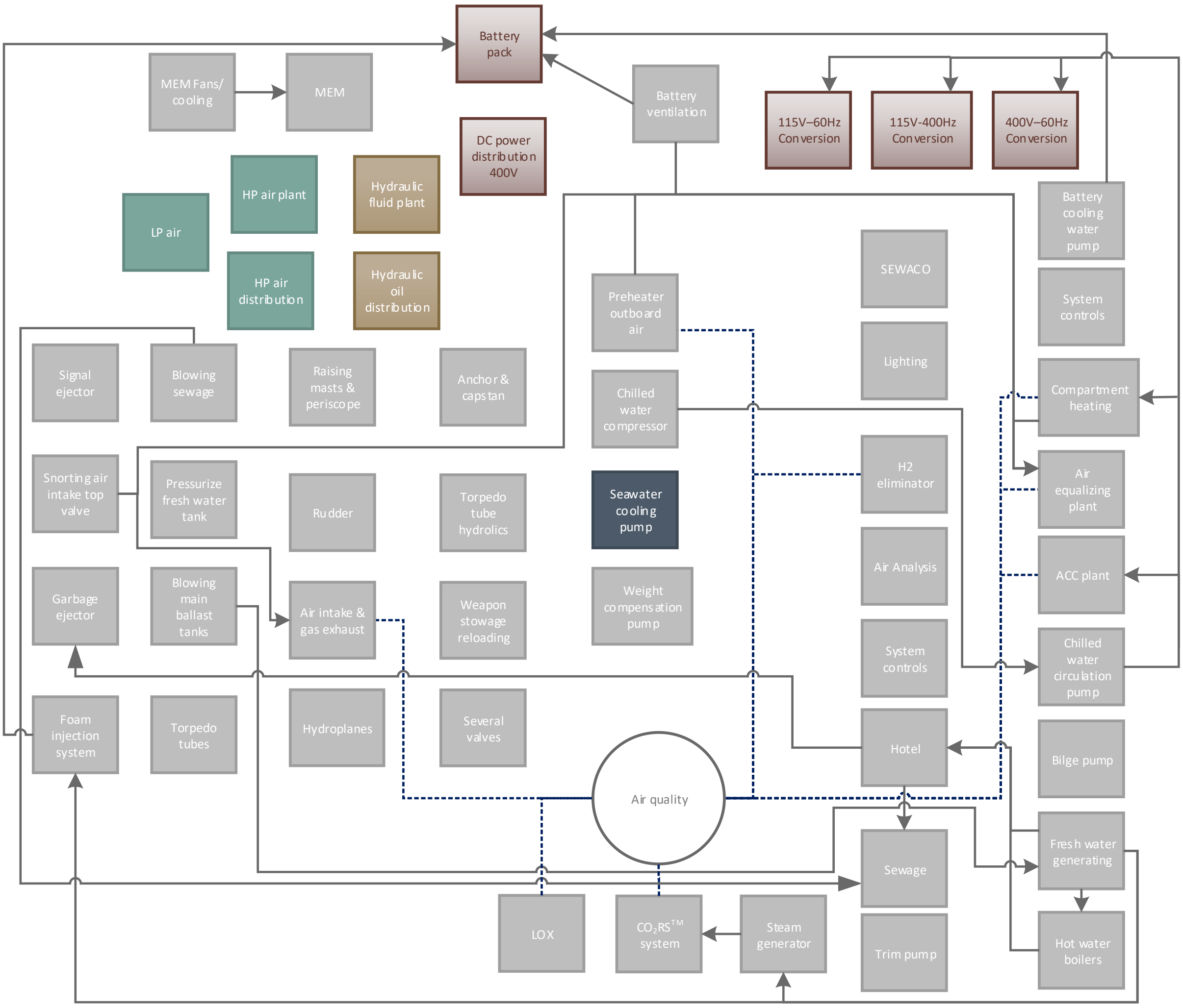

Figure 19: Global relations between systems: Air quality and general relations. Starting point from Figure 6, updated for the concept design (new systems included).

8.2.1 Battery system

The battery system is built up from lithium-ion battery cells into a battery system, which can deliver multiple MWh. The battery system is a system that provides a supply of energy for the submarine. Only a lower level (internal) distribution network will be part of this system. The boundary of electrical distribution is at the border of the battery compartment, so without any switchboards. Included in this system is the lower level BMS's to provide safe use. The BCU is located outside the system boundary since it is physically located outside the battery compartment. Since the battery system will have a firefighting system distributed into the modules, the interface of both systems is at the top of each string in the form of a tube connection. The input and output for the battery system design support tool are listed in Table 9 and a schematic overview of the system boundaries is provided in Figure 20.

Table 9: Input and output battery system design support tool.

Input	Output
Diameter pressure hull	Number of strings in a cross-section
Height battery compartment (deck)	Layout of a cross-section
Amount of battery compartments	Number of battery modules and strings
Required battery capacity	Length and volume of the battery compartment
Battery cells in series and parallel	Volume of components
Battery cell and module size/weight	Weight of the battery system
	Maximum heat load
	Installed capacity

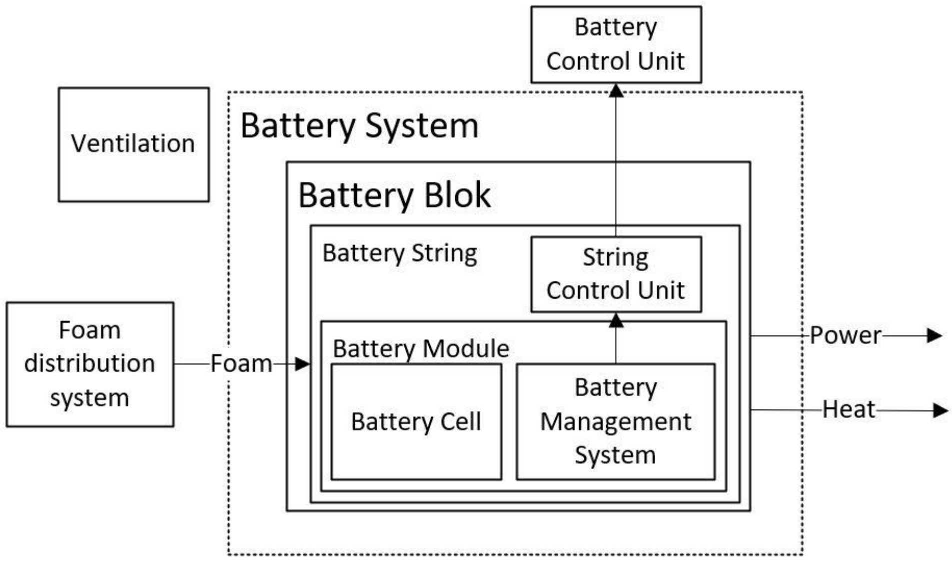

Figure 20: System boundary of the battery system.

8.2.2 Foam injection system

The foam injection system consists of a supply, distribution and control part. The boundary of the distribution side of this system is at the connections of the consumers. This means that the distribution system, with piping and valves is part of the foam injection system. The system requires pressurized air, power and deionized water. The system boundaries are defined at the point where it receives these consumables. The input and output of the foam injection system design support tool are listed in Table 10 and a schematic overview of the system boundaries is provided in Figure 21.

Table 10: Input and output foam injection system design support tool.

Input	Output
Number of strings in a cross-section	Amount of premix required
Number of rows in a battery block	Volume and weight of different components
Number of battery blocks	Volume and weight of the total systems
Foam required for other consumers	Required high pressure air
	Number of row splits

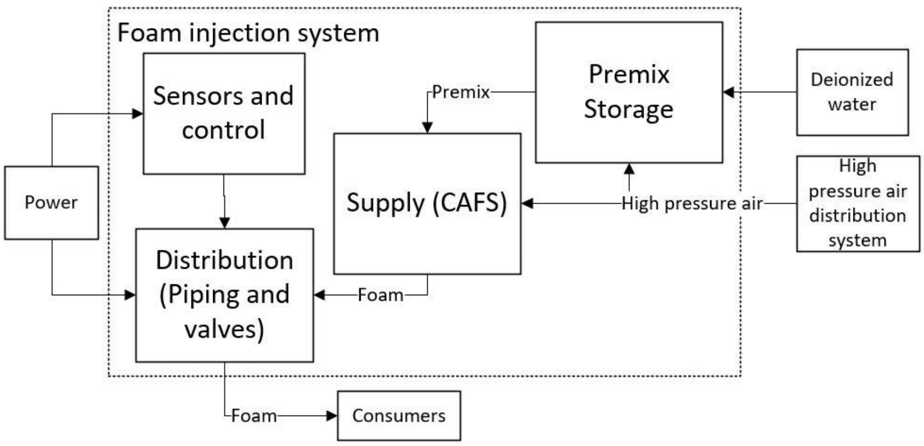

Figure 21: System boundary of the foam injection system.

8.2.3 Pressurized air system

The pressurized air system provides high pressure and low pressure air to consumers. It consists of HP air storage bottles, HP air compressor, air drying system and a distribution system. The system boundary of this system is at the connection of the consumers. This means that the distribution network is included in the pressurized air system. The input and output of the pressurized air system design support tool are listed in Table 11 and a schematic overview of the system boundaries is provided in Figure 22.

Table 11: Input and output pressurized air system design support tool

Input	Output
Required high pressurized air	Required number of storage bottles
	Volume of the pressurized air system
	Weight of the pressurized air system

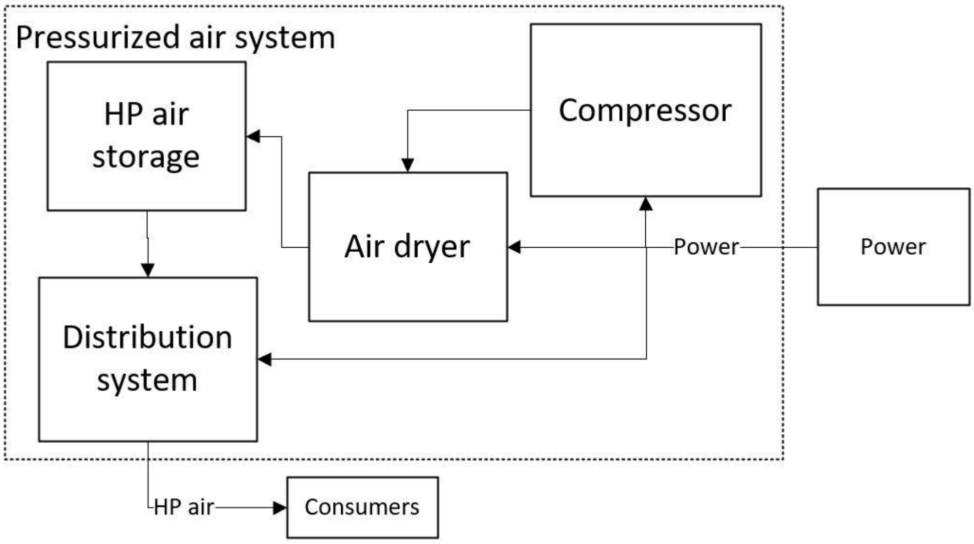

Figure 22: System boundaries pressurized air system.

8.2.4 HVAC system

The HVAC system consists of multiple subsystems that together control the temperature and humidity of the air inside the submarine. Depending on the crew, environment and systems on board, the HVAC must have enough capacity to balance the temperature and humidity. The HVAC consists of heating, equalizing ventilation and air conditioning. The systems require power and chilled water and are part of the environmental systems as can be seen in Figure 23. The equalizing ventilation is also required for the performance of the air quality systems, which makes the total integration more complex. The input and output of the HVAC system design support tool are listed in Table 12.

Table 12: Input and output HVAC system design support tool.

Input	Output
Heat load crew	Volume HVAC system (per component)
Heat load systems	Weight HVAC system (per component)
Temperature and humidity requirements	Required energy HVAC system
Ventilation requirements	Heat load HVAC

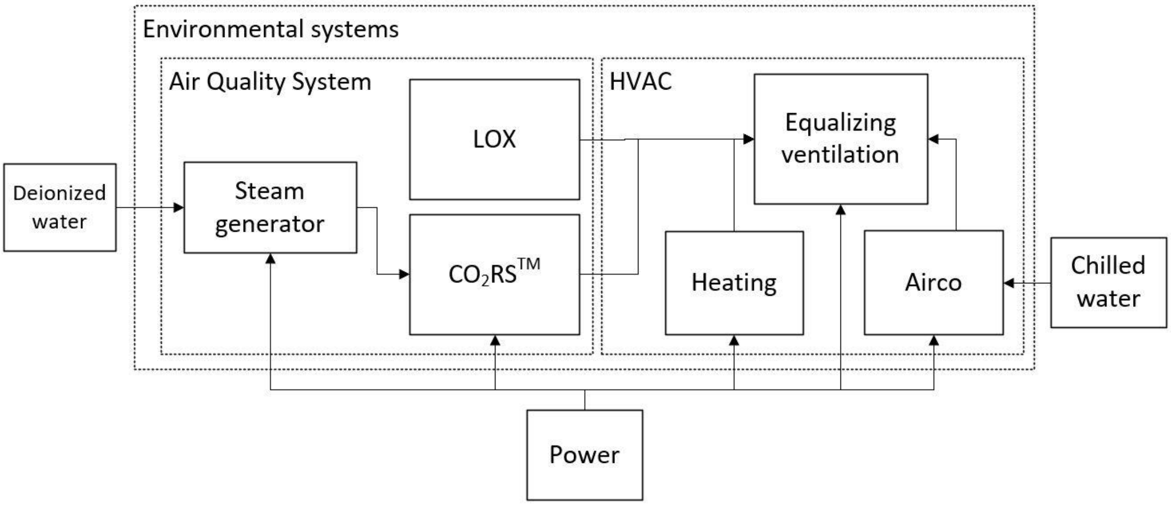

Figure 23: System boundaries of the environmental systems.

8.2.5 Air quality system

The air quality systems provide oxygen, remove carbon dioxide and clean the air. Depending on which type of system is used, it requires energy. The chalkholders and oxygen candles from the reference submarine barely use any energy. In chapter HVAC and air quality alternative systems are explored, which all use significant amounts of energy. A regenerative CO_2 removal system is already shown in Figure 23, which also requires a steam generator and deionized water. The input and output of the air quality system design support tool are provided in Table 13.

Table 13: Input and output air quality systems design support tool.

Input	Output
Endurance submarine Amount of crew	Volume of the air quality systems Weight of the air quality systems Required energy Heat load

8.2.6 Chilled water and seawater cooling system

The chilled water and seawater cooling system provide cold water to systems that need to be cooled. It has interfaces with different consumers that are located at the heat exchangers. The system consists of a seawater distribution system that transports waste heat of various systems to outboard, a chilled water transport system that transports heat from consumers to the chiller plant and the chiller plant that cools the water. The system boundaries of these subsystems are at the heat load of the consumers and the energy required for the system. The input and output of the chilled water and seawater cooling system are listed in Table 14. The chilled water and seawater cooling system are not implemented in a design support tool in this research.

Table 14: Assumed input and output chilled water and seawater cooling system

Input	Output
Heat load consumers	Volume of the chilled water and seawater cooling system Weight of the chilled water and seawater cooling system Required energy

8.2.7 Hydraulic system

The hydraulic system provides pressurized hydraulic fluid to its consumers. The system consists of a distribution system and a hydraulic oil plant. The last one filters, stores and cools the oil and delivers the pressurized oil to the distribution system. In the reference submarine the hydraulic oil plant consists of pumps, filters, accumulators, storage tanks, service tanks and a handpump. The distribution system consists of a supply ring line and a single return line. The boundary of the complete hydraulic system is located at the connection with the consumers.

When studying this system two questions should be taken into account. The first one is: is it is possible to reduce the number of hydraulic consumers? Making a consumer consume energy from the electrical system instead of hydraulic oil could be more efficient, because less energy is lost in the hydraulic oil pumps, accumulators and distribution system. It also might be the case that the complexity of the hydraulic system will be reduced.

The second question is: is the hydraulic system still required inside an entirely battery powered submarine? Without the hydraulic system, the mechanical complexity and the number of systems is reduced. Furthermore, cables require less space than the hydraulic distribution system and without the hydraulic pump to pressurize the hydraulic system less noise is generated.

The hydraulic system is hereinafter not addressed in this research and thus not implemented into a design support tool.

Table 15: Assumed input and output of a hydraulic system design support tool.

Input	Output
Oil consumption of all consumers	Volume of the oil plant and distribution system Weight oil plant and distribution system Required energy

9 Battery system

The battery system of the battery powered submarine is significantly different compared with a conventional diesel-electric submarine. As mentioned in section Required systems not only the battery type will change, but also the amount of batteries and its required auxiliary systems. In this chapter a lithium-ion battery system design will be developed together with a design support tool to estimate the size, weight and heat load in an early stage design.

9.1 System design

9.1.1 Requirements

The battery system of an entirely battery powered submarine is different than the battery system of a conventional diesel-electric submarine: different type of battery, different layout, different risks, different controls and different maintenance. Both systems have the functional requirement of storing energy and providing energy. From the EVOG perspective, the battery system of the reference submarine is a vital system [7]. This means that the system should always work, unless the situation is severe enough that the crew has to leave the submarine. For an entirely battery powered submarine this is not different. But, where a diesel-electric submarine has multiple power sources, an entirely battery powered submarine only has one. If something happens with the batteries of a diesel-electric submarine when submerged, it has to surface where the diesel generators can deliver power. Considering an entirely battery powered submarine this would not be possible. This means that the battery system should work at all times, even when it is surfaced. The requirements for the lithium-ion battery system are listed in Table 16. For some of the requirements a possible solution is listed on the right side in the same table.

Table 16: Requirements battery system.

The battery system must:	
Receive energy	
Store energy	
Deliver energy	
Support thermal runaway mitigation system	Foam injection system (part of firefighting system)
Be monitored	BMS on module level, SCU on string level (and a Battery Control Unit outside the battery compartment)
Deliver required amount of voltage, current, Capacity	Size and amount of the strings
Have short circuit protection	Short circuit protection in String Control Unit (SCU)
Have internal and external ventilation	Ventilation (part of HVAC)
Low maintenance	Lithium-ion batteries are low maintenance
Be identical on module level	
Satisfy reliability requirements	Multiple battery blocks/compartments
Satisfy shock standards	Shock resistant modules are available on the marked

9.1.2 Break down

A system break down structure will help to define the different components of the battery system and is listed in Table 17. The size of the battery module and the string control unit is justified as well.

Table 17: Battery system break down.

- Battery block
  - String
    - String control unit
    - Module
      - Battery management system
      - Battery cell
    - Foam injection connection
  - Cables

9.1.2.1 Battery module

S. A. Los has made a lithium-ion battery design for the battery powered submarine [2]. The battery design described in his thesis will be used as much as possible, but worked out in more detail. For this purpose, the same battery supplier will be used, but with their more recent developed commercially available battery cell. The battery module design consists of:

- Kokam 150 Ah ultra-high energy cell with NMC chemistry.
- 18 battery cells in a module.
- The dimensions of the cell and module are provided in Table 19.
- Six modules in series form a string with 108 battery cells in series, which result in a typical operational voltage of 400 V DC.

In the research of L.P.W. Rietveld a packing factor for volume of 1.6 and weight of 1.3 is adopted to estimate the battery compartment [4]. To see if these packing factors are still a good representation for estimating the size and weight of a battery module, information from Kokam has been studied. Several existing modules and its battery cells are compared as can be seen in Table 18. Packing factors vary, but the more compact modules indeed reach the packing factors of 1.6 for volume and 1.3 for weight. For this reason, these packing factors are used to estimate the dimensions of the battery module.

Table 18: Different Kokam battery cells and modules with their corresponding packing factors [42].

	Module type		Battery cell					Battery module				Packing factor	
Model	**Cell type**	**Capacity (Ah)**	**weight**	**Width**	**Depth**	**Height**	**Amount**	**Weight**	**Width**	**Depth**	**Height**	**Weight**	**Volume**
KBM255 2P 20S	SLPB130255255P	75	1.83	268	13.7	265	40	92.5	310	643	312	1.3	1.6
KBM460 20S 1P	SLPB80460330	100	2.315	462	8.1	396	20	57.5	480	225	396	1.2	1.4
KBM216	SLPB60216216	25	0.555	226	6.3	227	13	12.5	245	191.4	285	1.7	3.2
KBM216	SLPB60216216	25	0.555	226	6.3	227	14	13.5	245	204.2	285	1.7	3.2
KBM216	SLPB78216216	31	0.72	226	8.1	227	13	15	245	191.4	285	1.6	2.5
KBM216	SLPB78216216	31	0.72	226	8.1	227	14	16	245	204.3	285	1.6	2.5
KBM216	SLPB100216216	40	0.94	226	10.3	227	13	17.5	245	191.4	285	1.4	1.9
KBM216	SLPB100216216	40	0.94	226	10.3	227	14	19	245	204.2	285	1.4	1.9
KBM216	SLPB120216216	53	1.095	226	12	227	13	20	245	191.4	285	1.4	1.7
KBM216	SLPB120216216	53	1.095	226	12	227	14	22	245	204.3	285	1.4	1.7

Table 19: Kokam 150 Ah Ultra-high energy cell and used module dimensions ([42]).

	Cell	**Module**
Height [mm]	327	382
Length [mm]	462	540
With [mm]	10.5	221
Weight [kg]	3.020	70.7

108 lithium-ion battery cells in series provide a similar voltage as the battery bank from the reference design as shown in Table 20. Since the cells are in series the current is the same for all 108 cells in the battery string. To reach the required power and capacity multiple strings are connected parallel. This topology is displayed in Figure 24.

Table 20: Voltage characteristics on cell and battery string/block level [2].

	Concept	Reference
Max. cell voltage [V]	4.1	2.09
Avg. cell voltage [V]	3.7	1.95
Min. cell voltage [V]	3.4	1.75
Numbers of cells in series (module)	108	210
Max. string/block voltage [V]	442.8	437.9
Avg. string/block voltage [V]	399.6	409.5
Min. string/block voltage [V]	367.2	367.5

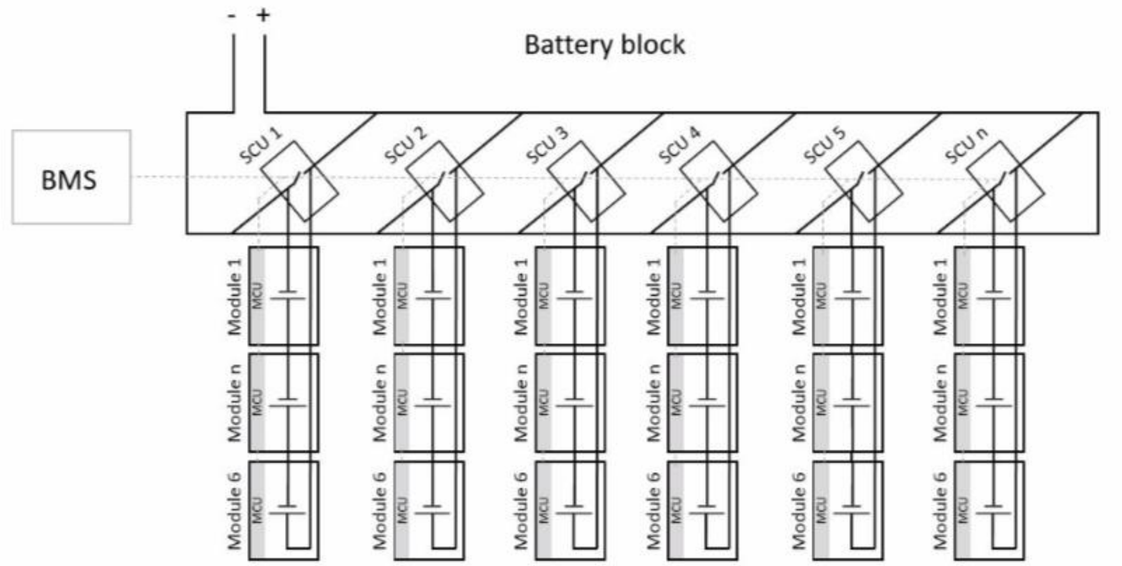

Figure 24: Topology of created lithium battery blocks [2].

9.1.2.2 String control unit

When a short circuit occurs in a cell, the whole string is affected because the cells are connected in series. To prevent and mitigate thermal runaway, the short circuit protection should be implemented on string level as a part of the SCU. The size of the SCU is estimated based on the short circuit protection. The short circuit protection that is part of the SCU has to be able to switch short circuit currents of approximately 9.3 kA [2]. A search on the Internet gives several short circuit switches with sizes as shown in Table 21. For the estimation of the size and weight of the SCU, the width and the weight are doubled to make place for the data and control components. Included in the SCU is a connection for the foam injection system. This is a small tube and it is assumed that it has not much impact on the size of the SCU.

Table 21: Sizes and weights of several short circuit switches as example for the size and weight of the SCU.

Product	Size [mm]	Weight [kg]
Tmax Ts3 [43]	170 x 105 x 104	
LV438801 [44]	161 x 140 x 186	2.4
JGL37100D81 [45]	191 x 105 x 127	2.4
SCU for reference	**Size [mm]**	**Weight [kg]**
	190 x 260 x 120	5

9.1.2.3 Direct foam injection system connection

The fire extinguishing system will have a connection on the topside of the battery string. Through tube connections and T-junctions inside the modules the suppression foam is guided into all the modules of one sting.

9.1.2.4 Cables

As part of the heat load, weight and volume calculations, an assumption of the length of the cables has to be made. A simple layout is used which is scalable with the size of the battery compartment. Every row of strings has two cables; positive and negative, from one side to the other and then to the front or aft part of the battery compartment where they accumulate into one thick cable. A schematic layout of the cables is provided in Figure 25.

The thickness of the cables is also required to perform the calculations. The battery system in the reference submarine uses a cable cross-section of $3 \cdot 10^{-4} [m^2]$. As an example, this thickness is also used for the design support tool. This is a rather conservative example because the cables in the reference design are used for the entire battery compartment, while in the design support tool they are only used for one row of strings.

9.1.3 Design

Based on the requirements and system breakdown structure the battery system can be designed. The battery is divided in compartments and they are called battery blocks. These battery blocks can operate independently from each other and provide enough power for the submarine to operate. The presence of multiple battery blocks provide redundancy. This is necessary because the complete battery system is a vital system.

Each battery block consists of multiple rows of strings in the length of the battery compartment, as is illustrated in Figure 25. Each string consists of 6 modules with each 18 battery cells, adding up provides 108 battery cells per string. Every module has a lower level BMS, which measures temperature, voltage and State of Charge (SOC). This data is sent to the String Control Unit (SCU), which analyzes the data to ensure the safe operation of the battery cells. If the SCU receives alarming data, it can protect the complete battery string by switching it off with the use of a circuit protection switch. The data from the SCU is transmitted to the Battery Control Unit (BCU). The BCU receives the data from all the SCU's from one battery block and uses the information to determine the status of the battery block.

A cross section of the battery block is illustrated in Figure 26. In this figure it is visible how the modules are stacked into strings. In this figure the interface (connection) for the firefighting foam can be seen on top of the battery string. Further, a margin is used for the hull structure and support structure for the batteries, which is visible in Figure 27.

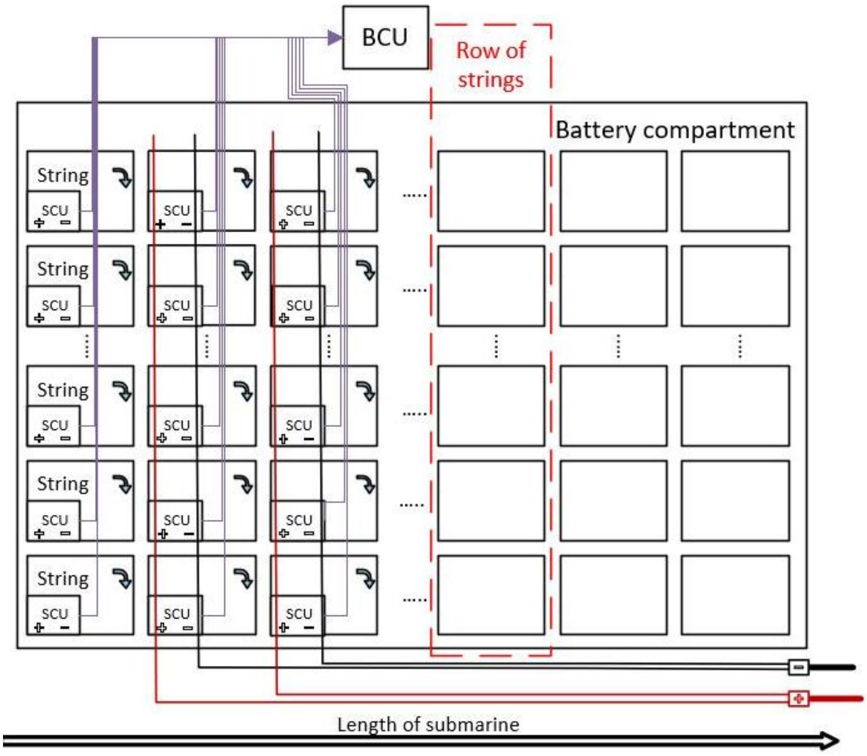

Figure 25: Schematic top view of the battery block.

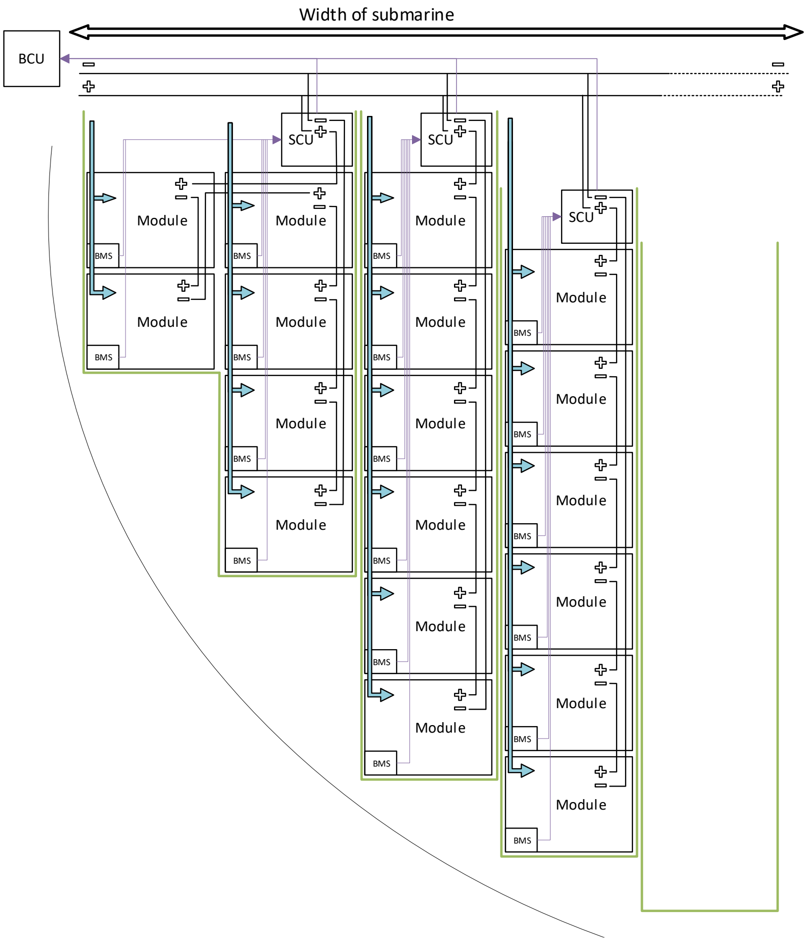

Figure 26: Schematic cross-section of the battery block.

9.2 Tool development

9.2.1 Purpose of tool

The battery system design support tool should be able to determine the size and weight of a battery block/compartment. Additionally, it should be able to determine the maximum heat load generated by the components of the battery compartment.

The tool should be able to calculate the weight and length of the battery compartment when the required capacity is known. Alternatively, the size of a battery compartment can be provided to estimate the number of modules/strings that fit into the compartment.

9.2.2 Method

The battery system consists mostly of standard components which are justified in the previous section (but can easily be changed by the user of the tool). The size or amount required of these components depends on the capacity required. The main characteristics of these components are obtained from the manufacturer. This information will form the foundation of the design support tool. Subsequently, the battery system design is used to add up the required components in such a way that the output parameters are calculated.

With the input of the pressure hull radius and deck height, the number of modules that fit in the cross section is calculated. This includes the SCU. An example of such a cross-section layout is provided in Figure 27. The tool keeps enough space available for a SCU on every stack of modules. Not every stack of modules requires an SCU, causing a higher number of SCUs than is actually required as can be seen in Figure 27.

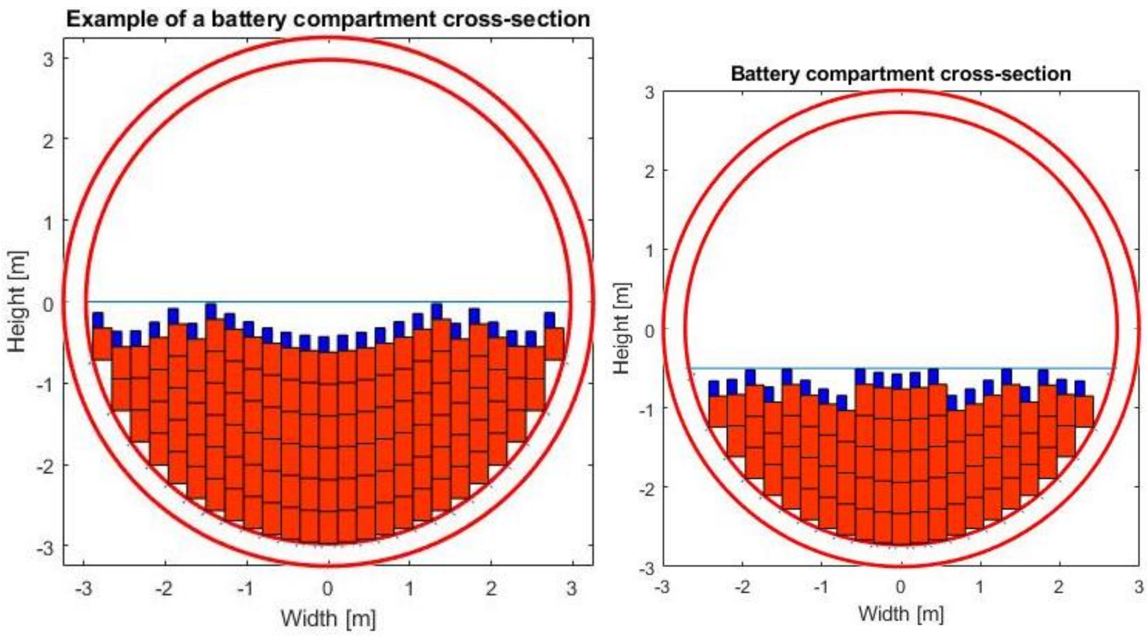

Figure 27: Two examples of a battery compartment cross-sections generated with the design support tool. The outer circle is the pressure hull, the straight line is the deck (ceiling of the battery compartment), the red squares are the battery modules and the blue squares are the SCU's. The right figure has a smaller pressure hull diameter and a lower deck.

With the number of strings that fit in the cross section, the length of the battery compartment is determent based on the required capacity of the battery. As a result of using completely filled rows, the total capacity is higher than the required capacity. With this method the following output can be calculated.

- Number of modules and strings in cross section of the submarine.
- Number of strings required in the length of the submarine.
- Length of the battery compartment.
- Total number of strings and installed capacity
- Volume of all modules and SCU's.
- Volume of the battery compartment.
- Total weight of all components in this battery compartment.

A flow chart of the battery system design support tool is provided in Figure 28.

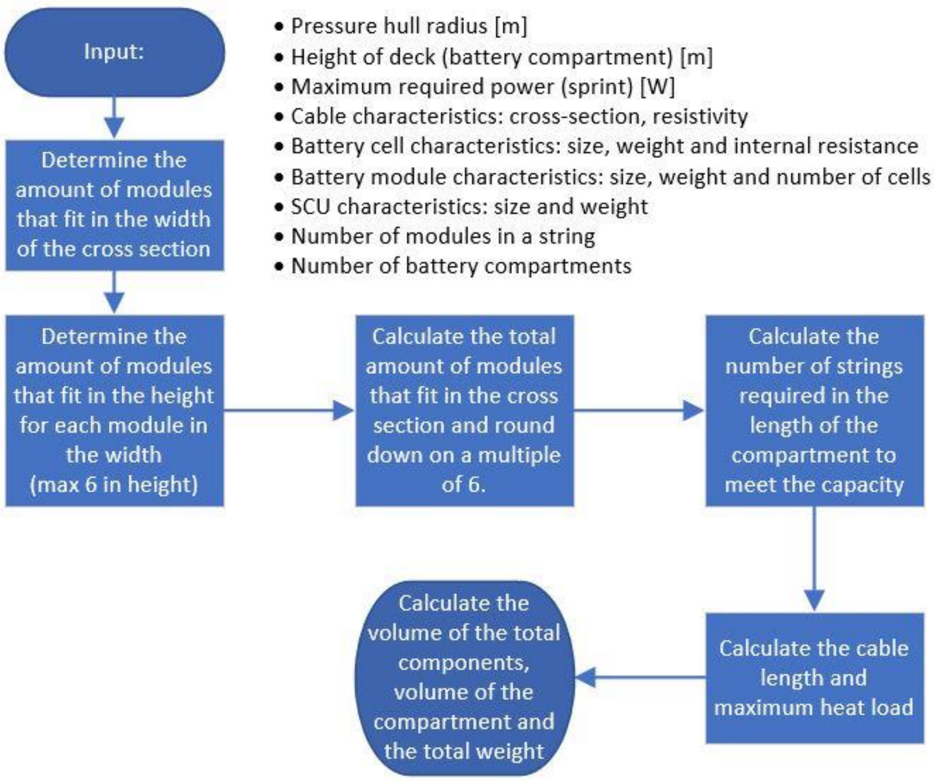

Figure 28: Flow chart battery system design support tool.

Besides these output parameters, the heat load is also an output of this tool. The heat load is divided into the heat load from the battery cells and the heat load from the cables inside the compartment. Assuming the heat load is equal to the power loss of the cables and battery cells. Information needed for this calculation is the internal resistance of the battery cells, the internal resistance of the cables and an estimation of the cable length inside the battery compartment. The estimation of the cable length can be found in a previous section and the resistivity of copper is $1.68\ 10^{-8}\ [\Omega \cdot m]$. The cross-sectional area $[m^2]$ of the cables is an input for the tool. With this information the resistance of the cables can be calculated with Equation 1. With the resistance of the cables and the discharge current the heat load of the cables can be calculated with Equation 2.

$$R = \frac{\rho \cdot l}{A} \qquad \textbf{Equation 1}$$

$$P_{heat\ loss\ cable} = {I_{cable}}^2 R_{cable} \qquad \textbf{Equation 2}$$

The heat load of the battery cells can be calculated with the use of the internal resistance of the battery cells and the discharge current as can be seen in Equation 3. The internal resistance of the battery cells is approximately $0.45\ [m\Omega]$ [2]. The most interesting heat load to know is the maximum heat load, since this indicates the need or size of a cooling system.

$$P_{heat\ loss\ cell} = {I_{discharge}}^2 R_{cell} \qquad \textbf{Equation 3}$$

9.2.3 Restrictions

The design support tool uses information from suppliers and from reference components from the Internet. These parameters can be changed easily to improve the output of the tool. The method of the design support tool has its restrictions when considering different design options:

- Only one type of cross-section layout is possible.
- Only usable to fill lower half of submarine. In case of an entirely battery powered submarine it might be preferable to fill other parts of the submarine with batteries as well.
- One battery compartment at the time.
- On top of every stack of modules there is room for a SCU while this is not always required.
- A maximum stack of six modules. Creating unused spaces.
- When calculating the length of a compartment based on the required capacity, the tool will fill every cross-section. This creates a battery compartment with the same or higher installed capacity compared with the required capacity.

The restrictions of this design support tool are considered not a problem. Because, finding a solution for these restrictions would improve the level of detail of the tool. But, this would require more information on the input side of the tool. Consequently, the tool might lose its early design stage support characteristic.

9.3 Sensitivity study

Using different width-height ratios for the modules results in different specific volumes for the battery compartment. In Figure 29 the specific volume of the battery compartment is calculated for different pressure hull radii. In this calculation the shape of the battery modules is constant. For this constant shaped battery module an optimal radius would be approximately 2.9 meter to reach the maximum possible specific volume. This experiment is also performed the other way around; with a constant radius but with different width-height ratio of the modules. The result of this calculation can be found in Figure 30. In a like manner can be seen that the width of a battery module and the specific volume of the compartment have a strong relation. An optimum in specific volume can be found at a module width of 0.165 meter. Making the modules to wide, results in a strong drop of the specific volume.

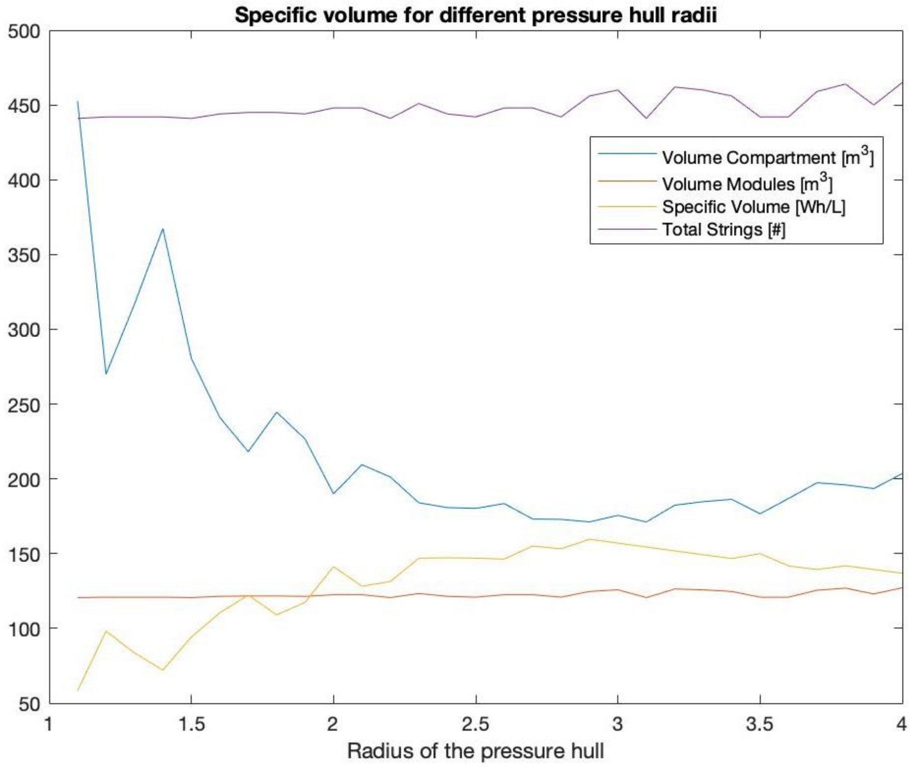

Figure 29: Sensitivity pressure hull radius on specific volume. With module dimensions: width=0.221, height=0.382 length=0.54 meter.

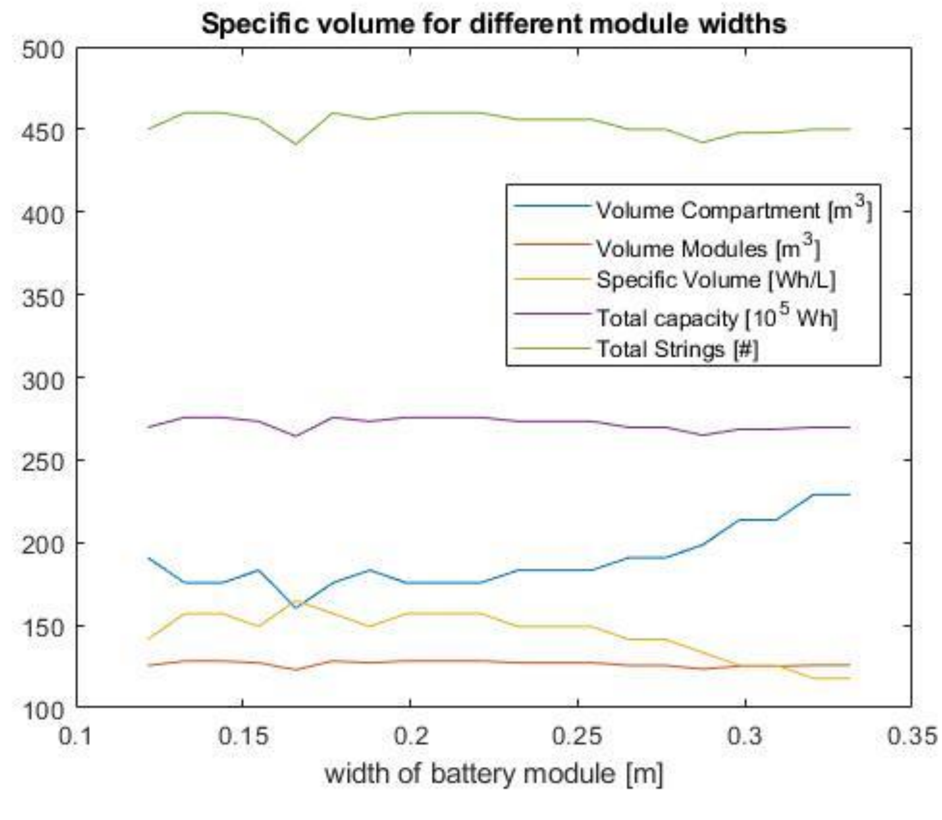

Figure 30: Sensitivity specific volume of the battery compartment for different module widths. Pressure hull diameter of 6 meter and a deck height of 3 meter.

Two different sizes battery compartments are simulated with different capacities. Both have the same maximum power requirement (based on the discharged current of the concept design during sprint: 3700 kWh). The number of strings and the heat-load (power loss) are listed in Table 22. It is interesting to see that the smaller battery compartment generates more heat than the larger one. This can be explained due to the higher power consumption per battery cell. The higher current causes more heat-loss as can be seen in Equation 2 and Equation 3. This information is important to make an estimation of the heat balance and to decide if additional cooling is required.

Table 22: Heat-loss for different sizes of battery blocks with the same maximum power requirement.

	Large battery block	**Small battery block**
Number of strings	532	342
Heat-loss [kW]	12.07	17.31

9.4 Conclusion

For the lithium-ion battery system a high level design is introduced. The design is based on lithium-ion battery cells which are stacked into modules, strings and eventually in a battery compartment. They are stacked in such way that they provide the required voltage and capacity. For the design the lithium-ion battery system is assumed to require no maintenance, the battery modules are identical, satisfy shock standards and reliability requirements and will be monitored with the use of a multi-level battery management system.

Based on the high level system design a design support tool is developed. The tool uses standard components as input, which can easily be changed. The tool provides the designer the possibility to estimate the size, weight, capacity and heat load of the battery system in an early design stage. The sensitivity analysis shows that there is an optimum in the specific volume based on the relation between width/height of the battery module and the pressure hull diameter.

The design support tool has some restrictions. One of the restrictions is the standard layout; every stack of modules receives a SCU on top, while this is not always needed. In a later stage a more detailed design might reveal a more efficient use of space and thus a higher specific volume. Developing the tool further, might include this level of detail to improve the estimation.

For the safety of the battery system, a foam injection system can inject foam directly into the damaged modules to extinguish and cool down the battery. For this reason the battery system has a connection to the foam injection system for every battery string. In the following chapter the foam injection system will be discussed and a design support tool will be developed.

10 Foam injection system

A fire on board of a submarine is extremely dangerous because it extracts oxygen from the air, and it heats the environment. Since the pressure hull of the submarine is an enclosed body, the crew on board can choke on the absence of oxygen or the presence of smoke. The presence of a firefighting system is of utmost important for the safety of the crew and the performance of the submarine. A firefighting system inside a submarine is specially composed for the systems on board. Changing systems, such as the battery system, demand a reevaluation of the firefighting system. The risks of lithium-ion batteries and possible risk mitigation solutions have been studied in chapter Lithium-ion battery implementation. The demand for extinguishing a lithium-ion fire and to mitigate thermal runaway, introduced a new kind of firefighting foam. A Compressed Air Foam System (CAFS) will be implemented and the system designed by FiFi4Marine will be used as reference [46].

10.1 System design

10.1.1 System description

The purpose of the foam injection system is to provide a special type of foam to several systems to extinguish a fire and to cool down the components. The foam is made by mixing a premixture with HP air and subsequently a dedicated distribution system brings it to the correct location.

10.1.2 Requirements

As can be seen in the description of the firefighting system of the reference submarine, there is no firefighting system available for the battery system [7]. That is due to the lead-acid batteries, which have no risk of thermal runaway or other type of fire. With the lithium-ion batteries a specialized firefighting system is required. The requirements of this firefighting system are listed in Table 23.

Table 23: Requirements firefighting system.

• Extinguish fire	
• Cool down battery cells	
• No effect on other battery strings	
• Sufficient capacity	Sizing premix bottles
• Usable for all submarine systems / compartments	Suitable distribution system
• Not toxic for humans	
• Non corrosive	
• Limited risk on short circuit	
• Low maintenance	
• High reliability	Multiple supply setups (tank with premix and a mixing chamber)
• Back-up function	Using seawater

10.1.3 Break down

The foam injection system is composed of different components. These components are listed in a break down structure in Table 24.

Table 24: Foam injection system break down.

- Fire extinguishing system
    - Control system
        - Controller
        - Gas sensor
        - Temperature sensor
    - Premix

- Deionized water
- Concentrate
- Pressurized air connection
- Mixer (CAFS)
- Distribution system
  - Pipes and tubes
  - Valves

10.1.4 Design

The firefighting system is based on the foam injection system from FiFi4Marine. Their system is designed for general lithium-ion battery systems. A schematic overview of their system buildup is illustrated in Figure 31. This system consists of a supply part and a distribution part. The foam supply consists of a storage bottle with premix and a mixing chamber. The premix bottle is pressurized with high-pressure air from the pressurized air system. Next, the premix flows to the mixing chamber (i.e. CAFS) where it is mixed with high-pressure air into foam. For this process a mixing ratio is used of 1:10 – 1:15. This mixing ratio is favorable since only 7-10% volume premix is required for the required volume foam. The foam injection system is a VITAL system, and thus requires high reliability. For this reason, the supply system for foam is divided over the watertight compartments. From those supply systems a distribution network, based on the zonal distribution network principal as described in Figure 8, provides redundancy and thus reliability. A schematic view of supply and distribution system can be seen in Figure 32. This figure includes the distribution system inside the battery compartments. This part of the distribution system is also based on the zonal distribution network principal. If needed, the foam injection can be activated per row of strings. Every row has two connections on the distribution network, which provide redundancy in case one of the valves fails to open.

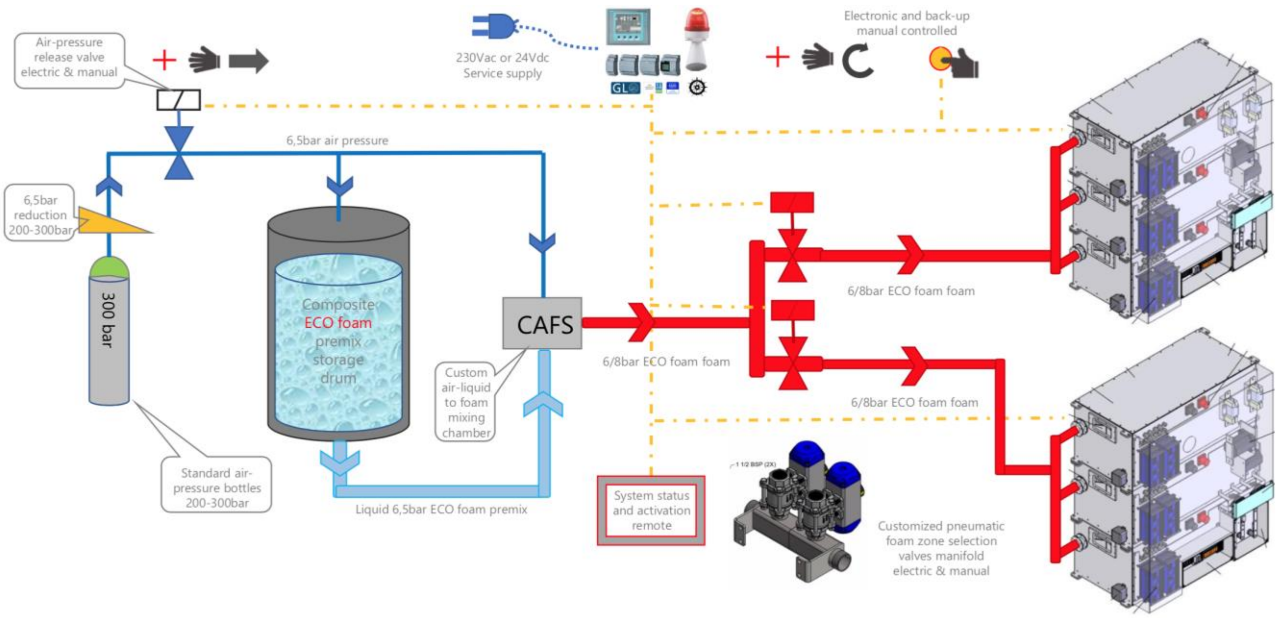

Figure 31: Schematic overview of the foam injection system from FiFi4Marine [46].

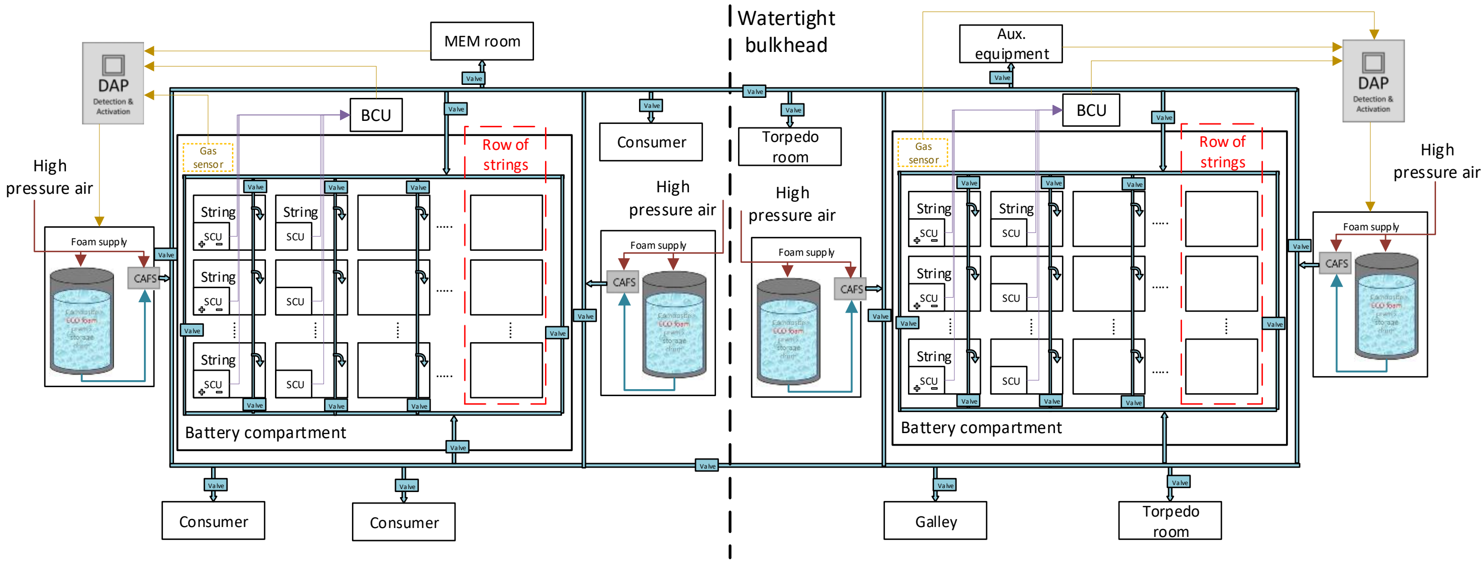

Figure 32: Schematic top view of foam injection system including the general and battery specific distribution network.

Besides the battery, there are other consumers such as: the galley, auxiliary equipment room, torpedo room or MEM compartment. Due to several different reasons, most systems on board of a submarine could experience a fire. Depending on the system, the fire is easy or difficult to extinguish. When a fire difficult to reach, for instance in an electrical switchboard or a control panel, an inside sprinkler could be a solution. The foam can be injected with a connection on the distribution network, but another option could be a handheld foam dispenser, which can be connected to the targeted component. There are different types of handheld foam dispensers developed as can be seen in Figure 33. On the right a simple premix tank with an inside air pressure bottle. In the middle, a setup with a premix tank and a separated air bottle. It is even possible to connect an air mask to an extra air pressure bottle to breathe, as can be seen on the right. All these setups can easily be refilled with premix and pressurized air if needed.

Figure 33: Different types of handheld foam dispensers [46]

10.1.5 Design philosophy

The amount of premix taken on board of the submarine depends on the consumers. Foam required for general consumers can be calculated using the surface that has to be extinguished and the thickness of the foam layer. Assumed is that each watertight compartment should have enough premix to extinguish the largest required surface of the general consumers. This provides redundancy on submarine level, since premix from other watertight compartments can be used to extinguish the fire for a second time.

Probably the most demanding consumer will be the lithium-ion battery system, because the damaged battery cells have to be cooled multiple times. At any time during the mission there should be enough foam available to extinguish and to cool down a certain amount of battery strings. To determine if the battery system is the largest consumer, it is necessary to know the amount of foam required for the other consumers.

An assumption is made about the empty space inside the battery modules. It is assumed that 10% of the module is empty and this part can be filled with foam. This is based on the assumed packing factor for the module, which is 1.6 times the cell volume. This means that 62.5% of the module consists of battery cells. The other 37.5% consists of structural material, BMS, a foam distribution tube and empty space. In case this assumption is not valid for the actual used module by the designer, the parameter can easily be changed in the design support tool. The required amount of foam scales linearly with the amount of empty space; a larger percentage of empty space will cause an increase in required premix.

To determine the amount of foam required for the battery system, an extinguishing philosophy is used as listed in Table 25. On the left side the assumption is listed and on the right side the justification.

Table 25: Extinguishing philosophy for the battery system.

One faulty cell at the time, or multiple in one row of strings. Row of strings in which the faulty cell is present, is called the main row of strings. The adjacent rows of strings are called secondary rows of strings.	If more faulty cells occur at once, the situation might be uncontrollable and the submarine has to surface.
In case of a faulty cell, the main row of strings and the secondary rows of strings are turned off.	To minimize the chance of propagation by stopping the self-heating due to discharge and reducing the chance on short circuit due to the presence of the foam.
The main row of strings is directly injected with foam to extinguish the fire, cool down the battery cells and to reduce the chance of an explosion. After a certain time interval, or if the temperature passes a threshold temperature, the main row of strings receive a refill of foam. The refill exists of 10%-20% of the filling volume and can be repeated 30 times.	This method has been tested by FiFi4Marine and is deemed sufficient.
The secondary rows of strings will not be filled immediately with foam. Only if the temperature rises above a threshold temperature, foam will be injected to fill the strings completely. Just as the main row of strings, the secondary row of strings can receive refills as well. In this case, 10 refills will be sufficient.	If foam injection is not needed, the secondary battery strings might be used again after the incident.
Each battery compartment should be able to receive enough foam to handle two faulty cell incidents. (If needed, premix could be refilled with the use of premix concentrate and deionized water)	If more cells are damaged the safety of the system is at risk. If the system runs out of foam, water could be injected into the battery strings. This is an unfavorable intervention, but not extinguishing can cause an even more severe condition.
The supply of the foam will be divided into two setups per battery compartment. In case one fails, a second setup can take over. This provides redundancy on the battery compartment level.	Zonal distribution network on battery compartment level.
Between the different compartments a connection can transport foam from one to another. This gives redundancy on submarine level.	Zonal distribution network on submarine level.

With these assumptions the size and number of setups can be calculated. The method is further described in the following section.

10.2 Tool development

10.2.1 Purpose of tool

The purpose of the tool is to determine the amount of premix that has to be taken on board, the volume and weight the system will occupy and the amount of pressurized air the system requires.

10.2.2 Method

The amount of premix required for the battery system will be calculated based on the philosophy as described in the previous section. There are more input parameters required than described in Table 10. The input necessary to perform the complete calculation is listed in Figure 34 together with a flow chart of the design support tool.

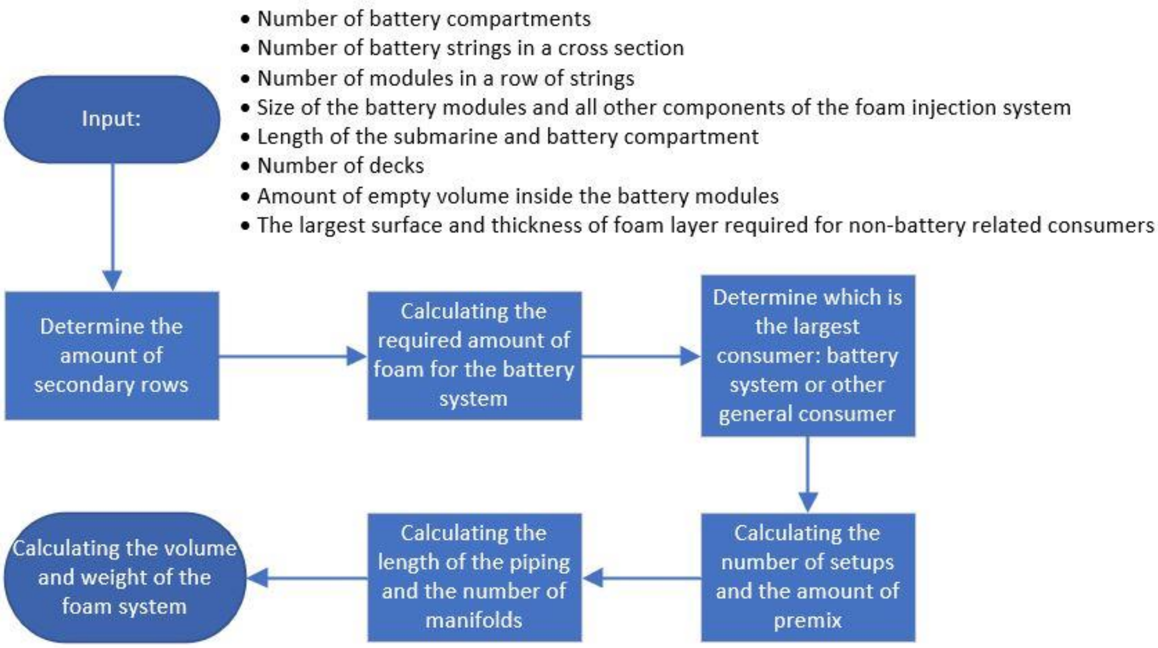

Figure 34: Flow chart foam injection system design support tool.

10.2.3 Restrictions

The foam injection system design support tool has some restrictions.

- All premix storage tanks have the same size
- Assumed length for the distribution system based on the length of the submarine and number of decks of the submarine.

Making the tool more precise would require more input data and more assumptions. Since the tool is developed for a high level and early design stage size estimation, it is not necessary to make it more precise. Keeping the tool "high level" as it is now, keeps it useful for an early design stage estimation.

10.3 Sensitivity study

A trade-off has to be made when designing the foam injection system for the battery compartment. For every row of strings, at least two valves are needed to ensure the injection of foam when needed. This means that with two valves the whole row has to be filled. This requires a large amount of foam and thus large storage tanks. Splitting the rows in two or more sub-rows requires less foam per injection. The downside is the increase in the number of valves. Per spit an additional amount of two valves is required and also the complexity of the system increases. In Figure 35 the row of battery strings is divided into two sub-rows. The consequences for the volume and weight of the Foam injection system are calculated and shown in Figure 36.

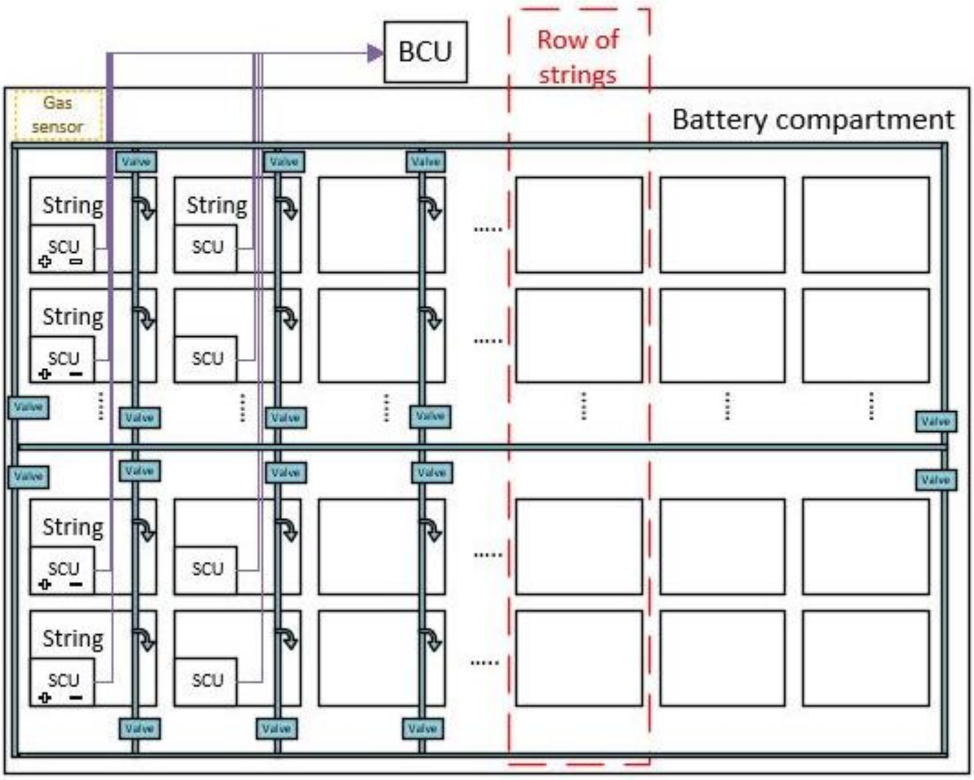

Figure 35: Splitting the row of battery strings requires additional manifolds.

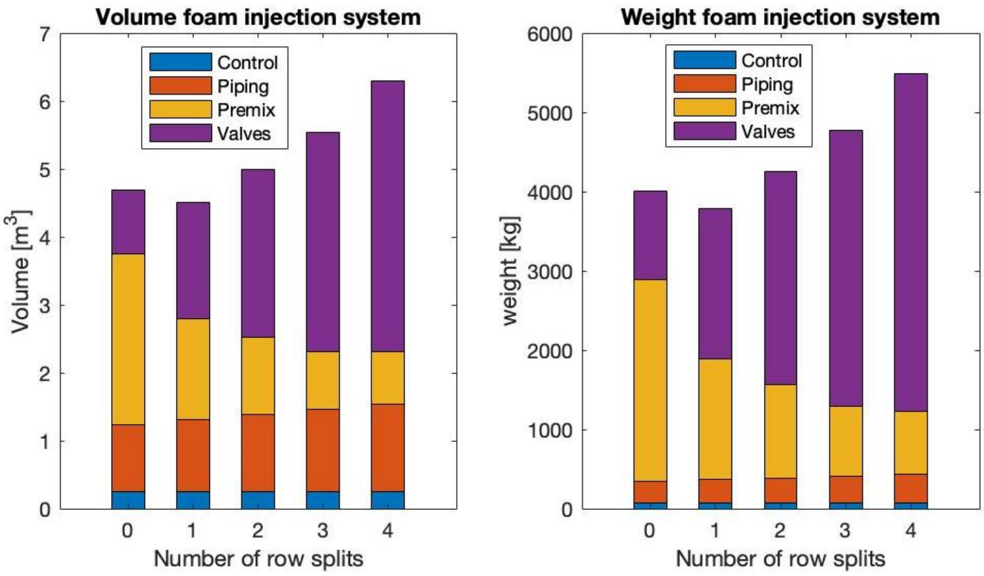

Figure 36: The weight and volume of the foam injection system against the increase of row splits. (low empty volume fraction)

The increase in row splits causes an increase in weight and volume of the manifolds and tubes, and a decrease in required premix. Based on the total volume and total weight of the system an optimum amount of row splits can be seen in Figure 36. Another interesting point is the required amount of premix which stops getting smaller. This is because it has reached the minimum amount required by the other general consumers.

The amount of required premix also dependents on the empty volume fraction of the battery modules. An increase from 10% to 20% empty volume means that double the amount of foam is needed to fill the modules. As a consequence, the optimum for the weight and volume of the system will shift to the side with more row splits as can be seen in Figure 37.

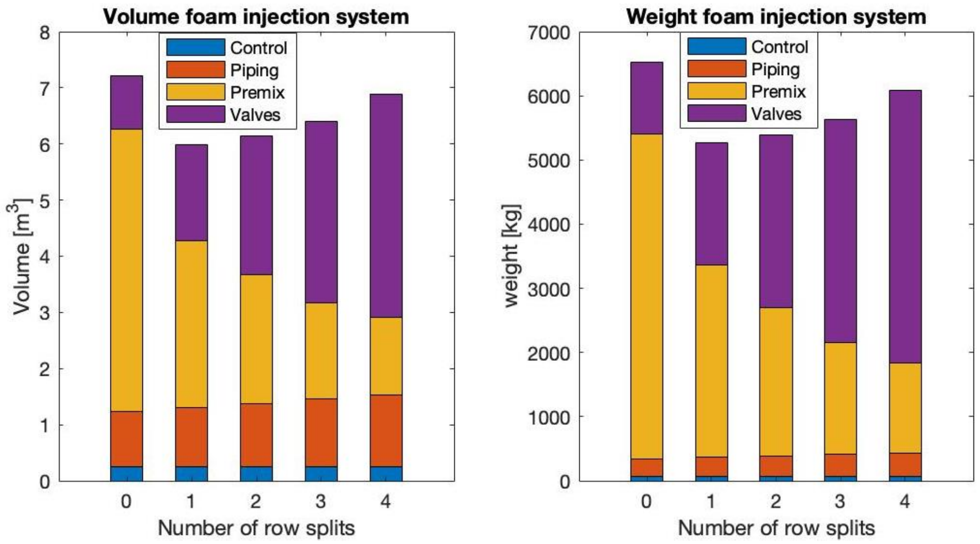

Figure 37: The weight and volume of the foam injection system against the increase of row splits. (high empty volume fraction)

Using a different filling philosophy will change the required amount of foam for the battery system. For instance, if only the main row of strings is injected with foam, less foam is required because the secondary rows stay empty. The lower premix requirement can be seen in Figure 38. It is clearly visible from the chart that the general consumers determine the required amount of premix from 1 row split or more. Making more row splits in the battery compartment does not lower the volume and weight of the foam injection system.

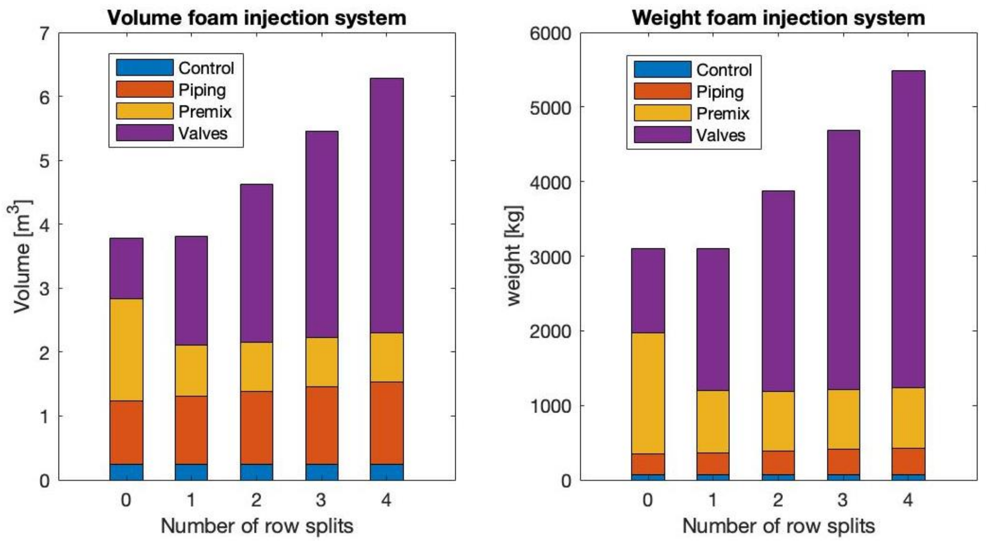

Figure 38: The weight and volume of the foam injection system against the increase of row splits. (No secondary modules injected)

10.4 Conclusion

The new firefighting system, foam injection system, is introduced as a consequence of the lithium-ion battery implementation. Besides being able to extinguish and cool down a lithium-ion battery, the system is also capable of extinguishing other fires. For this foam injection system, a high level supply and distribution system is designed. The distribution system consists of pipes and valves and is based on a zonal distribution system on battery compartment level and submarine level. This causes the distribution system to be redundant. For the supply of the foam, a redundant setup is chosen as well. Every watertight compartment receives two separate premix storage bottles that are sized based on a philosophy to ensure sufficient capacity.

The foam injection system design support tool helps the designer estimating the size, weight and HP air consumption of the system. It does that by calculating the amount of required premix and the corresponding distribution network based on the different consumers.

Considering the battery system, the required premix depends on the number of battery strings that will be filled at once. Reducing the number of strings that are filled at once, will cause less required premix storage. The downside of this is the increase of the required number of valves and pipes and the increase of the complexity of the distribution system. Depending on the size of the battery system, the size of the battery modules and the empty space inside the battery modules, an optimum can be found in the numbers of strings that will be filled at once.

Besides premix, the foam injection system requires high pressure air. The required amount of HP air depends on the amount of premix that is taken on board. Changing the filling philosophy or distribution system has consequences for the amount of HP air. In the next chapter the HP air system is reviewed and a design support tool is developed to investigate the consequences of the new battery system and foam injection system.

11 Pressurized air system

In the previous two chapters two design support tools are developed; one for the battery system and one the foam injection system. The foam injection system is partly sized based on the battery system and requires high pressure air. The pressurized air system is sized based on its consumers. The diesel-electric reference submarine has several consumers which will be removed due to the new power plant configuration. Without these auxiliary systems and with the presence of the new foam injection system the amount of required pressurized air storage will change.

To see what the consequences of the new power plant configuration are for the pressurized air system, the list of consumers will be evaluated. The focus will be on the amount of high pressure air storage and the question if a compressor is still required for an entirely battery powered submarine.

11.1 System design

The pressurized air system of a conventional diesel-electric submarine consists of several sub systems: compressors, dryers, storage bottles, pipes, valves and fittings. Together they provide high pressure air to the consumers. In a conventional diesel-electric submarine the storage bottles can be refilled during snorting. An entirely battery powered submarine does not necessarily have to snort during its mission, since it does not have diesel-generators to charge the batteries.

Because there is no need or possibility to charge the batteries during the mission, snorting and surfacing might be avoided if there is enough pressurized air to fulfill the whole mission. This requires a large enough pressurized air storage. If the storage can meet these requirements, a compressor might not be needed anymore. This makes the HP air system less complex; there is no room or mass required for a compressor and air dryer. Additionally, no power is consumed to refill the storage bottles, which improves the submerged endurance of the submarine.

11.1.1 System description

The function of the pressurized air system is to provide high pressure air to its consumers. It does this using stored pressurized air and a distribution system. The size of the storage is based on the required pressurized air of the consumers. Increasing the submerged period will increase the amount of stored pressurized air as well. The storage consists of standard 0.9 m^3 bottles with a weight of 1.7 ton and a working pressure of 275 bar.

11.1.2 Requirements

An entirely battery powered submarine is not capable of doing independent ocean going missions [2]. S.A. Los has investigated three relatively short mission profiles for his battery powered concept design. Varying from one to three weeks, and sailing from relatively fast to relatively slow, the submarine can sail submerged for the entire time of the mission (except leaving and entering the harbor). For these feasible mission profiles one with the longest possible submerged period will be reviewed: 600 hours submerged sailing.

11.1.3 Consumers

Based on two diesel-electric reference submarines a list of pressurized air consumers are provided on the left side of Table 26. Based on the entirely battery powered submarine concept design of S. A. Los the list of consumers is reduced to the consumers listed on the right side of the same table. Due to the absence of the diesel-generators, no starting air and fuel oil service and conditioning is required anymore. Also, pressurized air for the air intake is not required anymore since snorting is not part of the operational profile. The foam injection system is added to the list of consumers.

Table 26: Pressurized air consumers.

Diesel-electric reference submarine	**Entirely battery powered submarine**
Starting air	
Air intake	
Fuel oil service and conditioning	
Air conditioning system	Air conditioning system
Domestic fresh and hot water	Domestic fresh and hot water
Workshops, portable tools	Workshops, portable tools
Garbage Ejector	Garbage Ejector
Sewage system	Sewage system
Underwater signal ejectors	Underwater signal ejectors
Torpedo tube holding and firing	Torpedo tube holding and firing
	Foam injection system

S.A. Los has made an estimation of the high pressure air consumption in case of a 600 hours submerged period for the entirely battery powered submarine concept design as can be seen in Table 27. Without the foam injection system the total consumption would be 1597.8 Nm^3 of pressurized air. A first estimation of the maximum required air for the foam injection system would be approximately 50 Nm^3. This is not a significant amount when considering the other consumers.

Nm^3 stands for "Normal cubic meter". It is a volume of gas based on standard reference conditions of a temperature of 0°C and a pressure of 1.01325bar.

Table 27: High pressure air balance for a 600 hours submerged period [2] [7].

Consumer	Number	Frequency	Consumption each		Total consumption [Nm^3]
Fresh water tanks	-	Cont	0.06	[Nm^3/h]	36
General users	-	Cont	1	[Nm^3/h]	600
Engine room	2	18.75 hours	10.2	[Nm^3/h]	382.5
Sewage tank	1	1 per day	9.12	[Nm^3]	228
Garbage ejector	1	1 per day	0.6	[Nm^3]	15
Blowing all MBT's	-	1	320	[Nm^3]	320
				Total	**1581.5**
Torpedo tubes	2	1	7.7	[Nm^3]	15.4
Signal ejectors	2	1	0.47	[Nm^3]	0.9
				Total	**1597.8**
Foam injection	1	1	50	[Nm^3]	50
				Total	**1647.8**

"The engine room consumers consists of the workshop and portable tools working on high pressure air. The maintenance requirements are expected to be less. The total maintenance requirements for mechanical engineering are expected to be halved. Therefore, the use of the workshop and potable tools is halved as well" [2]. The general users group consists of systems such as air control units and equalizing ventilation and consume continuously 1 Nm^3/h.

In the table it is assumed that blowing the MBT's is only required once. This is based on the principle that every time the submarine is surfaced, and has blown the MBT, it can refill the air storage bottles with the use of the compressors. In this way there is always enough air to surface again. In case of an entirely battery powered submarine without a compressor, the number of times it has to surface should be taken into account and is probably higher than one. Blowing out the MBT multiple times requires more storage bottles.

11.1.4 Storage bottles

For the storage of the high pressure air the parameters of the storage bottles from the diesel-electric reference submarine are used. In the reference submarine nine bottles of 900 liter are installed. Each have a weight of 1.7 ton and displace a volume of 1.1 m^3. Based on an operational pressure of 275 bar, the capacity of each bottle would be 247.5 Nm^3. When the required capacity is known the number of bottles can be calculated and accordingly the weight and volume of the storage bottles.

For the total consumption of Table 27 this would mean a total amount of seven high pressure air storage bottles are required.

11.1.5 Distribution system

For completeness of the design support tool a simple distribution system is added. The distribution system is based on the distribution system from a second diesel-electric reference submarine as described in a study performed by Nevesbu [41]. The distribution system is based on the length of the submarine, the mass of the reference distribution system, the share of appendages weight in total piping weight, the average pipe outer diameter, the area of cross-section of the pipe and the density of the material: CuNiFe30. Equation 4 and Equation 6 are adopted from the study, but the submarine specific variables (mass, length and share of appendages) are changed for the variables from the reference submarine.

$$m_{piping\&appendages} = m_{piping\&appendages\,ref.submarine} \cdot \left(\frac{L_{submarine}}{L_{ref.submarine}}\right)$$

Equation 4 [41]

$$m_{piping\&appendages} = 3.8 \cdot \left(\frac{L_{submarine}}{66.5}\right)$$

Equation 5 [7]

With:

- $m_{piping\&appendages\,ref.submarine}$ = weight of the piping of the reference submarine
- $L_{submarine}$ = length over all of the scaled submarine
- $L_{ref.submarine}$ = length over all of the reference submarine

$$V_{piping\&appendages} = \left(\frac{m_{piping\&appendages} \cdot (1-\gamma)}{(A_{out}-A_{in}) \cdot \rho_{CuNiFe30}} \cdot \frac{\pi}{4} \cdot (dia_{HPair})^2\right) + \left(\frac{m_{piping\&appendages} \cdot \gamma}{\rho_{CuNiFe30}}\right) [m^3]$$

Equation 6 [41]

$$V_{Piping\&Appendages} = \left(\frac{3.8 \cdot \left(\frac{L_{sub}}{66.5}\right) \cdot (1-0.474)}{5.06 \cdot 10^{-4} \cdot 8.94} \cdot 7.07 \cdot 10^{-4}\right) + \left(\frac{3.8 \cdot \left(\frac{L_{sub}}{66.5}\right) \cdot 0.474}{8.94}\right) [m^3]$$

Equation 7 [7]

With:

- $A_{out} - A_{in}$ = area of cross-section of pipe [m^2]
- γ = share of appendages weight in total piping weight of $m_{piping\&appendages\,ref.submarine}$
- dia_{HPair} = average pipe outer diameter [m]
- $\rho_{CuNiFe30}$ = density of CuNiFe30 [t/m^3]

The results of these equations are expected to be accurate enough as an estimation. Even though the equations are based on a diesel-electric submarine, the reduction in consumers (and thus piping and appendages) is compensated with the presence of the foam injection system with its multiple connections to the distribution system. Moreover, a few less or more connections will not have a significant influence on the total weight and volume of the pressurized air system.

11.2 Tool development

The pressurized air system design support tool can be seen as an extension of the battery system design support tool and foam injection system design support tool.

11.2.1 Purpose of the tool

The purpose of the pressurized air system design support tool is to calculate the weight and volume of the pressurized air storage. The required amount of pressurized air storage will result in a number of required storage bottles. With this tool the designer can investigate if it is feasible to design a pressurized air system without the compressors and air dryers.

11.2.2 Method

This high level design support tool will use a list of consumers to calculate the required amount of stored air. Together with the equation provided in the sections Storage bottles and Distribution system the number of storage bottles, the weight and volume of the system can be calculated. This is schematically displayed in a flow chart in Figure 39.

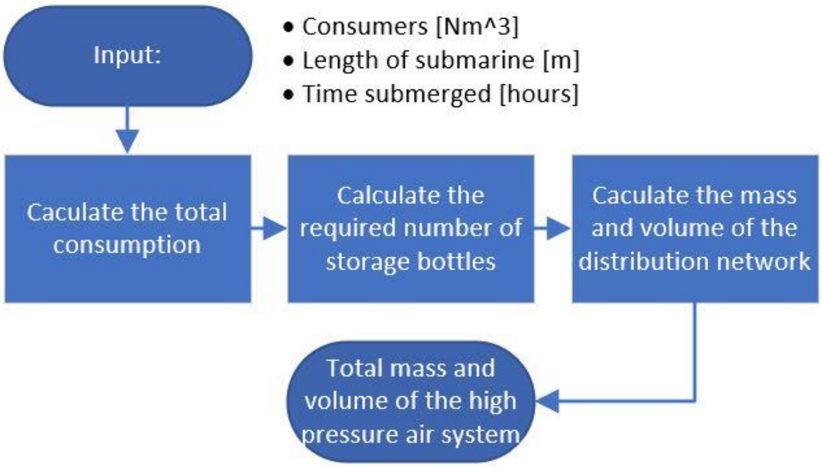

Figure 39: High pressure air system design support tool flow chart.

11.3 Sensitivity study

As mentioned in the section Consumers, blowing the MBT's multiple times during a mission means that more pressurized air has to be stored on board. In Table 28 the increase of required storing bottles is listed in combination with the number of blowing MBT's. Blowing the MBT's multiple times during a mission requires a significant amount of additional pressurized air. If a mission profile demands multiple blow outs of the MBT's, it might be a better solution to implement a compressor. This is a trade-of between volume, weight and energy the designer has to make based on the mission profile.

Table 28: Sensitivity of the HP air system when changing the number of blow outs of the MBT's. Based on storage bottles of 900 liter and 275 bar and a mission time of 600 hour.

Blowing MBT's	Total required capacity [Nm^3]	Number of storage bottles	Mass [ton]	Volume [m^3]
1	1648	7	15.7	8.21
2	1968	8	17.4	9.31
3	2288	10	20.8	11.51
4	2608	11	22.5	12.61
5	2928	12	24.2	13.71

The capacity of one storage bottle at 275 bar is 247.5 Nm^3. As mentioned in the section Consumers, the foam injection system will approximately require 50 Nm^3. Even if the foam injection system requires twice as much air as calculated, it would still be a small amount in comparison with all the other consumers. Looking at Table 28 learns that in most cases there is enough spare storage capacity to double the air consumption of the foam injection system.

The 50 Nm^3 is based on a battery system without row splits (for the entirely battery powered submarine). In case the designer decides to implement row splits to reduce the required amount of foam, the required amount of pressurized air will also be reduced. Making the required air even less significant on the total required HP air capacity.

For different mission times, different amounts of pressurized air and thus storage bottles are required. For the consumers as described in Table 27 a plot has been made with a varying mission time from one week to six weeks as can be seen in Figure 40.

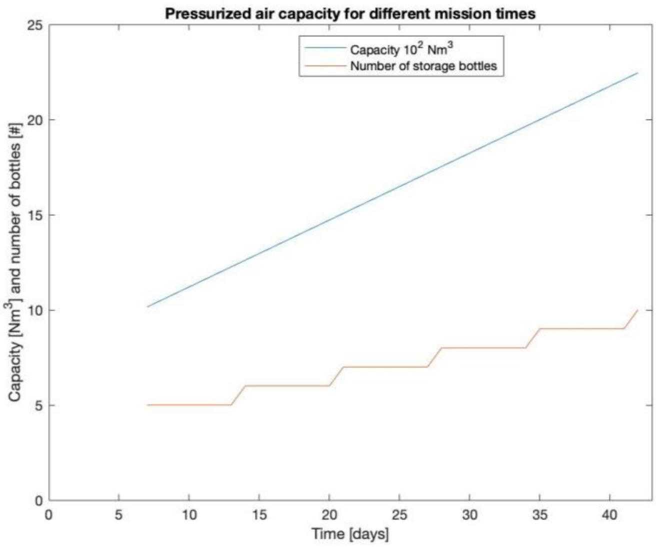

Figure 40: Sensibility of the required pressurized air capacity and storage bottles for different mission durations.

11.4 Conclusion

In a conventional diesel-electric submarine the HP air system would consists of a HP air compressor, storage bottles and a distribution network. In this chapter the high pressure air system has been reviewed for an entirely battery powered submarine. Because of the possibility to perform a different type of mission profile in which the submarine does not have to snort, the feasibility of a HP air system without compressor has been studied.

The list of HP air consumers from the reference submarine is modified for the consumers of the entirely battery powered submarine to investigate the feasibility of a HP air system without the possibility to refill during the mission. From this overview it became clear that the new foam injection system is only a small consumer and won't cause a large increase in HP air storage. Whereas, the air required to blowout the MBT's is a larger volume. The number of required blowouts determines the feasibility of a HP air system without a compressor.

Besides the storage of HP air, also some operational aspects should be taken into account when considering a HP air system without a compressor. During an operation there is always a chance of unusual circumstances with extra surfacing or repairs. In such a case the HP air system should be able to deliver more HP air than initially required. Also when visiting a harbor, other than the home port, it is inconvenient to arrange a compressor to refill the HP air storage tanks. For these reasons it is recommended to install a compressor regardless of the amount of HP air storage that is taken on board.

11.5 Discussion

For some HP air consumers it’s the question if HP air is the most optimal energy source. When pressurized air is used inside the pressure hull, for instance pressurizing the freshwater tank or using portable tools, the used air is released into the pressure hull, causing a pressure increase. This is a slow process, but can accumulate over time. Also, the oxygen candles which generate oxygen cause a small pressure increase. These pressure increases are unfavorable for the wellbeing of the crew and in case of an entirely battery powered submarine with a larger endurance, this could compromise the health of the crew.

Instead of pressurizing a freshwater-, or other type of tank to deliver a liquid to the consumer, an electric pump could be used as an alternative. Furthermore, portable tools can be powered electrically, which would generate less noise and could be more efficient. In both cases less HP air would be consumed. In the same way, more consumers could be considered for changing from HP air to electricity.

In a conversation with (retired) Main engineering officer P. Besseling, he told that (in a diesel-electric submarine) in some situations the air compressor was used to reduce the atmospheric pressure and to store the air back into the storage bottles. However, this is a risky operation because the large air compressor produces a lot of noise and therefore can reveal the location of the submarine. Using a compressor could also work for the entirely battery powered submarine. A small, low noise producing compressor would be convenient to slowly extract the air from the atmosphere without compromising its stealthiness.

Further research into the advantages and disadvantages of using electrical powered components instead of HP air powered components, can provide more arguments to decide what is most optimal for the entirely battery powered concept design.

12 HVAC and air quality

Conventional diesel-electric submarines used to have a mission profile in which they had to surface or snort to recharge the batteries. During recharging the air could be refreshed to maintain a good air quality. In case the submarine had to stay submerged for a longer time, it could use certain consumables to extract CO_2 and add O_2. With the capability to stay submerged for a long time, an entirely battery powered submarine cannot refresh the air with air from outside. Meaning that more consumables have to be taken on board or other systems should be reviewed to see if there are more suitable alternatives.

First, the tasks of the HVAC and air quality systems and how they relate are discussed. Second, the challenges of designing these systems and why chalkholders and oxygen candles are not desirable solutions for an entirely battery powered submarine are discussed. Next, some alternative systems are reviewed and a regenerative CO_2 removal system and Oxygen supply are considered for implementation. Finally, a sensitivity study is performed for the regenerative CO_2 removal system.

12.1 System description

As described in the section Climate control, the systems under this part of the SWBS are responsible for the environment of the submarine. Most of the systems in this category have relations to one and another, making them more complex. For example, the air conditioning uses cold water from the chilled water system to cool the air. The air quality systems and HVAC use the equalizing ventilation to gather dirty air and to distribute the purified and cooled air. Controlling the temperature is done by abstracting heat from the equipment and heat from the air as schematically displayed in Figure 41.

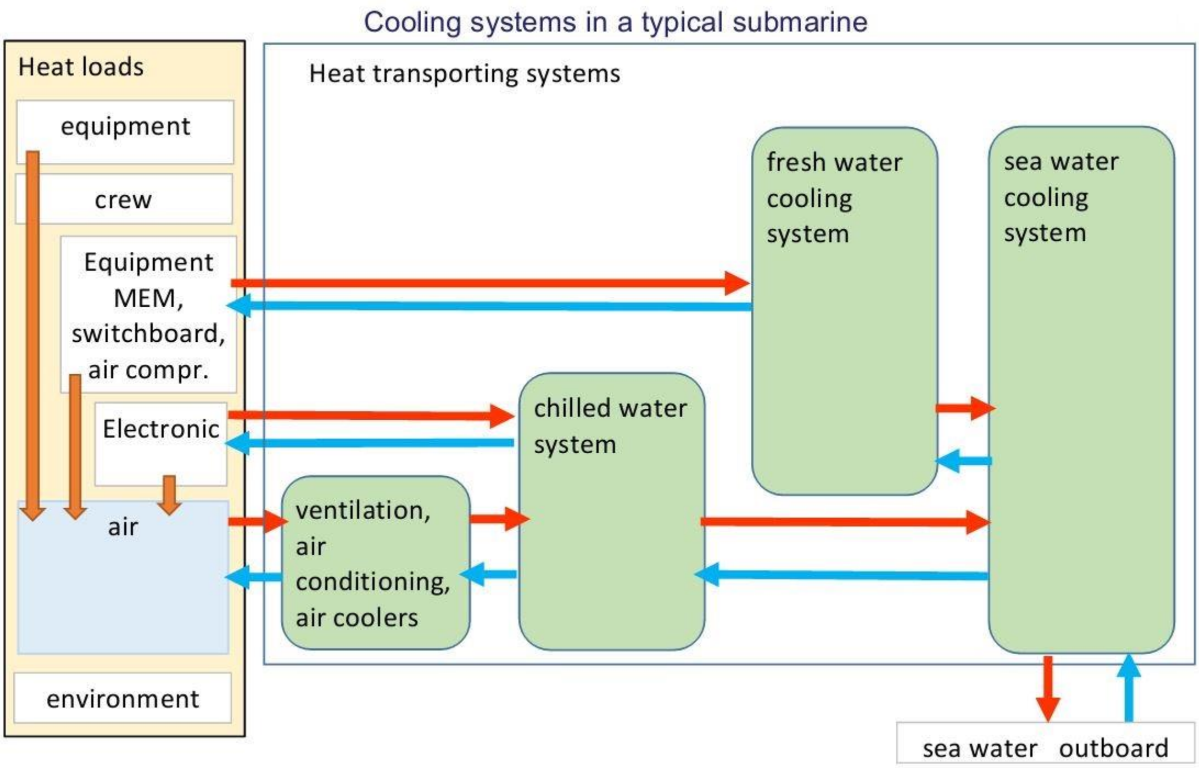

Figure 41: Cooling systems in a typical submarine. [47]

12.1.1 Heating

Heating the air to the required temperatures is done with electric heaters in the supply ducts to the accommodation or operational spaces. Besides these heaters, there are heaters in local spaces to provide extra heating. An example of such a space is the torpedo room.

12.1.2 Ventilation

The ventilation system moves air through the submarine to exchange the atmosphere. “There are a number of reasons for doing this including distributing clean/refreshed air for the crew respiration, supplying sufficient air to support diesel engine operation, evacuation of hazardous gases or atmosphere exchange to ventilate unpleasant fumes/vapors” [48].

The equalizing ventilation maintains a good equalizing of the air through the submarine and for equalizing different gasses, such as O_2, CO, CO_2 and H_2 gasses. When surfaced or snorting the system ensures air refreshment of the air through the submarine. It also removes smoke or other gases in surfaced or snorting condition.

For common diesel-electric submarines the equalizing ventilation ventilates the lead-acid battery compartments to ensure that there is no buildup of H_2 gases. In case of a lithium-ion battery compartment the H_2 gases are not present. Unfortunately, other toxic gases can be developed by the battery in case of failure. These gases should be ventilated locally to prevent build up, but they cannot exit the battery compartment because it will poison the submarine crew. When surfaced, the ventilation system should be able to ventilate the battery compartment with fresh air.

12.1.3 Air Conditioning

The air conditioning sub system cools down the air with the use of a chilled water cooled air cooler and it has a condensation drip-tray to catch moisture from the air. The sub system also has a dust filter, fine filter, and an electrical fan.

12.1.4 Air quality

An important task of the climate control systems is maintaining the air quality. Good air quality is required for crew habitability and operational performance. Air quality is maintained by filtering the CO_2 and other undesirable gases and particles from the air and by providing a sufficient level of O_2.

12.1.4.1 Carbon dioxide

One person produces on average 1 kg CO_2 per day [49]. “The CO_2-level in a room should be limited to 0.1 - 0.25% CO_2 because of health reasons. In special cases, like submarines, higher CO_2-levels (1.0 - 1.5%) are accepted” [22]. In conventional diesel-electric submarines often CO_2 scrubbers with chalkholders are used to subtract the CO_2 from the air. Air is blown through the scrubber where CO_2 binds to the chalkholder. The advantage is that this system does not use any additional power because it uses the airflow from the equalizing ventilation system. On the other hand, the main disadvantage is that the chalkholders have to be replaced when they are saturated with CO_2. This means that for a longer submerged period or a larger crew size more chalkholders are required. Also, the percentage of CO_2 in the air fluctuates due to the inconsistent filtering rate of the chalkholders, which is inconvenient for the crew.

12.1.4.2 Oxygen

In the diesel-electric reference design and most other diesel-electric submarines, oxygen candles are used to generate oxygen. Inside oxygen candles a chemical reaction releases the oxygen. Just like with the chalkholders, more oxygen candles are required for longer submerged periods or larger crew sizes.

Oxygen levels below 19% are unfavorable in terms of performance of the crew and might be harmful for the body [50]. One person needs on average 0.84 kg O_2 per day [49].

12.2 Challenges

Designing a HVAC system for a submarine is a difficult task. Each sub system/component has to be sized precisely according to the requirements but also has to match with the other sub systems/components. If sizing is done wrong, a component could limit the overall use of the system or it could be too large and heavy. The HVAC system should work in different operational settings like surfaced, snorting and submerged. It also has to be capable of handling different types of environmental conditions, such as the artic climate and tropical climates. Other important requirements for a HVAC system, that makes the system more complex, are the low energy consumption and low noise requirements.

The low noise requirements impose large ventilation ducts, so the air speed can be low. Unfortunately, volume is critical inside a submarine, making large ventilation ducts unpractical. The right balance between noise and space consumption should be found.

In a conventional diesel-electric submarine the diesel generator sets are used in surfaced and snorting conditions to suck in fresh air from outside. It uses the equalizing ventilation to gather the air from within the submarine and it disposes the exhausts gases, with the use of the over-pressure from the diesel generator, to outside. As is schematically shown in Figure 42. The generated under pressure sucks in fresh air into the submarine from outside. Without the diesel generators fresh air has to be brought into the submarine in another way.

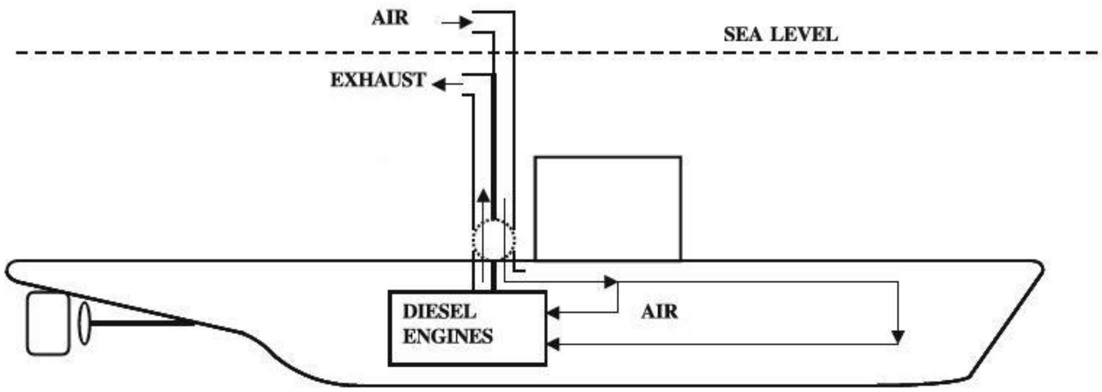

Figure 42: A schematic diagram of the airflow through a diesel-electric submarine in snorting condition [51].

An important aspect of the entirely battery powered submarine is the improved submerged endurance. The capability to stay submerged for a longer time, means that the air cannot be refreshed with air from outside. This would imply that the systems on board have to ensure the air quality for a longer time. With the existing chalkholder system and the oxygen candles the mass and volume of the additional consumables are unfavorable. S. A. Los has calculated the amount of chalkholders and oxygen candles that has to be taken on board to fulfill a mission of 600 hours submerged sailing, as can be seen in Table 29 and Table 30.

Table 29: Effect of the entirely battery powered submarine on the CO_2 absorption system. [2]

	Reference	Concept	
Number of crew	35	34	
Submerged period	3x 25, 1x 160	1x 600	[h]
Required number of chalkholders	432	1288	
Weight chalkholders	1944	5670	[kg]
Volume chalkholders	1728	5040	[l]

Table 30: Effect of the entirely battery powered submarine on the O_2 generation system. [2]

	Reference	Concept	
Number of crew	35	34	
Submerged period	3x 25, 1x 160	1x 600	[h]
Required number of oxygen candles	46	163	
Weight oxygen candles	575	2037.5	[kg]
Volume oxygen candles	391	1385.5	[l]

The increase in weight and volume of the stored chalkholders and oxygen candles is extremely unfavorable for a submarine in which available volume and weight is extremely scarce. In case of an entirely battery powered submarine with a higher endurance the required amount of chalkholders and oxygen candles will be even more. For this reason it could be interesting to look at other alternative systems to maintain the air quality.

Air quality systems, other than the chalkholders and oxygen candles, often use a high amount of energy to maintain the air quality. Instead of a large number of consumables they reuse the consumables. These regenerative systems are often complex, large and heavy, and the high power demand is a disadvantage because it comes at the expense of the submerged endurance.

Besides the challenges to maintain the required CO_2 and O_2 levels, other contaminants will accumulate inside the submarine during prolonged submerged operations. Gases, particulates, microbial pollutants, electric pollution can be filtered from the air with the use of a mechanical filter, activated filter, electric filter and a germicidal lamp. M.E. Venema introduces in his report an air filter system, which is already been tested by the Italian Navy [6]. The KOALA system seems reliable, effective, small, light and uses as little as 40 W per system [52].

12.3 Alternative systems

In this section the air quality systems in other industries are investigated/reviewed to see if there are other technical solutions on the market or in development.

12.3.1 Nuclear powered submarines

Nuclear powered submarines have solved the air quality problem for many years. These types of submarines can stay underwater for extremely long times without ever surfacing or snorting. The endurance restriction is based on the food they can take on board for the crew. The only time they have to surface is to resupply the food. The nuclear based powerplant provides a large amount of power which makes it possible to use large energy consuming equipment; something an entirely battery powered submarine cannot do.

With the “endless” power supply oxygen is generated by electrolysis. During this process electricity is used to split water into hydrogen and oxygen. The oxygen is released into the air and the hydrogen is discharged overboard [53]. CO_2 is captured from the air with the use of a regenerative CO_2 system which also uses a large amount of energy.

12.3.2 Solutions for spaceflight

Astronauts in space encounter several of the same environmental challenges as submarine crew. They are both in a closed environment without excess to fresh air. Where submarines do have excess to (sea)water, spacecrafts have to rely on their own supply. Though spacecrafts have a large energy supply by means of solar power, diesel-electric or entirely electric submarines have only as much energy as they can store in their batteries.

NASA aims to do long duration human missions beyond low orbit. For this reason they research into new technologies in the field of environmental control and life support systems [54]. They already have a lot of knowledge and specialized systems to support the people on board of the International Space Station. “The current state-of-the-art (SOA) in atmosphere revitalization includes CO_2 removal at ppCO2 <4 mmHg and O_2 recovery >50% from CO_2” [54]. They are now looking into the gaps of the current technology. Their aim is to improve the CO_2 removal and the recovery of O_2 from CO_2. To reach these goals, they are investigating multiple technology paths [54] [55].

- Liquid Amines are used for regenerative CO_2 absorption and have the advantage to be low power, low mass and highly reliable. The method is already used in submarines but “face challenges associated with chemical stability and liquid containment in microgravity” [54].

Further research is necessary and is focused on diglycolamine before implementation is feasible in microgravity.

- Structured sorbents are used in a temperature swing absorption process and might be interesting to replace the 4-Bed CO_2 Scrubber. Simulations have demonstrated that there might be a system design that mitigate the required amount of CO_2 generation. Tests have shown the first positive results but further research is required to understand and improve the technology [54] [55].

On the International Space Station oxygen is currently generated by using water electrolysis to separate hydrogen and oxygen. “The oxygen is released to the cabin air, while the hydrogen is vented overboard” [54]. This system/method is not efficient enough for long duration human missions beyond low orbit. New technologies are developed to increase the recovery of oxygen.

- “The Plasma Pyrolysis Assembly is a methane post-processor that aims to achieve a higher recovery of oxygen from carbon dioxide” [54]. It would be an addition to the existing technology, making the total process more complex and energy demanding. With this extra step the theoretical oxygen recovery would be 90% with a realistic recovery of 85%.
- Spacecraft Oxygen Recovery: “The Bosch process, Equation 8 has been considered by NASA since the 1960s and is theoretically capable of recovering 100% of the O_2 from metabolic CO_2. Bosch technologies catalytically react ambient CO_2 and, with the H_2 by-product from water electrolysis, produce solid carbon and water. The water may be recycled to produce addi-tional O_2” [54]. The technology is not ready for use, but work will continue on the technology development [55].

Bosch process: $$CO_2 + 2H_2 \leftrightarrow 2H_2O + C$$ **Equation 8 [54]**

- High pressure Oxygen is a technology mainly investigated for the use of extravehicular activity. Several solutions to achieve high purity oxygen at 250 bar are investigated [54]. A high pressure water electrolysis unit had been tested for a duration of 140 hour. In 2019 testing continued with durations up to one month [55]. Because this technology works on the electrolysis principle it consumes energy, which makes it less interesting for the use inside a submarine.

Both CO_2 technologies require significant amounts of energy to provide temperature or pressure swings for the regeneration process. The recovery of oxygen from carbon dioxide uses a large amount of energy as well. This makes the technologies not a feasible alternative for the systems on board of a non-nuclear submarine. Besides, these new technologies are still in development and not available for commercial use. It still remains interesting to see the new technologies NASA is developing. Keeping an eye on these research topics might be convenient for the future.

12.3.3 Direct Air Capture of Carbon Dioxide

Direct air capture is an umbrella term for different technologies which capture carbon dioxide from the air [56]. These emerging technologies are focused on removing CO_2 from the atmosphere and have the potential to play a significant role in climate mitigation. The captured CO_2 can be used in the industry or can be stored to reduce the amount of CO_2 in the air. The general idea is visualized in Figure 43.

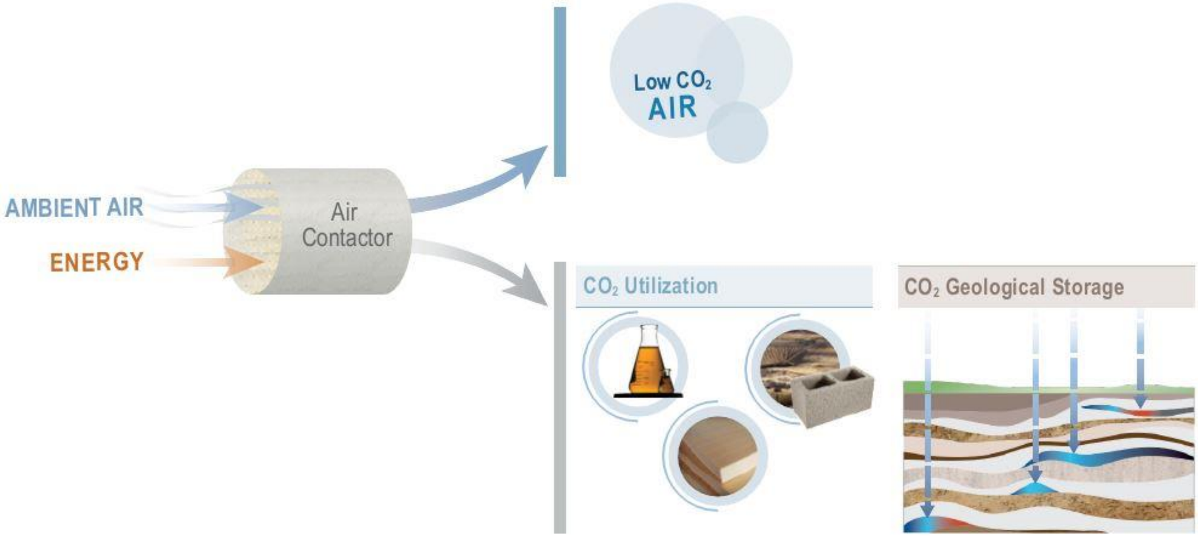

Figure 43: General working principle of Direct Air Capture of CO_2 [56].

The technologies available for Direct Air Capture and those in development, could be interesting for CO_2 removal inside the submarine. For now the available technologies use large amounts of energy which makes it not favorable to use inside a submarine. Because of the current global interest in reducing greenhouse gases, new and improved technologies will be developed. Keeping an eye on these technologies might be interesting for the future.

12.3.4 CO_2RS^{TM}

Airbus, mainly known of its aircrafts, is also a significant player in the field of defense and space technology. For the development of a regenerative CO_2 removal system they started in the late '80s with the investigation of over 55 different technologies and materials. The most promising one is further developed into an environmental control system for the ISS and later optimized for nuclear and AIP submarines. The system is already implemented/tested in several submarines and the ISS [49] [57] [58] [59].

The system ventilates air from the submarine trough a resin bed of Astrine^{TM}, where the CO_2 is captured. When the Astrine^{TM} is saturated with CO_2, regeneration is necessary to use it again in the next cycle. Regeneration of the Astrine^{TM} is done with over pressurized and super-heated steam. This means that one bed of Astrine^{TM} does not provide a continuous flow of purified air. Two or preferably three beds of Astrine^{TM} are required to ensure a permanent scrubbing process. Besides the Astrine^{TM} beds, a filter of Zeolite filters Volatile Organic Compounds (VOC) from the air and H_2 , CO particles and aerosol are filtered with the use of a particle filter. A schematic overview can also be found in Figure 44.

Advantages and disadvantages of the Regenerative CO_2 Removal System are listed in Table 31.

Table 31: Advantages and disadvantages of the Regenerative CO_2 Removal System CO2RS^{TM}. [49]

Advantages	**Disadvantages**
Save control of CO_2 level between 0.003-0.5%	Power consumption due to ventilation and steam generation
Continuous CO_2 absorption	System with active elements
No Exchange of cartridges	
Automatic process	
Individual customer adaptation	

The biggest disadvantage of this system is the use of over pressurized and super-heated steam. Generating the steam has a large impact on the endurance of the submarine since it consumes a lot of power.

12.3.5 LOX

As an alternative system for Oxygen generation on board of an entirely battery powered submarine, Liquid Oxygen (LOX) would probably be a feasible and convenient solution. LOX is already a proven and used method to facilitate the required oxygen in submarines. Several diesel-electric submarines with AIP are equipped with a Fuel-Cell that requires LOX. The crew only requires a small amount of LOX in comparison with the FC, making it convenient to extend the LOX tank with the required volume for the crew. In case of an entirely battery powered submarine there will not be a FC, but the proven technology can still be used to provide Oxygen for the crew. Using LOX to add oxygen to the air will increase the atmospheric air pressure, but this could be solved by extracting air from the atmosphere as discussed in chapter Pressurized air system.

12.4 Implementation of alternative systems

As discussed, a large number of chalkholders and Oxygen candles is unfavorable for an entirely battery powered submarine. In this section the regenerative CO_2 removal system from Airbus, CO_2RS^{TM}, is investigated to see if the implementation into an entirely battery powered submarine is feasible. Even though it is known that the system requires power, it might be more suitable than the voluminous chalkholders. Also the implementation of LOX as an Oxygen supplier is investigated.

12.4.1 Regenerative CO_2 removal

As described in section CO_2RS^{TM} the system from Airbus is already implemented in several AIP submarines [59]. The system is optimized to be small, light and energy efficient. This is especially the case if it is combined with an AIP Stirling Engine. The heat from the Stirling Engine is used to reduce the energy consumption for the steam generation. Without the Stirling Engine the regeneration of the Astrine^{TM} is an energy consuming process.

The system consists of:

- "CO_2RE^{TM} removes carbon dioxide and parts of volatile organic components like Methanol, Acetaldehyd, Ethanol and others by ASTRINE™ a specific highly porous functionalized ion exchange resin ("solid amine") as adsorbing material [49]."
- "Option: CO_2Pressor, an AIRBUS solution to pump wet CO_2 out of the boat up to a pressure difference of 45 bar [49]."
- "Option: Steam generator for desorption process [49]."
- "Option: Volatile Organic Compounds (VOC) by Zeolite, a specific porous ceramic structure adsorbing material [49]."
- "Option: H_2, CO particles and aerosol by means of particle filters [49]."

A schematic overview and the working principle is shown in Figure 44.

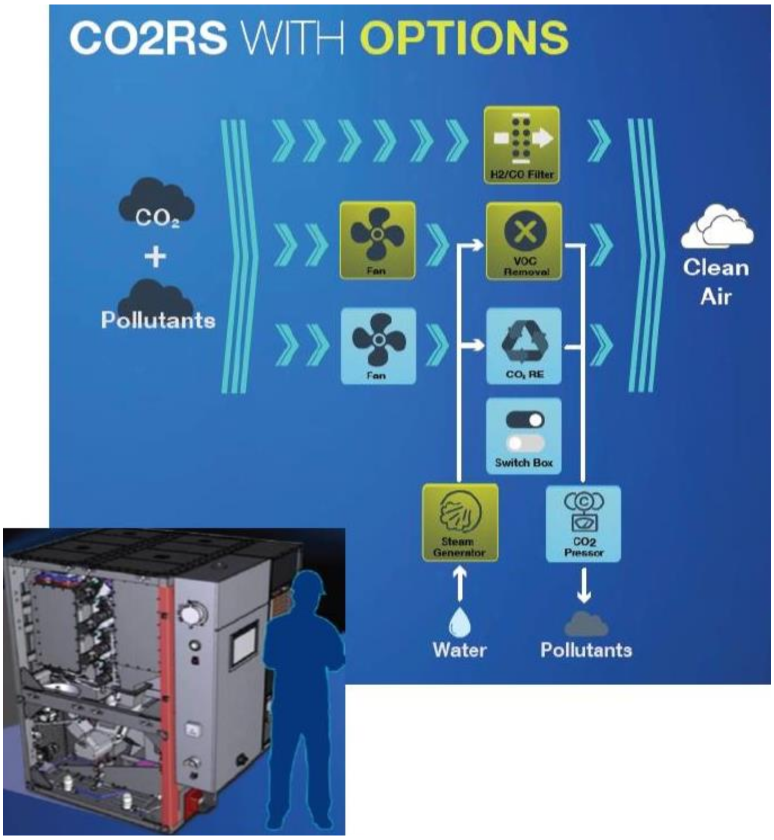

Figure 44: Schematic overview of the Airbus Regenerative CO_2 Removal System CO_2RS^{TM} [49].

One setup of the CO_2RS^{TM} consists of a rack structure with three Astrine^{TM} beds, ventilator, CO_2 pressor, heat exchanger, switch box, Zeolite filter and particle filter. For the steam production a separate steam generator, that uses electric heaters and demineralized water, is required. The rack structure dimensions and power consumption (without steam generation) are listed in Table 32 and an illustration of the rack can be seen in Figure 45.

Table 32: Main parameters of a CO_2RS^{TM} rack structure (without a steam generator) [49] [59].

Weight	1800 [kg]
Height	1800 [mm]
Width	1350 [mm]
Depth	1160 [mm]
Power consumption	4.5 [kW]

Figure 45: illustration of the CO_2RS^{TM} rack [49].

To complete the regenerative CO_2 absorption system, a steam generator has to be added to the setup. One rack structure can filter approximately 850 NL CO_2 per hour, which is sufficient for more than 35 persons and requires 6.7 to 8 kg of steam per hour [49]. A suitable steam generator has been found on the Internet to see what the total system dimensions would be [60]. The dimensions are listed in Table 33 and an illustration of the steam generator is provided in Figure 46. Since this is a commercial of the shelf product, it is not known if this steam generator satisfies shock requirements or other submarine specific requirements. If a designer has more information available, more weight, volume or a higher energy consumption can be taken into account.

Table 33: Dimensions of the steam generator [60].

Capacity	4.5 – 8	[kg/h]
Weight	52	[kg]
Height	1000	[mm]
Width	550	[mm]
Depth	390	[mm]
Power consumption	3.3 – 4.8	[kW]

Figure 46: Steam generator [60].

The total power consumption of the system with a dedicated steam generator would be approximately 8.8 kW. This is a significant amount when considering the total auxiliary load of the reference design during slow submerged sailing; approximately 125 kW as can be seen in Figure 4. Besides the steam generator, the system uses the equalizing ventilation system to receive CO_2 rich air and distributes purified air.

The freshwater generating unit from the reference submarine is also capable of generating deionized water. It has a capacity of 2 m^3 per day at approximately 3 kW. The steam generator will consume 5.4% - 9.6% of the installed capacity of the freshwater generating unit. The extra consumer for the freshwater generating unit and the probably lower number of crew members for the concept design cancel each other out. In that case the system can probably remain the same.

For the reference submarine the CO_2 absorption system has an operational classification [7]. This implies that a form of redundancy is favorable but full-redundancy is not required. Two separate systems with different working principles and capacities might be sufficient. One system, in this case the chalkholders, can take over the task of the CO_2RE^{TM} system in case of a failure. The chalkholers can meet the required absorption rate but only for a small amount of time and still need power for the equalizing ventilation. Another system: Reactive Plastic Curtain, could also take over the absorption of CO_2. These special curtains do not require ventilation and are thus suitable for situations in which the power supply fails [61]. As well as the chalkholders, the Reactive Plastic Curtains can only absorb CO_2 for a limited amount of time.

Because the chalkholders will be used for redundancy reasons, the system integration of the chalkholders cannot be removed in case the CO_2RE^{TM} system is integrated. This causes only a reduction in volume and weight due to the reduction of the chalkholders.

12.4.2 Oxygen supply

Storing Liquid Oxygen in a well-isolated tank is a suitable method as discussed in section LOX. Such system consists of a LOX tank and a subsystem that can control the evaporation process of the LOX into Oxygen.

Assuming that the crew requires 0.84 kg per day, the size of the LOX tank can easily be determent by multiplying with the number of crew members and the length of the mission profile [49]. For instance, a crew of 33 and a 600 hour endurance, 693 kg of Oxygen has to be provided. With storage factors of 2 kg and 1.8 liters of tank per kg of Oxygen, only a relatively small and low weight tank is required [62].

The evaporation process requires energy to heat up the Oxygen to the room temperature. Different small solutions are possible: an ambient air vaporizer uses ambient air to heat up the oxygen or an electric vaporizer uses electricity to exactly heat up the oxygen to the required temperature [63]. These systems can be combined and an integration with the hot return water from the cooling system might be possibility to increase efficiency.

In the reference design the O_2 generation system has an emergency classification. This means that full redundancy is required and that at all times, even during an emergency, O_2 should be generated. For this reason it is also required to have O_2 supply divided over all watertight compartments. The LOX storage is situated in every watertight compartment and backup (emergency) O_2 supply is done with Oxygen candles in case the LOX system fails.

12.5 Sensitivity study

In this section the sensitivity of the HVAC and air quality systems is reviewed. For a designer it is useful to know what happens with these systems if certain design parameters are changed. Also a look at the sensitivity of the regenerative CO_2 absorption system and chalkholders should give more inside about the choice which system is more favorable in which situation.

12.5.1 Crew members

Environmental control systems such as the HVAC, CO_2 absorption and O_2 generating systems, are implemented to support the crew. These systems are designed based on the maximum number of crew. If the number of crew members changes, the requirements and thus parameters of the systems changes as well.

Less crew members means a reduction in the produced CO_2. If the reduction is permanent the size, weight and power consumption of the regenerative CO_2 system can be reduced. If the reduction of the crew is only temporary the size and weight will remain the same but the power consumption will decrease. A lower power consumption will result in an increased endurance of the submarine.

A permanent reduction in the number of crew members also has an impact on the size of the LOX storage tanks if the mission profile does not change. But when the endurance increases because of the reduced power consumption of the CO_2 absorption system, the amount of required LOX might stay the same.

The amount of heat and moist produced by the crew members is also depending on the number of crew members. A reduction in crew means a reduction in produced heat and moisture and thus a reduced load for the air conditioning systems. This results in a lower power consumption and thus in an increased endurance.

This really shows the importance of a minimized amount of required crew members. The lower power consumptions and space requirements result in an increased endurance, which is one of the most important aspects of a submarine.

12.5.2 Environment

The operational environment of the submarine is an important factor in the design requirements of the HVAC systems as well. Dependent on the capability requirements of the submarine it will encounter different types of environments with different sea water temperatures and air temperatures. In case of a mission profile within the artic, the submarine has to have enough heating capacity. If a mission profile in tropical waters is required, the air conditioning and other cooling systems must have enough capacity to dispose the heat.

12.5.3 Regenerative or not?

Given the power consumption of the regenerative CO_2 absorption system and thus the reduction of the endurance, the system will not necessarily be the preferred choice. It depends on the number of crew members, length of the mission profile and the amount of power available if the CO_2RE^{TM} is the more favorable system to absorb CO_2.

To gain a better understanding about the size, weight and power consumption of the CO_2RE^{TM} system it will be compared with the size and weight of the chalkholders from the reference submarine. The information about the chalkholders is gained from the research of S.A. Los and M.E. Vennema and internal documentation about the reference design [2] [6] [7]. The CO_2RE^{TM} can be customized for the required capacity but limited information is available about these customizations. The CO_2RE^{TM} system will have a minimal of two Astrine^{TM} beds to provide a continuous flow of purified air. The three bed configuration is assumed suitable for the 30 or 35 crew members; only the power consumption varies. For 20 crew members 2 beds and for 40 crew, 4 beds, are assumed suitable. The system size is adapted by removing or adding the approximate size of one Astrine^{TM} bed.

Table 34: Comparison between the regenerative CO_2RE^{TM} system (inclusive steam generator) and chalkholders for a constant endurance of 600 hours.

Crew size	**25**	**30**	**35**	**40**
Weight [kg]	1752	1852	1852	1952
Volume [L]	2.611	3034	3034	3242
Energy consumption [kWh]	4260	4820	5250	5960
Weight chalkholders [kg]	4158	4968	5832	6642
Volume chalkholders [L]	3696	4416	5184	5904

In Table 34 can be seen that the CO_2RE^{TM} system is smaller and lighter for every number of crew size that is looked into. Based on energy consumption the CO_2RE^{TM} system will always use more energy than the chalkholders, since the chalkholders do not use energy. In this case the choice has to be made between energy consumption or size and weight.

Table 35: Comparison between the regenerative CO_2RE^{TM} system (inclusive steam generator) and chalkholders for a constant number of crew size of 35.

Duration	300 [h]	600 [h]	900 [h]	1200 [h]
Weight [kg]	1852	1852	1852	1852
Volume	3034	3034	3034	3034
Energy consumption [kWh]	2625	5250	7875	10500
Weight chalkholders [kg]	2862	5832	8748	11718
Volume chalkholders [m^3]	2544	5184	7776	10416

Even with only 300 hours of submerged time the CO_2RE^{TM} system is lighter. Only the volume is larger in case of the 300 hour submerged time. For longer periods the CO_2RE^{TM} system is smaller and lighter than the chalkholders. Again, the CO_2RE^{TM} system always uses more energy.

12.6 Conclusion

This chapter has shown some of the challenges of designing environmental control systems, such as the HVAC, CO_2 removal and O_2 generation systems. Finding an optimum for size, weight and power consumption is important to maximize the endurance of the entirely battery powered submarine.

There are many different new technologies in development in the field of environmental control. Nasa is concentrating on the efficiency of Oxygen recovery from CO_2 and trying to find new technologies for regenerative CO_2 removal. Large scale CO_2 removal technologies are developed under the name of Direct Air Capture and is mainly designated for industrial scale. Most technologies are not usable yet, but might bring interesting solutions for the future.

The regenerative CO_2 removal system from Airbus is already implemented in the AIP submarine from Sweden. In this submarine the CO_2RS^{TM} system uses rest heat from the Stirling Diesel Engine to generate Steam for the regeneration of the Astrine™. Unfortunately, this is not possible inside an entirely battery powered submarine, causing an even higher energy consumption for the new system. Comparing the CO_2RS^{TM} system with the chalkholders shows that the system is smaller and lighter in nearly all cases. Only the high energy consumption is a large disadvantage of the system.

Designing a new environmental control system for an entirely battery powered submarine is a complex and time consuming task. Using new technologies to improve the efficiencies will only amplify this and during this process a lot of design choices have to be made. Designing and optimizing such a new and complex system is outside the scope of this thesis, but it might be suitable for it to be a separate graduation assignment. An interesting addition for such a design assignment could be the integration of these systems in a submarine with a Fuel Cell as AIP. Using the rest heat from the FC might improve the efficiency of the regeneration process.

13 Demonstration design support tools

In this chapter a case study will be performed. The developed tools from the previous chapters will be used to calculate the main system parameters for the selected systems of the entirely battery powered submarine which is developed by S.A. Los. The tools are mainly developed to use in an early design stage when designing from scratch. However, this case study will show the usability of the tools and what the impact will be on the total submarine design. Furthermore, this case study allows to compare the output with the manually designed concept design. The general arrangement of the concept design is provided in Figure 47.

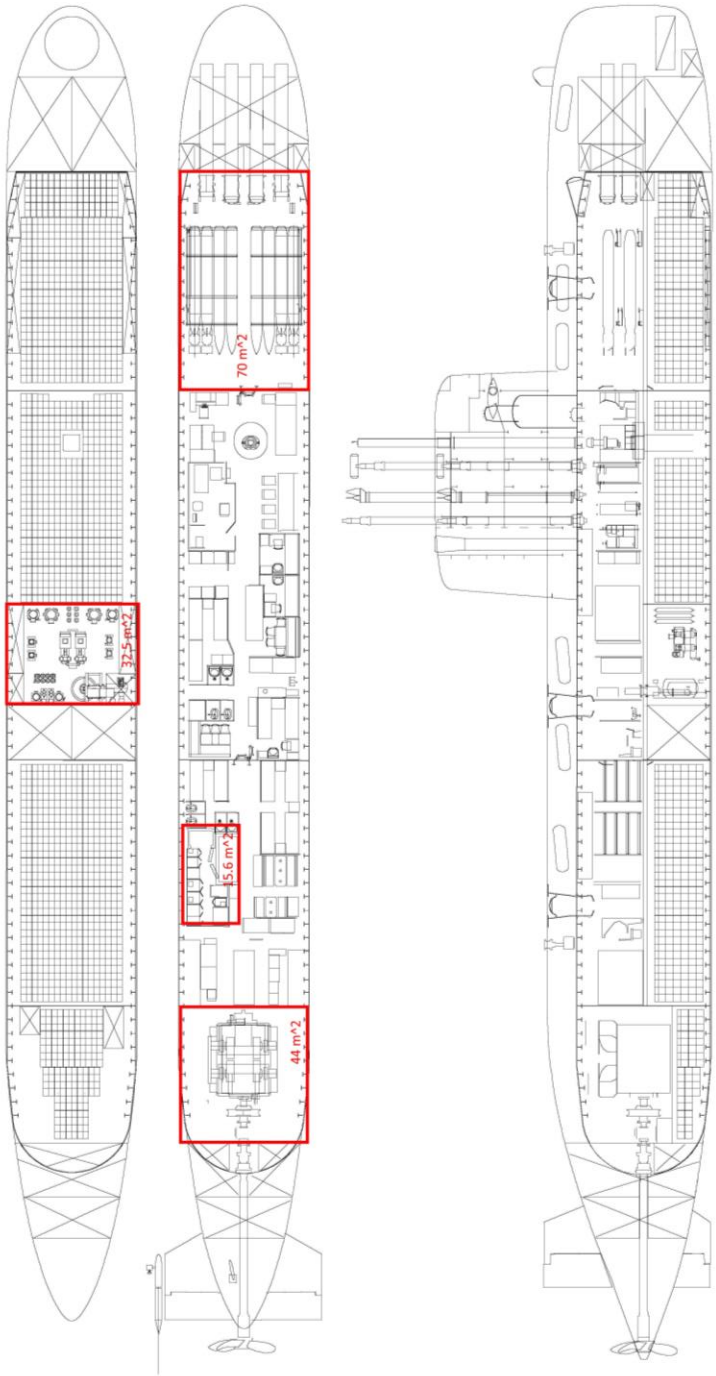

Figure 47: General arrangement entirely battery powered submarine concept design [2]. In red some estimated surfaces which are used in the section Foam injection system.

13.1 Lithium-ion battery compartment

In the concept design the battery system is divided into four battery blocks as can be seen in Figure 47 and Table 36. This gives a total of 1476 battery strings with a combined capacity of 88.5 MWh. S.A. Los designed the battery compartments by drawing the modules and SCUs into a 3D model. Multiple iterations were required to reach the level of detail as illustrated in the general arrangement.

For the battery system design support tool, different modules and SCUs are used compared with the concept design. These battery modules are based on a more recently developed commercial battery cell, but the packing factors remain the same. This will result in a slightly lower gravimetric and volumetric energy density for the battery modules. On battery compartment level there is less details incorporated in the design support tool than the concept design.

In Table 36 and Table 37 the used input parameters are listed. The design support tool creates one battery compartment at the time and with a constant cross-section. As can be seen in Figure 47, the aft and forward compartments are the most suitable to design with the help of the design support tool because of the constant cross-section.

Table 36: Input parameters based on the concept design of the entirely battery powered submarine [2].

Diameter pressure hull	6.5 [m]	
Height deck	3.25 [m]	
Battery compartments	4	
- MEM compartment	68 strings	4.1 [MWh]
- Aft compartment	528 strings	31.6 [MWh]
- Fwd compartment	440 strings	26.4 [MWh]
- Torpedo compartment	440 strings	26.4 [MWh]
Maximum required power	3700 [kW]	

Table 37: Battery cell, module and SCU parameters derived in chapter Battery system.

	Cell	Module	SCU
Height [mm]	327	382	190
Length [mm]	462	540	260
With [mm]	10.5	221	120
Weight [kg]	3.020	70.7	5

In Table 38 the output from the design support tool is presented for both the forward and aft battery compartment. For both compartments the number of strings is higher than in the concept design. This is due to the fact that the tool fills every cross-section completely. The extra strings cause a higher installed capacity. The cross-sections could be filled slightly more efficient, because the tool places a SCU on top of every stack of modules, while this is not always required. Therefore, the total number of SCUs is equal to the number of stacks. If some of the superfluous SCUs are removed, additional modules can be placed. This can clearly be seen in Figure 48, which is derived by the design support tool. Comparing Figure 48 with Figure 49, the different size of the battery module can be seen. The cross-section of the modules used by the design support tool is smaller but has a larger length.

Table 38: Output of the battery system design support tool for the forward and aft compartments of the concept design of the entirely battery powered submarine.

	Forward	**Aft**
Strings in cross-section	19	19
Strings in length	24	28
Total number of strings	456	532
Length of compartment	13.2 [m]	15.4
Block weight	195720 [kg]	228330 [kg]
Volume compartment	195.44 [m^3]	228.0 [m^3]
Volume components	139.37 [m^3]	162.6 [m^3]
Total installed capacity	27.33 [MWh]	31.89 [MWh]
Power loss (heat loss)	13.6 [kW]	12.1 [kW]

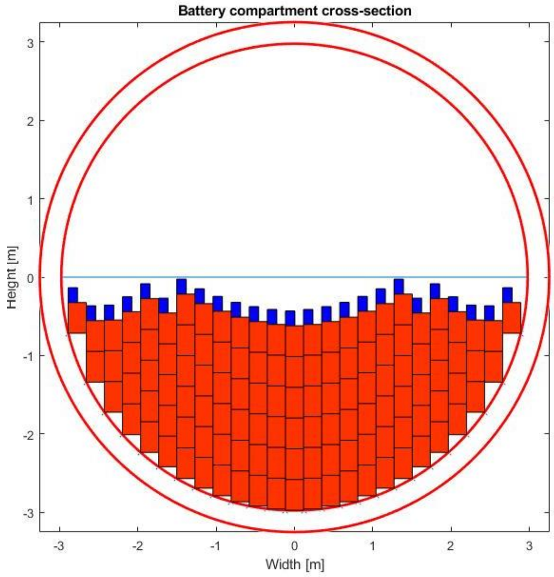

Figure 48: Cross-section of the forward battery compartment created by the design support tool.

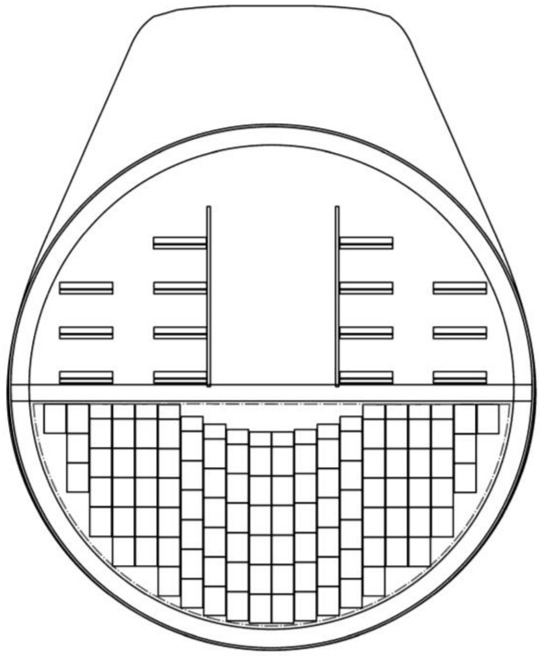

Figure 49: Cross-section of the battery compartment of the concept design [2].

Looking into the differences between the aft battery compartment generated by the design support tool and the one from the concept design, there is a volumetric difference between the components of 39%. This can be explained by the use of a different battery cell and thus different module size. The volumetric difference between the two types of battery cells is 36.2%. The other 2.8% increase can be related to the extra strings and the superfluous SCUs, compared with the manual layout in the concept design. The energy density and specific energy for both compartments are listed in Table 39.

Table 39: Energy density and specific energy for the forward and aft battery.

	Energy density [Wh/L]		**Specific energy [Wh/kg]**
	Component based	Compartment based	
Forward compartment	196.0	139.8	139.1
Aft compartment	196.1	139.9	139.7

Table 40: Difference between the battery cell used in concept design and the battery cell used for the design support tool.

	Concept design [2]	Design support tool	Difference
Height [mm]	300	327	
Length [mm]	290	462	
With [mm]	13	10.5	
Volume [m^3]	0.001131	0.001541	**36.2 %**
Weight [kg]	2.12	3.02	**42.5 %**

To see if the design support tool can derive a comparable result as the manual layout from the concept design, the tool is run with the module dimensions as used in the concept design. The module dimensions are listed in Table 41 and the results of the design support tool are illustrated in Figure 50 and listed in Table 42.

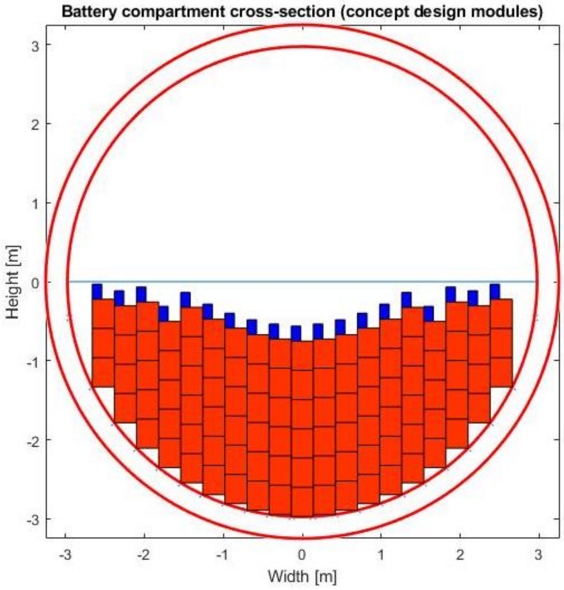

Figure 50: Cross-section of the Aft battery compartment created by the design support tool with the module dimensions from the concept design.

Table 41: Module dimensions as used in the concept design [2].

	Module
Height [mm]	360
Length [mm]	350
With [mm]	270
Weight [kg]	53.41

Table 42: Output of the battery system design support tool for the aft compartment of the concept design with the module dimensions from the concept design.

Strings in cross-section	16
Strings in length	33
Total number of strings	528
Length of compartment	11.88 [m]
Block weight	171840 [kg]
Volume compartment	175.9 [m^3]
Volume components	121.8 [m^3]
Total installed capacity	31.6 [MWh]
Power loss (Heat-loss)	11 [kW]

The energy density and the specific energy of battery compartment calculated with the design support tool for the concept design are listed in Table 43. As expected, the energy density and the specific energy are both higher with the battery cell from the concept design. Consequently the compartment size is comparable with the concept design.

Table 43: Energy density and specific energy for the aft battery compartment based on the module dimensions from the concept design.

	Energy density [Wh/L]		**Specific energy [Wh/kg]**
	Component based	Compartment based	
Aft compartment	259.8	179.9	184

The lithium-ion battery cell selected in chapter Battery system is a commercially available cell. S.A. Los used a battery cell that was available during his research, but not anymore [64]. It is assumed that the cell nowadays is only available for military applications. The battery cell manufacturer has derived comparable numbers in their research for lithium-ion battery implementation in a submarine: 223Wh/L and 132Wh/kg [11]. These numbers are lower than the results in Table 43 due to the (assumed) integrated lead for weight compensation. This is done because of the modules are designed for replacement of the lead-acid batteries in an existing submarine, which are heavier than the lithium-ion batteries. For this reason, the battery cell selected in the research of S.A. Los and the results from the battery design support tool will be used for the demonstration of the other design support tools.

13.2 Foam injection system

The Direct foam injection system design support tool is used after the output of the Battery system design support tool is derived. To demonstrate the Foam injection system design support tool, a simplification is introduced to the battery compartments of the concept design. The four compartments are not shaped and sized identically. Especially the MEM compartment is different than the other three. It has only 68 strings and is thus really small. For this reason the total number of strings (1476) is kept the same but divided over three identical battery compartments with each 492 battery strings.

An estimation has been made of the surfaces inside the compartments/rooms with higher fire risk as can be seen in Figure 47. The torpedo room is estimated to have the largest surface of approximately 70 m^2. With the input from Table 44 and the component parameters from Table 41, Figure 51 is derived.

Table 44: Input parameters direct injection system design support tool.

Length submarine	66.5 [m]
Number of decks	2
Number of battery compartments	3
Number of strings in cross-section	16
Number of strings in length of compartment	31
Percentage of free space inside battery module	10 %
Largest surface and thickness of foam for non-battery application	70 [m^2] , 0.1 [m]

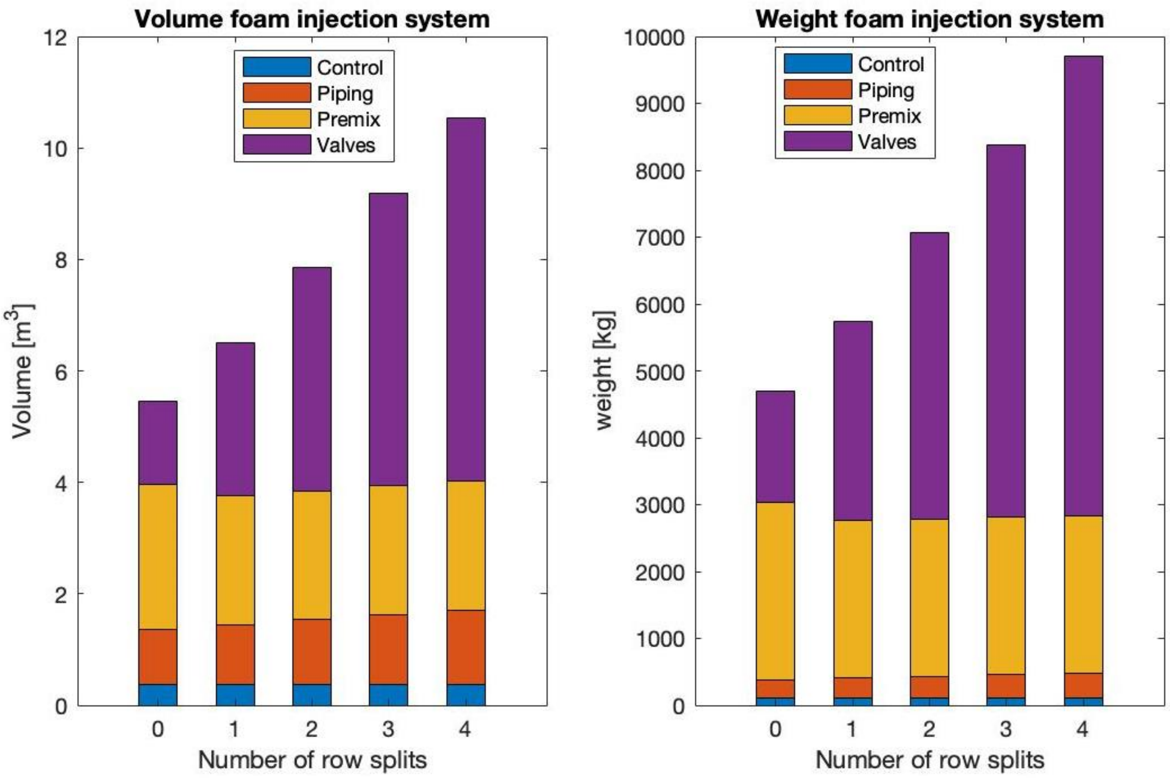

Figure 51: Output Direct injection system design support tool for the entirely battery powered submarine concept design.

Based on Figure 51, zero row splits were chosen. Without a row split the total volume and weight are the lowest. With this choice the output from the tool is displayed in Table 45.

Table 45: Output parameters Direct injection system design support tool for the entirely battery powered submarine concept design

	Volume [m^3]	**Mass [kg]**
Total premix (incl. storage bottles)	2.61	2647
Valves	1.48	1666
Pipes	1.00	279
Control	0.37	105
Total	5.45	4698
Number of premix storage units	6 (2 per battery compartment)	
Required HP air	24 [Nm^3]	

The use of pressurized air will increase the air pressure inside the battery compartment. When in an extreme case all foam is used in one compartment, 24 Nm^3 air is injected. Assuming an atmospheric pressure before the incident, the pressure will increase with 13.6%. This should not cause any problem, because the battery compartment must be able to withstand pressure changes in case of venting batteries.

13.3 Pressurized air system

With the information derived from the previous sections, the number of required pressurized air bottles, mass and volume of the storage and distribution system can be derived. In the concept design a HP air balance was already derived as described in the chapter Pressurized air system. The required HP air is added to Table 46.

Table 46: High pressure air balance for a 600 hours submerged period including the required amount of air for the Direct injection system ([2]).

Consumer	Number	Frequency	Consumption each		Total consumption [Nm^3]
Fresh water tanks	-	Cont	0.06	[Nm^3/h]	36
General users	-	Cont	1	[Nm^3/h]	600
Engine room	2	18.75 hours	10.2	[Nm^3/h]	385.2
Sewage tank	1	1 per day	9.12	[Nm^3]	228
Garbage ejector	1	1 per day	0.6	[Nm^3]	15
Blowing all MBT's	-	1	320	[Nm^3]	320
				Total	**1581.5**
Torpedo tubes	2	1	7.7	[Nm^3]	15.4
Signal ejectors	2	1	0.47	[Nm^3]	0.9
				Total	**1597.8**
Foam injection	1	1	24	[Nm^3]	24
				Total	**1621.8**

Table 47: Output pressurized air system design support tool.

Number of HP air storage bottles	7	
	Volume [m^3]	**Mass [kg]**
Storage bottles	7.7	11900
Distribution system	0.514	3800
HP air system (total)	8.214	15700

As expected, the foam injection system does not have a large impact on the required pressurized air and the number of air storage bottles.

13.4 Air quality control systems

S.A. Los has discussed a crew reduction of seven to potentially eight members. This will reduce the crew size to 27 or 26 persons [2]. M.E. Venema did a crew size analysis as well. He was able to reduce the crew size from 34 to 23 for the concept design of a fuel cell electric submarine [6]. Because this fuel cell electric submarine has more systems and is more complex than the entirely battery powered submarine, the conservative assumption that the crew can be reduced to 27 seams realistic.

For the air quality control systems a crew of 27 is used for a submerged time of 600 hours. This gives an estimation of the CO_2RS^{TM} system and chalkholders as listed in Table 48.

Table 48: Estimation of the regenerative CO_2 removing system for the concept design.

Crew size	**27**
Weight [kg]	1852
Volume [L]	3034
Energy consumption [kWh]	4620
Weight chalkholders [kg]	4482
Volume chalkholders [L]	3984

From the table it is clear that the CO_2RS^{TM} system requires less weight and volume than the chalkholders. The CO_2RS^{TM} system is based on a three Astrine^{TM} bed configuration together with a steam generator as described in the sections "Regenerative CO_2 removal" and "Regenerative or not?" The Energy consumption is estimated to be a bit lower than the 30 person configuration.

The 4620 kWh is approximately 5.2% of the total installed battery capacity. This is a significant amount and would cause a reduction of the endurance of approximately 1.3 days. Another option is to add 77 Battery strings to cope with the energy consumption of the CO_2RS^{TM} system. Adding 77 battery strings would mean an increase of 34336 kg and 18.4 m^3 of the battery system.

With a crew of 27 and a 600 hour endurance, 567 kg of Oxygen has to be provided. With storage factors of 2 kg and 1.8 liters of tank per kg of Oxygen, a LOX tank of 1200 kg and 1.1 m^3 would be more than sufficient.

13.5 Update concept design

The results from the tools in the previous sections are used to update the concept design. The new systems are added to the 3D model to see if they fit and to better understand the practical implementation.

The battery system is not changed compared with the concept design since this is implemented on a higher level of detail than the design support tool is capable of. Comparing the cross-section of the concept design and the design support tool, they come to a comparable result.

Figure 53, Figure 52 and Figure 54 show the implementation of the foam injection system. The premix storage bottles and the distribution system inside the battery compartment are good visible. In the figures they are all located on the starboard to improve their visibility in the picture. In reality they can also be located on other places inside the pressure hull.

Figure 55 presents all addressed systems. The HP air storage bottles are the same as in the concept design and are located outside the pressure hull. the LOX tank, the regenerative CO_2 removal system and the steam generator are presented in light blue. They are located in a room where 7 beds used to be. Which can be reduced due to the reduction in crew size.

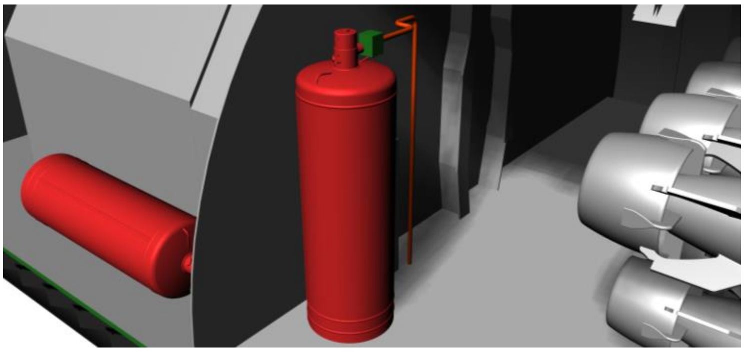

Figure 52: Premix storage bottles together with the mixing chamber implemented in the concept design.

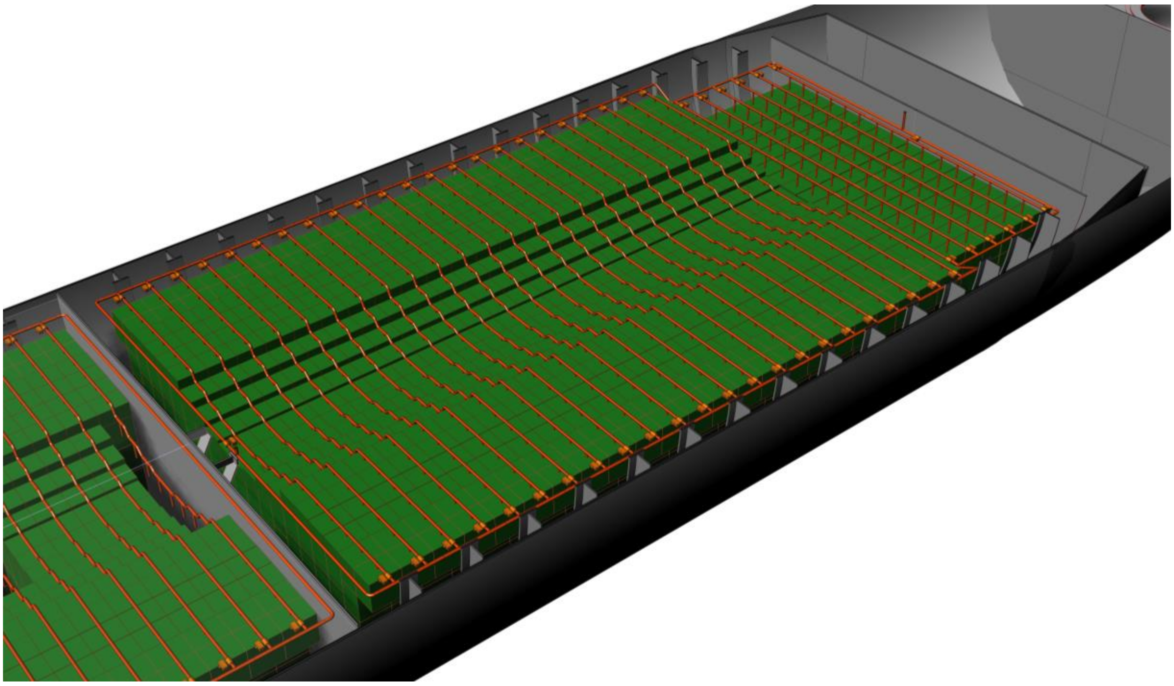

Figure 53: Battery system with the foam injection distribution system for the updated concept design. The ring distribution inside the battery compartment with the two valves per row of battery strings can clearly be seen.

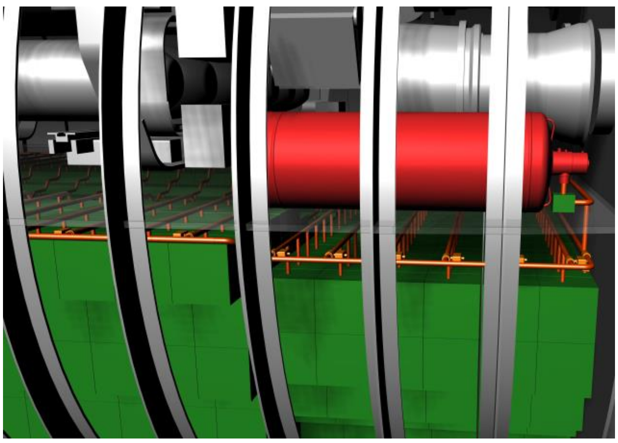

Figure 54: Premix storage bottle and part of the foam injection distribution system. The deck between the storage bottle and battery compartment is made transparent.

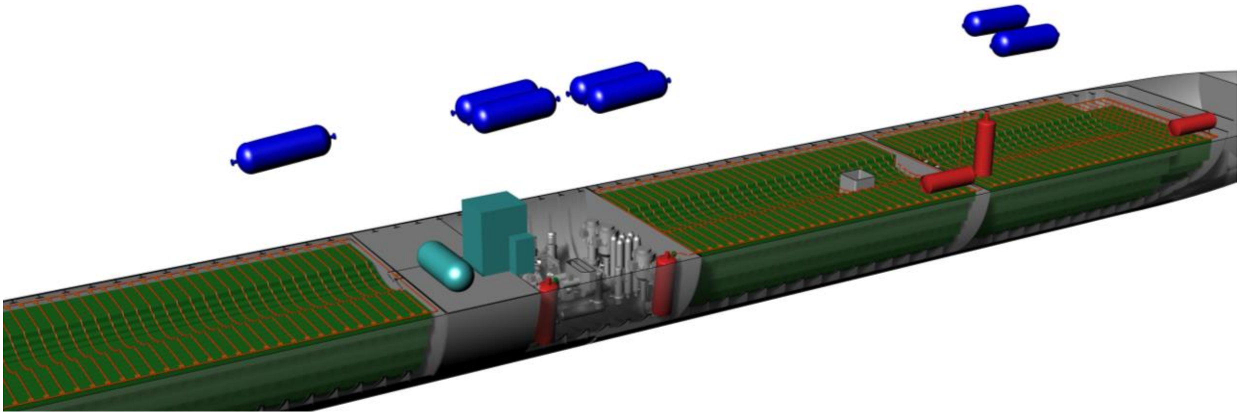

Figure 55: All addressed systems, which received an update in the concept design, are made visible.

13.6 Analysis

13.6.1 Volume

The pressurized air system has not been changed due to the implementation of the foam injection system. Consequently, the number of HP air storage bottles remained the same. The battery system was already present in the design and remains the same. For the implementation of the foam injection distribution system there was enough space available between the batteries and the deck. Also, the foam injection storage bottles could be placed in the available empty spaces. Based on volume, these systems do not have a large impact on the design. However, the implementation of the air quality systems requires the removal of seven beds, which is a large change and will have impact on other systems such as HVAC and stores. The implemented systems can be seen in Figure 58 and an overview of the volumes of these systems is provided in Table 49.

Table 49: Overview of added system volumes inside the concept design.

System	Volume [m^3]
Foam injection system	5.54
Regenerative CO_2 system	3.03
LOX tank	1.10

13.6.2 Weight

Removing a large part of the oxygen candles and chalkholders caused a reduction in weight of 7000 kg. For redundancy reasons a combined weight of approximately 700 kg of oxygen candles and chalkholders is still on board. In case of an emergency, this would be enough for approximately 3 days.

The reduction in crew and the removal of the related accommodation caused a reduction in weight of approximately 1000 kg.

All these changes are listed in Table 50 and the corresponding LCGs and VCGs are derived from the 3D model. Cumulative, these changes result in a relative small weight reduction of 248 kg at the LCG of 1.1 meter and VCG of -0.62 meter. The changes are processed in the trim and stability tool of the concept design, which resulted in a small difference. The resulting trim polygon is shown in Figure 57 next to the trim polygon of the concept design in Figure 56. The changes result in a shift of both the BG and GM of 0.001 meter. It can be concluded that the updates for the concept design do not have a significant impact on the weight, stability and trim polygon.

Table 50: Weight changes for the concept design.

	Weight [kg]	LCG [m]	VCG [m]
Foam injection system	+ 4700	48.4	2.7
LOX	+ 1200	31.3	4.1
CO_2RS^{TM} + Steam generator	+ 1852	31.3	4.1
Chalkholders + O_2 candles	- 7000	39.2	4.4
Accommodation + crew	- 1000	31.3	4.1
Total	- 248	1.10	-0.62

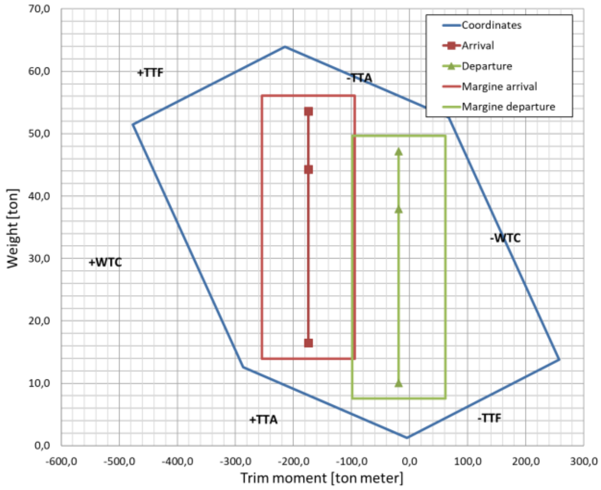

Figure 56: Trim polygon concept design [2].

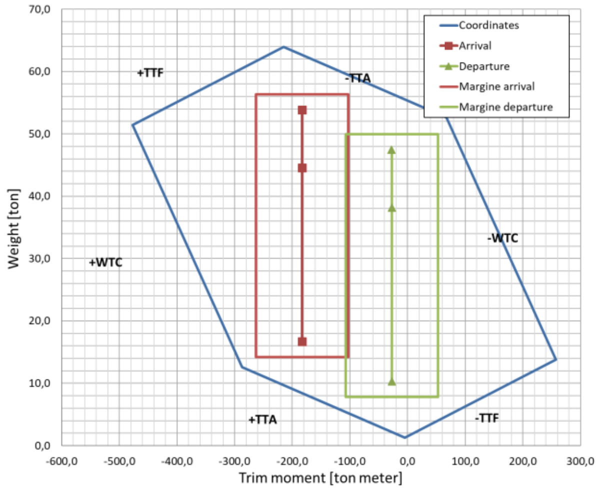

Figure 57: Trim polygon updated concept design.

13.6.3 Endurance

The regenerative CO_2 absorption system requires a significant amount of energy. For a crew of 27 and a 600 hour endurance the system will require approximately 4620 kWh, which is 5.2% of the total installed battery capacity. This could lead to a reduction of the endurance of one to two days.

13.6.4 Safety

The addition of the foam injection system has improved the safety of the entirely battery powered submarine. This system mitigates the risk and consequences of thermal runaway and can be used as firefighting medium for other consumers as well. The foam injection system provides the crew with a safer working environment.

When using chalkholders the CO_2 level in the air fluctuates due to the inconsistent filtering rate of the chalkholders. Due to the more constant filtering rate of the regenerative CO_2 absorption system, the level of CO_2 will be more consistent, which is better for the health of the crew.

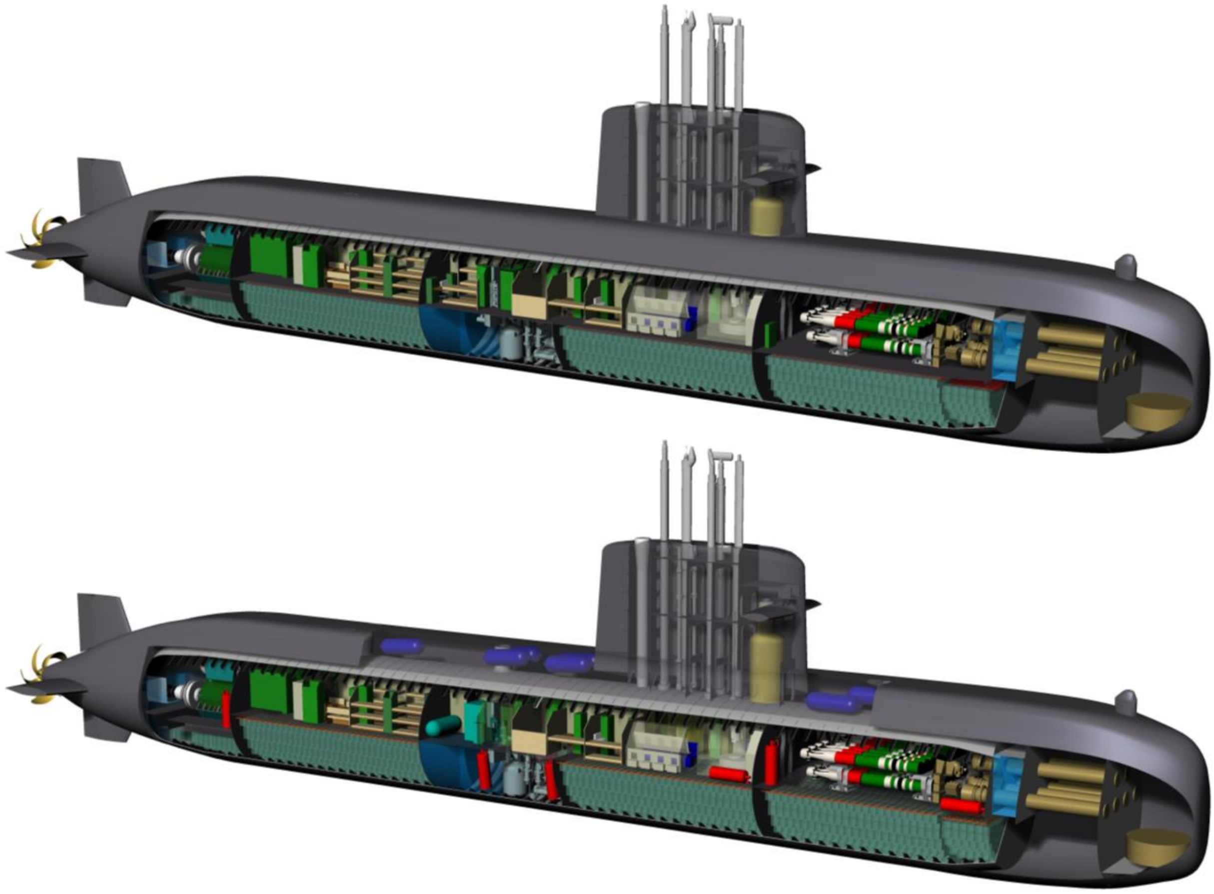

Figure 58: Upper submarine is a render of the original concept design made by S.A. Los and the lower submarine is the updated concept design with the results from the tools.

13.7 Conclusion

In this chapter a case study is performed to test the usability of the tools and to find out what the consequences are for the submarine design. The battery design support tool seems usable when compared with the manual layout and calculations done by S.A. Los. The other tools did not provide any unexplainable result either; the high pressure air storage did not change due to the implementation of the foam injection system. Furthermore, changing the input parameters, such as cell/module dimensions, HP air consumers and crew size is done easily.

The impact on the concept design is significant. The crew size is reduced by seven and also their beds have to be removed to make space for the regenerative CO_2 absorption system and the LOX tank. The safety of the submarine is improved by implementing the foam injection system to mitigate the risk on thermal runaway. Furthermore, approximately 5% of the total installed battery capacity is used by the regenerative CO_2 scrubber, which will reduce the endurance.

The concept design is already further in the design process than the design support tools are initially developed for. In the case study the fortuitous possibility to reduce the crew with seven persons, helped implementing all systems. However, if the crew could not have been reduced, it would have caused an extra challenge to fit all systems. This shows even more the usefulness of the tools. If the tools are used in an earlier stage of the design, the results could have been taken into account in the early design stage.

14 Conclusion

The objective of this thesis was "to gain knowledge about, and quantify the direct and indirect consequences for the auxiliary systems when lithium-ion batteries are implemented on a large scale in an entirely battery powered submarine. Design support tools will be developed to support the designer during the design of the battery and auxiliary systems. With these tools it should be possible to determine the main parameters of the auxiliary systems in an early stage submarine design. The end goal is to connect or integrate the separate tools. Before this is possible, design support tools for the separated systems will be developed. With the developed tools a better insight should be provided of the direct and indirect consequences of the integration of the lithium-ion batteries."

The research was divided into two parts: a literature research and the thesis. During the literature study the first half of the objective is dealt with. An inside is given into the different systems and their relations on board of a conventional diesel-electric submarine. Several submarine specific requirements were discussed like: weight, volume, energy consumption water pressure and redundancy. Together with research into the safe implementation of the lithium-ion batteries, an overview is provided of the consequences for the overall submarine design. A reduction in the number of systems, a reduction in the number of required crew members, a lower demand of cooling and an increase in required air quality systems are a few of these consequences.

During the execution phase design support tools were developed for the lithium-ion battery system, the foam injection system and the pressurized air system. Furthermore, a research into the challenges of the environmental systems and possible alternatives has been performed.

All these addressed subjects have contributed to the answering of the research- and sub- questions.

14.1 Answers to sub questions

1. What does literature say about sizing submarine auxiliary system components and the implementation of lithium-ion batteries?
   1.1. What are the relations between different auxiliary systems for conventional submarines, where have system boundaries typically been defined and can the system boundaries be similar in a battery powered submarine?

The first part of this sub question in answered in the literature research. Figure 5 and Figure 6 from the chapter Submarine systems provide a visual overview of most relations between the different systems.

It is up to the designer to determine where certain system boundaries are defined. As described, a useful method to define systems, subsystems and components is the SWBS. Based on this coded system, the systems are ordered into an organized and logical manner. It does not necessary describe the interfaces between different systems. This might be something that changes due to the choice of the designer or when different systems are used. For instance, the new foam injection system has a distribution system that reaches to the top of each battery string. At the top of the battery string the boundary of the distribution system is formulated, even though there is a small local distribution pipe inside the battery string. These small local distribution systems are part of the battery system, since this is more practical. If more convenient, the choice can also be made to include the small distribution pipe with the foam injection distribution system.

   1.2. Which auxiliary systems are needed for a safe, large-scale implementation of lithium-ion batteries in a submarine?

This sub question is answered in the chapter Knock-on effects. Due to the different type of battery, different support systems are required. With the implementation of a multi-level Battery Management

System the complete battery system is monitored and controlled to ensure safe operation and optimal performance. Included in the BMS is a short-circuit protection/switch on battery string level.

The lead-acid battery system did not have a firefighting system. The lithium-ion battery system on the other hand, requires one to cope with the risk of thermal runaway. This risk must be made as small as possible and potential damage has to be mitigated. A foam injection system developed by FiFi4Marine is designated as a promising solution for this problem. In the chapter Foam injection system a design is made for the foam injection system, including a distribution system that provides redundancy.

The maximum discharge current is expected to be relatively low due to the high number of installed battery strings and thus high amount of capacity. Extreme heat-loss is thus avoided and an additional cooling system will probably not be required as a safety system. However, controlling the battery temperature can improve the performance, but will reduce the specific energy of the battery system and will increase the complexity of the system. If possible, a battery system without temperature control would be favorable.

The battery compartments must be gastight, to prevent toxic gases to enter the manned spaces. A local ventilation system is required to prevent the buildup of toxic or explosive gasses. When surfaced, these gasses should be vented outside.

1.3. Based on the criteria for weight, volume, energy consumption and importance for the safe implementation of the battery system, which auxiliary systems will be selected for implementation into the design support tools? Are there other alternatives in the industry to replace the component/system with?

At the end of the literature study, in chapter System selection, a selection has been made of the systems that would be discussed further during the execution phase of this research. The selected systems were:

- Battery system
- Firefighting system
- HVAC
- Chilled water system and seawater cooling system
- Air quality
- Hydraulic system
- Pressurized air system

During the execution phase of the research not all of the mentioned systems were addressed. The Chilled water system, seawater cooling system and hydraulic system are not discussed because some of the other systems required more time than expected.

The battery system consists of a new type of batteries compared with the diesel-electric reference design. The lithium-ion batteries require other safety systems such as a new firefighting system: the foam injection system. In case of the pressurized air system, the components have not been changed. It is considered to remove the compressor; however, it is concluded that this would not be favorable due to practical reasons. The environmental control systems (HVAC and air quality systems) form a complex integral. Due to the different capabilities, such as improved endurance, the requirements of these systems change. Ensuring healthy CO_2 and O_2 levels in the air become more challenging when the submarine does not surface anymore. New types of systems have been reviewed to replace the existing chalkholders and oxygen candles. A regenerative CO_2 scrubber and LOX tank might be feasible solutions. The most important disadvantage of the regenerative CO_2 scrubber would be its relatively high energy consumption.

2. What is a suitable method of modeling the systems and their components? What will be the input parameters for the designer support tools?

Before the systems were modeled, a design of each system was made. The size of the design depends on the input parameters. The size of the design specifies the number of components required. For both the battery system and the foam injection system the main parameters of each component are input for the design support tools. Adding all required components for a system provides the size, weight and energy consumption.

The pressurized air system consists of an existing design, where the number of HP air storage bottles are determined by the HP air consumers. Furthermore, the HP air distribution system is estimated based on a trend analysis that uses the length of the submarine and the division between pipes and appendages.

The environmental control systems are not implemented in a design support tool. Nevertheless, new types of systems have been studied to replace the chalkholders and oxygen candles. Several estimation have been made about the size, weight and energy consumption of these systems and they are compared with the chalkholders and oxygen candles.

3. How do the auxiliary systems scale, when changing the input values? (Sensitivity analysis)

For each addressed system during the second part of this report, a sensitivity study has been performed.

The battery system design support tool shows there is an optimum in specific volume between the battery module size and the radius of the pressure hull. Furthermore, the length of the battery compartment can be determined based on the required capacity or the installed capacity can be calculated based on the size of the battery compartment.

The foam injection system is sized based on the amount, size of the battery compartments and the required foam for other non-battery related consumers. The system can be optimized by varying the number of row splits. Adding a split requires less foam for the battery, but requires an additional number of valves.

The number of required HP air storage bottles depends on the consumers on board of the submarine and the duration of the mission. Adding the foam injection system as a consumer did not have a significant impact on the total HP air consumption. One of the larger consumers is the blow out of the MBTs. The number of blow outs the system has to perform, has a large impact on the total HP air consumption and thus the number of HP air storage bottles. This was one of the reasons why it is recommended to install a HP air compressor on board to refill the HP air bottles after a blow out is performed. The HP air distribution system is based on an existing distribution system and is sized linearly with the length of the submarine and the division between pipes and appendages.

4. What are the consequences and knock-on, i.e. secondary, effects on auxiliary systems of implementing lithium-ion batteries, removing the diesel generator sets and the auxiliary systems for the diesel generator sets?

Removing, changing and adding systems has consequences on the weight of the submarine. The VCG and LCG will most likely change, and less compensation is required due to the absence of diesel oil as a consumable. These changes have to be taken into account during the design process.

A reduction in the number of systems on board of an entirely battery powered submarine reduces the number of crew that is required. Both will cause a reduction in the heat load of the total submarine. If this is indeed the case, less installed cooling capacity is required. Even though the number of crew is reduced, the increased endurance means that the air quality has to be controlled for a longer duration. For a three-week duration, chalkholders and Oxygen candles require a lot of space and weight. A regenerative CO_2 scrubber, such as the CO_2RS^{TM} from airbus, might be a solution for this problem. The downside of these regenerative systems is that they consume power and thus lower the endurance. Also, part of the environmental control systems is the equalizing ventilation. Without the diesel-generators there is the need for a different air inlet system.

The implementation of the lithium-ion batteries requires the installation of a foam injection system. This system mitigates the risk on thermal runaway and therefore increases the safety of the submarine. For the generation of the foam, pressurized air is required. An example showed that the amount of pressurized air required for the foam injection system is minimal compared with the other consumers. The addition of this system does not lead to a larger pressurized air storage.

14.2 Answer to the main research question

- How can a designer be supported, in an early design stage of an entirely lithium-ion battery powered submarine, when trying to determine the size, weight and energy consumption of systems that, among others, support the safe implementation of the new batteries?

Design support tools have been developed to support the designer during an early design phase of an entirely battery powered submarine. The tools estimate the main parameters of the battery-, foam injection- and pressurized air system. Weight, volume, heat load and energy consumption are estimated based on system designs and input parameters. The study into the environmental system has shown that the implementation of a regenerative CO_2 absorption system requires space and energy.

Besides supporting the designer with defining the main system parameters, the battery- and foam injection- system design support tools help optimizing the size and weight of the system. For the battery system the maximum specific volume can be found by changing the width-height ratio of the battery modules. Furthermore, the minimum weight and volume of the foam injection system can be estimated based on the number of row splits of the foam distribution system.

The case study has shown that the consequences for the concept design were significant. The implementation of the foam injection system made the submarine safer and the implementation of the regenerative CO_2 absorption system and LOX tank required the number of crew members to be reduced with seven. Furthermore, for a crew of 27 and a mission profile of 600 hours, the CO_2 scrubber would require more than 5% of the total installed battery capacity, which will cause a reduction in the endurance. If these results were available earlier in the design process, the concept design would not have been required to be changed drastically. Therefore, this shows the importance of including the results from the tools in the design as early as possible.

15 Recommendation

This chapter discusses some subjects for further research. The recommendations include subjects that were not included in this report due to insufficient time or subjects that are assumed to add value to the performed research.

15.1 Adding more design support tools

A selection of interesting auxiliary systems is placed at the end of the literature study to include in the thesis part of this research. Due to insufficient time the chilled water- and seawater cooling- system and the hydraulic system are not implemented into a design support tool. Future research could continue with the development of the separated design support tools.

During this research the challenges of the environmental control systems and some alternatives systems are mentioned. Further research into these subjects could be beneficial. Creating one large design support tool for the environmental control systems (including a regenerative CO_2 absorption system) can help the designer determine the main parameters in an early design stage of this complex system. It could also be interesting to see how the regenerative CO_2 absorption system can be made more efficient, for instance by using heat exchangers to use waste heat from the cooling water systems.

Furthermore, additional systems outside of the selection or auxiliary group could be interesting to implement into a design support tool to support a designer with the high level design of other systems.

15.2 Integration of all separate tools

In chapter Introduction an end goal is described as integrating the design support tools into one larger design support tool. Future research could look into the advantages for the designer of such overall design support tool. It might also be interesting to investigate the added value of integrating the design support tools with the first principle propulsion model developed by L.P.W. Rietveld and M. ten Hacken.

15.3 Influence of submarine specific requirements

In this research the submarine specific requirements are only briefly taken into account during the high level system design. To increase the level of detail and to make the tools more accurate, more research could be done into the submarine specific requirements and how they should be addressed in an early stage design support tool.

For instance, the shock requirements imply that certain systems have to be able to withstand certain shocks. There are different types of shock requirements for different locations inside the submarine and for different types of systems. Furthermore, there are multiple solutions to satisfy these shock requirements. It could be interesting to see what the impacts are on the different systems based on the location inside the submarine and the type of solution that is chosen.

15.4 Different type of battery

Currently other types of batteries are under development such as lithium-sulfur and solid state lithium-ion batteries, but it will probably take years before they are available [65] [66] [67] [68] [69] [70]. These batteries have better characteristics than the available lithium-ion batteries. If these new types of batteries become available for commercial or military use, it could lead to large improvements of the capabilities of an entirely battery powered submarine. Keeping track of the developments of these batteries might be beneficial in the future.

15.5 Relevance of the currently installed systems

The entirely battery powered submarine concept design provides a suitable starting point to look more critical at the currently installed systems, with the objective to make the submarine less complex, less energy consuming, easier to operate and to make it require less maintenance.

Systems that require a critical review are for instance the pressurized air system and the hydraulic system. The hydraulic system is mainly used to operate the rudders, periscopes, snort masts and some valves and actuators. The system has to be pressurized regularly, which makes noise and requires power. For some consumers it might be possible to be operated electrically instead of hydraulically. This provides the advantage of a less complex and smaller hydraulic system, which makes less noise. Furthermore, direct electrically powered consumers are probably more efficient because mechanical losses are avoided. In an extreme case, the possibility to remove the entire hydraulic system could be considered.

The same can be done with the pressurized air system. Energy losses can be reduced when consumers are electrically powered instead of using pressurized air. Furthermore, a reduction in consumers could mean a reduction in the number of storage bottles. Besides that, a side effect of using pressurized air inside the pressure hull is the increase in the ambient air pressure, which is unfavorable for the wellbeing of the crew. For the long endurance of an entirely battery powered submarine this would imply a large increase of the ambient air pressure. If some of the continuous users are switched to electrically actuated and also a compressor is be used to extract air from the atmosphere, this pressure increase can partly be avoided.

Another way to look at systems could be to start from zero. A completely new entirely battery powered submarine design where every system is designed from scratch, instead of using a diesel-electric reference design. This forces the designer/researcher to look into the usefulness and the implementation of all systems more critically. This could result in a system reduction or a simplification of the submarine design.

16 Discussion

This chapter discusses the usefulness and added value of the design support tools, if they are useful for other types of submarines and what the relevance of this research is.

16.1 Usefulness

Submarine design is a long and complex process in which small changes may cause a cascading reaction. The more information is available in an early design stage, fewer changes have to be made in a later stage. In the chapter Demonstration design support tools, the results proved that the tools provided useful information and that acquiring this in an earlier stage would have led to less drastic changes to the concept design.

Even though the foam injection system did fit into the concept design, this would not necessarily be the case. Because a submarine is volume critical, it will often be the case that there is not enough space to add a system in a later stage. Therefore, having as much information as possible from the start, will help the design process.

The designer can use the developed tools to see how the system changes when different input parameters are provided. For instance, choosing a different battery cell has a large impact on the total battery system. Which on its turn might change the required amount of premix and thus the size and weight of the foam injection system. The designer can use the tools to find the optimal configuration for its needs.

16.2 Different type of submarine

The tool is developed for an entirely battery powered submarine. An interesting question is if they are also useful for estimating system parameters for other types of submarines. A battery fuel cell powered submarine has a longer endurance and range than the entirely battery powered submarine [6]. In case this type of submarine uses lithium-ion batteries, the battery design support tool can be used for the battery design. The hypothesis is that the battery fuel cell design requires fewer batteries, but the battery system design will remain the same. For this battery system the foam injection tool can be used to estimate the required premix for the battery. However, additional research has to be done into the usability of the foam for the fuel cell. Furthermore, the impact of the fuel cell on the required premix storage and distribution system should be investigated as well. The pressurized air system design support tool can still be used for this other type of submarine as long as the consumers and the duration of the mission profile is known.

Regarding the environmental systems, the battery fuel cell powered submarine uses LOX as one of the fuels. This is convenient because, in this case the LOX tank can be used as fuel for the fuel cell and to supply oxygen for the crew. The regenerative CO_2 absorption system can use potable water from the fuel cell [6]. Furthermore, using the waste heat from the fuel cell to improve the efficiency of the steam generator might be a promising solution to improve the efficiency of the regenerative CO_2 absorption system.

For other types of submarines, such as conventional diesel-electric or diesel-electric with AIP, the battery system design support tool can be used as well. Just as for the battery fuel cell powered submarine, the foam injection tool can be used to calculate the required premix for the battery. However, the required foam for other systems has to be looked at as well. Regarding the environmental systems, for a conventional diesel-electric submarine the regenerative CO_2 absorption system might not be the suitable solution. The diesel-electric submarine has to snort to recharge the batteries and can refresh the air at the same time. Chalkholders and oxygen candles might still be the preferred choices for this type of submarine. In case of a diesel-electric submarine with AIP system, snorting is not always required and rest-heat from the AIP system might increase efficiency of the regenerative CO_2 absorption system.

16.3 Relevance of the research

This section discusses the scientific-, industrial-, and societal relevance of this research.

16.3.1 Scientific

Scientific relevance means that the research should fill a gap between the existing knowledge and that it should be relevant for other scientists.

The longer submerged periods of time will have consequences for the environmental systems. One of the recommendations in the research of M. ten Hacken is to look at the HVAC system more extensively [5].

L.P.W. Rietveld recommend in his research a more extensive look at the safety aspects of the lithium-ion battery technology [4]. Further, a more precise look at the packing factors of the battery system and the auxiliary systems necessary for the implementation of the battery system should be performed.

Similarly, S.A. Los recommended a closer look at the safety systems for a lithium-ion battery pack as well as the air quality inside the submarine [2].

In this research the safe implementation of lithium-ion batteries is discussed and suitable thermal runaway mitigation system is found. Therefore, the safety of the entirely battery powered submarine design is improved. Also, the packing factors are reviewed, which remain the same as assumed by L.P.W. Rietveld. Furthermore, the challenges of the HVAC and air quality systems are discussed and alternative systems are proposed for the chalkholders and oxygen candles.

Lithium-ion batteries are currently a hot topic in the submarine industry [11] [12] [37]. Scaling-up lithium-ion batteries/battery packs are useful for not only submarines but also for other industries; for instance civil ships [10] or the car industry [71].

16.3.2 Industrial

The industrial or practical relevance empathizes the relevance for the company/industry. Developing a tool that can size auxiliary systems in an early design stage helps a company improving the design process. When the systems are sized more precise during an early design stage, the risk of large deviations in later stages is smaller. This can result in a cost and time reduction of the design process.

With the researches done by Nevesbu in collaboration with the TU Delft, the company tries to improve the design process and the knowledge [2] [4] [5] [6]. This research has contributed to that.

Additionally, other companies are also investing in research on the topics of lithium-ion batteries and the safe implementation of large-scale lithium-ion batty packs [72] [73] [74] [75]. Moreover, it is claimed that a Japanese submarine has lithium-ion batteries implemented already [76].

16.3.3 Societal

This research is societal relevant because of:

- The costs reduction for the customer. The customer is in most cases a government that pays the project from tax money. So, the developed tools indirectly help reducing the societal cost of the submarine.
- This research has improved the safety of the lithium-ion battery implementation. This is beneficial for the marines that have to sail the platform.
- It might not be the main reason to choose an entirely battery powered submarine, but the submarine does not have any emissions. This has a positive effect on the environment and this research provides a step closer to the realization of such submarine.
- The research done for the implementation of lithium-ion batteries might also be used for other transportation platforms. Making transport safer and more sustainable.
- An entirely battery powered submarine is especially deployable near its home base. This makes the submarine good for coastal defense and less useful for operation far from its own country. This is ethically more justified than a submarine that is able to attack and operate far from its home base.

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18 Appendix

18.1 Battery design support tool basic script (CONFIDENTIAL)

18.2 Foam injection system design support tool script (CONFIDENTIAL)

18.3 Pressurized air system design support tool script (CONFIDENTIAL)