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Solutions for large batteries for waterborne transport

GRANT AGREEMENT No. 963560

D2.2 – Key Performance Indicators (KPI) List

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Project Abstract

The goal of the SEABAT project is to develop a full-electric maritime hybrid battery concept that is based on:

- Modularly combining high-energy batteries and high-power batteries,
- novel converter concepts and
- production technology solutions derived from the automotive sector.

The modular approach will reduce component costs (battery cells, convertors) so that unique ship designs can profit from economies of scale by using standardised low-cost components. The concept will be suitable for ships requiring up to 1 MWh of storage or more.

Public summary

The main goal for the SEABAT project is the development of a HESS for large marine applications. To understand the required performance of the product under development it is important to know how the marine battery systems currently on the market perform. This deliverable describes the analysis of the performance of 30 marine battery systems from 15 different suppliers.

The battery systems are analyzed based on 9 different parameters: costs, energy, power, lifetime, thermal management, safety, mechanical integration, electrical integration and the battery management system. In total 33 different battery properties are used to determine the overall score of the battery systems. Although not all information from all battery systems was available, the large number of inputs is assumed to be sufficient to make the effect of the missing data minimal.

The performance on each of the 33 battery properties is compared for all the 30 battery systems. Based on their performance compared to each other a rating system is developed. The performances are divided in 5 scoring ranges where each battery system can score between 1 and 5 points, where 1 point is the lowest score and 5 points is the highest score.

Finally, all the scores on all 33 battery properties are combined and divided by the amount of datapoints that were available for each battery system to result in a final overall score for each battery system. The average score of all battery systems together is 3.0. The lowest scoring battery system has an overall performance of 2.3. The highest scoring battery system has an overall performance of 3.6. Then a multiplying factor is given to individual categories to determine what type of battery systems perform best on the different aspects and what their strong points and their weak points are.

The conclusions describe the main performance indicators of the different types of battery systems. There are 6 different types of batteries defined: High energy, High energy (Heavy duty), Medium energy, Medium energy (Heavy duty), High power and High power (Heavy duty). Where High energy, Medium energy and High power is determined by the maximum continuous C-rates of the battery system and the Heavy duty is determined by the costs per cycled kWh.

Four different types of battery system designs are defined: modules, trays, racks and blocks. In the recommendations it is described which type of battery system design is preferred for the HESS development, where the focus points should be for the different system designs and what the performance of the HESS should be on the individual battery properties to develop a competitive battery system in the current market.

Contents

1 Introduction

In SEABAT Deliverable 1.3 [1] a first overview of battery system KPI's is provided showing the current level of performance and the goals for 2035. The discussed KPI's were:

- Cell to system weight ratio
- Cell to system volume ratio
- Operating lifetime expectation
- System costs in €/kWh
- Gravimetric energy density in Wh/kg
- Volumetric energy density in Wh/L
- Cycle life
- Hazard level

This document continues with the KPI analysis. A further investigation of the battery properties which are required for analyzing battery system performance and design describes the battery system in depth. The properties are divided in 9 main categories, each with several subcategories to determine the performance from different aspects. The 9 main categories are:

- Costs
- Energy
- Power
- Lifetime
- Thermal management
- Safety
- Mechanical integration
- Electrical integration
- Battery Management System

Information from 30 different, marine type approved, battery systems which are currently available on the market is used as input for this analysis. For each subcategory it is investigated how the battery systems are currently performing and based on this performance a distribution is determined to assign a score from 1 to 5. The combined score of all subcategories is then evaluated to rate the overall performance of the battery systems. Additionally, the performance of different system designs is analyzed to assist in taking design decisions in the continuation of the SEABAT project in WP 3. Finally this method is used to develop a rating system which can be used to compare different design options on multiple aspects.

1.1 KPI analysis

1.1.1 Methodology

The KPI analysis consists of four steps:

1. Identify the battery properties that are used to determine the performance of a battery system
2. Analyze existing marine battery systems based on each property
3. Determine a rating system based on the score of a battery system on a specific property
4. Develop a methodology to calculate the performance of a battery system based on the requirements of different vessel types

The developed methodology to calculate the performance of a battery system can be used to make certain design choices in work package 3.

1.1.2 Rating system

Each battery property will be divided in ranges to provide a scoring possibility from 1 to 5, where 1 will be the lowest and worst score and 5 will be the highest and best score.

Battery property		
Score	**Range**	
1	< a	(Worst score)
2	a-b	
3	b-c	
4	c-d	
5	> d	(Best score)

Table 1 Example of rating system for battery performance

1.2 Document structure

Chapter 2 describes the battery properties which are used to indicate the performance.

Chapter 3 describes the performance of current marine battery systems on their properties from chapter 2. The performance of the current marine battery systems is used to determine the rating system for each property.

Chapter 4 describes the methodology for calculating the performance of a battery system based on the requirements regarding costs, energy, power, lifetime and safety.

Chapter 5 describes the conclusions of the results and the recommendations for continuation of the work in the SEABAT project.

2 Battery properties

First the different types of battery systems designs are discussed. Then this chapter provides a summary of the 9 categories and their subcategories of battery properties which are used to determine the performance of the marine battery systems currently on the market.

2.1 Battery system designs

There are 4 main types of battery system designs identified: modules, trays, racks and blocks.

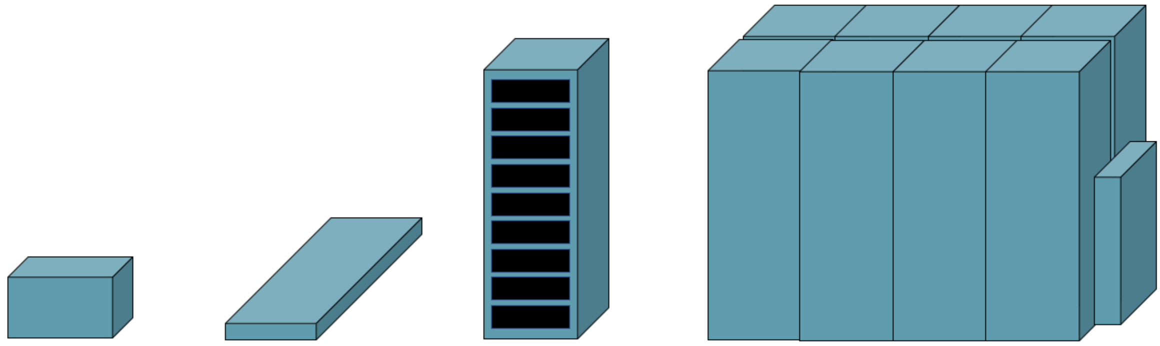

Figure 1 Different types of battery system design

Modules
The module based systems have modules which can be placed individually from each other and do not require a fixed racking system. Each module often has a certain output voltage, the system voltage can be varied by connecting multiple modules in series. Module based systems are in general flexible considering installation in relatively small battery spaces or on smaller types of vessels. Some module based systems also have the possibility of a racked option.

Trays
Tray based systems are mainly seen in the automotive industry. Most of the marine tray based systems come from the automotive industry originally and have been marinized to receive a marine type approval. A tray based system usually comes with a standard output voltage and they are not designed to be connected in series with each other.

Racks
Rack based systems have predefined racking solutions for their battery modules. Each rack can be placed individually in a battery space. In most racking systems the additional safety measures and cooling systems are integrated. Rack based systems can have some level of flexibility in their design, but are mainly bound to specific standard sizes.

Blocks
Block based systems are designed to reduce the required service space as a benefit for larger types of vessels. These types of systems usually are completely outfitted systems which makes it easy to integrate them on board of a vessel, but only if there is enough space available. Some block based systems consist of multiple racks combined, but in contrary to the rack based systems, these racks can't be placed in a battery space individually.

2.2 Costs

The battery system costs are analyzed from two perspectives: system costs and cycle costs.

The system costs are costs for the basic battery system without taking into account the costs for installing it on board of a vessel. The system costs are usually expressed in €/kWh.

The cycle costs take into account the expected lifetime of the batteries. The system costs are divided by the total expected energy throughput in kWh, calculated by the estimated number of cycles at 80% DoD. This will also result in a €/kWh price, but then per cycled kWh instead of installed kWh..

2.3 Energy

The energy density of the battery systems is divided in four subcategories. The gravimetric energy density is determined in Wh/kg to determine the energy per installed weight. The volumetric energy density is determined in Wh/L to determine the energy per installed volume.

The energy density is determined based only on the battery system itself and not on auxiliary equipment. Therefore also the volumetric energy density is determined without taking into account the required service space around the battery system. This will be separately evaluated in the chapter on mechanical integration.

The third subcategory is the cell to module weight ratio. This shows the ratio between the weight of a module and the weight of all the cells inside the module combined. This provides information about the efficiency of the design of the module considering weight.

The fourth subcategory is the cell to module volume ratio. This shows the ratio between the volume of a module and the volume of all the cells inside the module combined. This provides information about the efficiency of the design of the module considering volume.

2.4 Power

The performance based on discharge and charge power of the battery systems is determined by four subcategories.

The specific power of a battery system is expressed in a gravimetric specific power [W/kg] and a volumetric specific power [W/L]. The specific power is determined based only on the battery system itself and not on auxiliary equipment. Therefore also the volumetric specific power is determined without taking into account the required service space around the battery system. This will be separately evaluated in the chapter on mechanical integration.

Besides the specific power the power capabilities of the battery systems are also evaluated based on their maximum continuous discharge and charge C-rates.

2.5 Lifetime

Battery lifetime is determined by the cycle lifetime and calendar lifetime and depends on multiple factors such as the temperature, C-rates, SoC, the number of performed cycles and the DoD of the performed cycles. Often the expected cycle life of a battery cell is provided at a temperature of 25°C and an 80% DoD. This can be used as a reference for the cycling capabilities of different battery cells and systems and is therefore used as one of the two subcategories for rating the lifetime of a battery.

The second subcategory is the maximum design life of the battery systems. The suppliers of the analyzed battery has been asked what maximum design life is possible with their battery system considering a very light use of the batteries. As example for a very light use of the batteries one 50% DoD cycle per month is considered.

2.6 Thermal management

The thermal management of a battery system can be an air cooled system or a liquid cooled system. The performance of these systems is determined based on two subcategories the heat rejection at a 1C discharge and the required inlet temperature of the cooling medium. This approach was selected to determine the performance of the thermal management independently of the type of cooling system, air cooled or liquid cooled.

2.7 Safety

The safety of the battery systems is evaluated based on five different subcategories which can mainly be related to the event of a thermal runaway and fire fighting in the battery space.
At first the cell chemistry is evaluated for its thermal stability and sensitivity to thermal runaways. Secondly the thermal runaway propagation measures are compared, as a thermal runaway can be contained per cell or per module, resulting in different amounts of gas and heat being release. The amount of gas in liters that is released in case of a thermal runaway is the third subcategory and the method of ventilation required in the battery space to get rid of the released gases is the fourth subcategory. The final subcategory is the IP rating of the battery system, which has an effect on the type of firefighting system which can be installed in the battery space.
A final safety score is calculated because not all information for the different subcategories was available for all battery systems.

2.8 Mechanical integration

The mechanical integration of battery systems is evaluated based on three different subcategories to determine the flexibility of the battery system design. A high flexibility for mechanical integration results in a battery system that can be adjusted to fit easily on different types of vessels with different types of battery space dimensions and shape factors.

The flexibility is therefore expressed in the size of the building blocks of the battery system as small dimensions allow for larger flexibility. The volume in L is used for this flexibility and not the weight because lifting of heavy equipment is a very common practice for shipyards and is not considered as a challenge in most situations.

The ability of a battery system to optimize the usage of the available height in a battery space is an important aspect of this. The more of the height of a battery space can be filled by the battery system, the higher energy density of the battery system per volume of the battery space.

The required service space compared to the required floor surface of a battery system is an additional factor in the optimization of the energy density of a battery space.

The three subcategories are combined into an overall score for mechanical integration.

2.9 Electrical integration

The electrical integration of a battery system onboard a vessel can have two different approaches. The batteries can be connected through a DC/DC converter to a DC-bus with a fixed voltage (fixed bus), or the batteries can be connected directly to a DC-bus with a floating voltage which follows the voltage of the battery system (floating bus). The fixed bus and floating bus have different voltage requirements that need to be considered. The requirements for electrical integration as described here are based on common practices of the partners in the SEABAT project with experience in shipbuilding and designing battery powered vessels.

Floating bus

The voltage requirements of a floating bus are determined by the equipment for propulsion and power distribution that is connected to the DC-bus. These voltage requirements can vary significantly for different types of vessels and therefore the voltage requirements for the battery system also changes. For a flexible integration of a battery system to a floating bus it is beneficial if the voltage level of the battery system is flexible and can be adjusted to be as high as possible within the limits of the equipment connected to the DC-bus, as a high voltage results in lower currents.

The electrical integration of battery systems is evaluated by the flexibility of the battery system to adjust the voltage of the battery systems to the requirements of the vessel. This is firstly done by determining the maximum possible nominal voltage. Secondly the minimum and maximum possible system voltage, so the voltage range. Thirdly the voltage steps are determined. A voltage step is the voltage at which the system voltage can be adjusted by adding less or more battery cells or modules in series.

Fixed bus

There are currently two most common voltage requirements for fixed bus systems. To supply a 400Vac grid a 700 Vdc DC-bus is selected. To supply a 690 Vac grid a 1000 Vdc DC-bus is selected. The selection for a 700 Vdc or 1000 Vdc bus is based on the required power or maximum current of the combined consumers on the bus. A common guideline is that if the largest consumer on the bus is larger than 300 kW, or if the maximum current of all consumers on the bus combined is larger than 5000 A, then a 1000 Vdc bus is required. For a largest consumer below 300 kW or a total maximum current below 5000 A, a 700 Vdc bus is preferred. There are no common standards on the normal service steady state voltage range yet, but as an initial guideline a voltage range of +/- 7% is assumed to result in full functionality of the system. The difference between the percentage of the maximum voltage compared to the nominal voltage and the percentage of the nominal voltage and the minimum voltage are considered important to this aspect. A larger difference in voltage between 100% SOC and 0% SOC requires a larger power converter.

Because a fixed bus only has the requirements for a 700 Vdc and 1000 Vdc bus the flexibility of the output voltage as described for the floating bus is not relevant. However, for a battery system to be optimized for both a floating and a fixed bus system this flexibility of output voltage is still considered as a relevant aspect of the performance of the battery system.

From an installation and safety perspective it is also determined how many physical power connections are required per installed kWh. Having less power connections increases the ease of installation as well as the safety of the person performing the installation. Every connection that has to be made is a possible risk during the installation where human errors can be made.

2.10 Battery Management System (BMS)

The performance of the BMS is analyzed based on the architecture, the cell balancing and the integrated sensors. It is important to describe what is considered as the BMS for this section. In Figure 2 you see the overview of the different levels of what is considered as the BMS. The exact location of the functionalities as shown here can vary depending on the design of the battery system. Also additional functionalities can be added to a BMS. In this document the BMS is considered as all control and monitoring systems of the batteries at module level, string level and system level combined. In practice this are often separate and individual systems.

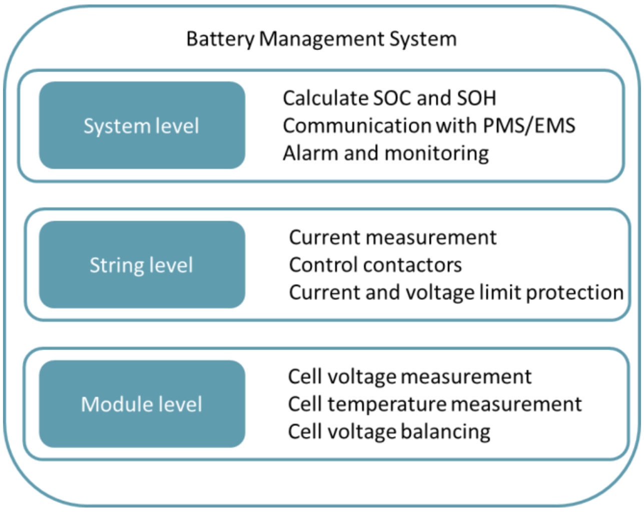

Figure 2 Schematic overview of BMS levels and functionality

Architecture

The architecture of the battery management system is analyzed based on the number of strings that can be connected in parallel to one BMS at system level. At system level the BMS has to communicate with the Power Management System (PMS), Energy Management System (EMS) and Alarm, Monitoring and Control System (AMCS) of the vessel. When installing a relatively large battery system, with a significant number of strings in parallel, the number of strings which can be connected in parallel on communication and control level reduces the efforts of integrating the battery system with the other related systems on board by having a smaller number of connections between different types of systems from different suppliers.

Besides the number of strings that can be communicated with in parallel at system level, the power consumption of the BMS is compared to make a comparison in efficiency in control of the battery system.

Redundancy is an important topic when it comes to safety of marine battery systems. Therefore it is often required to have a build in redundancy function in the BMS at system level. In case of a failure the BMS should be able to continue to operate without the vessel losing power.

Cell balancing

The voltage of the battery cells in a battery system is constantly changing according to the charging or discharging of the batteries. Although the voltage of the individual cells will remain more or less equal, there will always be a slight difference in the cell with the lowest voltage and the cell with the highest voltage. When this difference becomes to big it can affect the lifetime of the batteries and the cells with a lower voltage will tend to age faster. This will result in an uneven aging of the battery cells and a reduction of the overall lifetime of the battery system. Therefore it is important to keep te cell voltage levelled as much as possible between all the cells and this requires cell balancing.

There are 2 types of cell balancing considered: passive and active balancing. Passive balancing is when energy from a cell with a higher voltage is dissipated by a resistor to lower the voltage to an equal level as the cells with a lower voltage. Active balancing is when energy from a cell with a higher voltage is transferred to a cell with a lower voltage. Active balancing results in a more efficient battery system as no energy is dissipated compared to passive balancing. The balancing of cells will have to start automatically or the process has to be started manually by the crew of the vessel, but will be started based on a minimum difference in lowest and highest cell voltage. The lower this difference in cell voltage is, the higher the accuracy of the cell balance. The time required by the battery system for balancing all cells is determined by the balancing current. A larger current results in faster balancing of the battery cells. However, this also depends on the cell capacity, which is why the balancing current is determined based on mA/Ah, balancing current per Ah of cell capacity.

Sensors

The BMS consists of monitoring and control of the batteries. The monitoring is done based on different types of sensors inside the battery modules. The most important sensors monitoring the state and safety of the battery cells are voltage sensors and temperature sensors. The higher the number of voltage and temperature sensors per battery cell, the higher the monitoring accuracy of the battery system.

For most marine battery systems it is required to have gas detection sensors inside the battery space. In case of a thermal runaway the released gases can be detected to activate a ventilation system. Some battery systems already have an integrated thermal runaway gas detection sensor inside the system. This is considered to improve the accuracy as well as the safety regarding thermal runaways.

3 Results

The analysis is performed on 30 different marine battery systems from 15 different suppliers. Most of the systems are based on NMC cells, 20 out of the 30, 8 of the systems use LFP cells and 2 systems use LTO. For most of the results an overview is provided by a column chart with the columns number 1 to 30. The same numbers represent the same battery system in each figure.

Some of the characteristics could not be determined for all of the battery systems in this analysis. Therefore some of the properties are analyzed for just the battery systems where it was possible to find the required information.

3.1 Costs

3.1.1 System costs

The system costs are the costs in Euro per kWh of installed battery system. The most competitive priced battery systems currently on the marine market are priced at around 400 €/kWh. The majority of the marine NMC and LFP systems are priced between 400 €/kWh and 600 €/kWh. There are several battery systems on the market at a cost around 800 €/kWh and 900 €/kWh. These systems are either specialized as high power systems or offer a high cycle life.

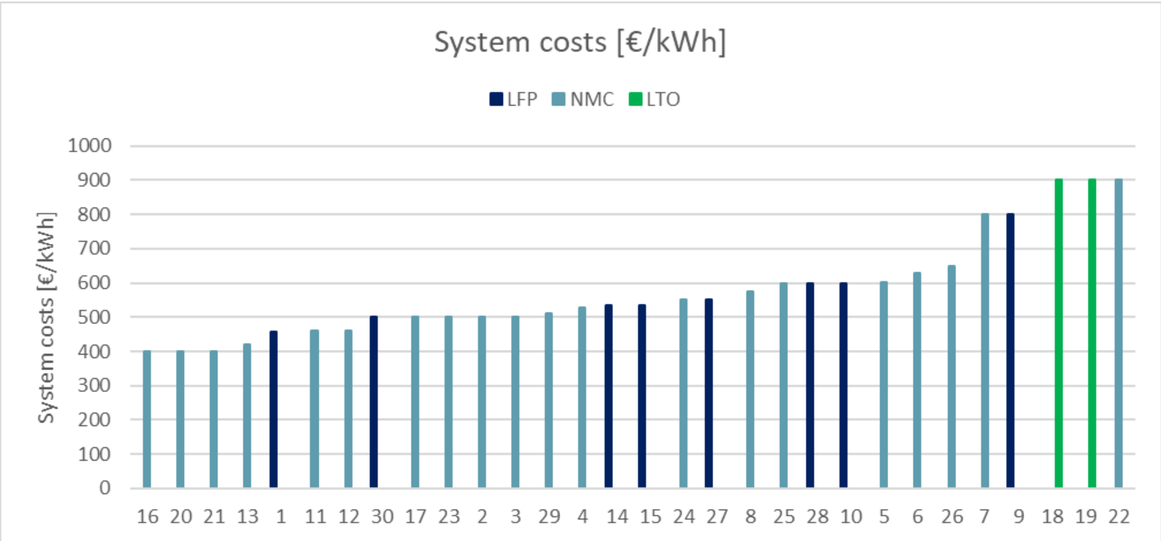

Figure 3 Battery system costs in Euro/kWh

The highest score for system costs is based on the lowest system costs of currently available marine battery systems. The lowest score is based on everything above the highest system costs. The remaining scores are determined based on the costs for the analyzed battery systems divided in equally sized groups.

System costs [€/kWh]	
Score	**Range**
1	> €900
2	> €630 – €900
3	> €500 - €630
4	€400 - €500
5	< €400

Table 2 Scoring ranges for system costs

3.1.2 Cycle costs

The cycle costs are determined based on the number of cycles each battery can perform at 80% DoD, as provided by the supplier. The system costs are divided by the number of cycles that can be performed times 0.8, to represent a full cycle of 100%, resulting in a €/kWh costs for each cycled kWh.

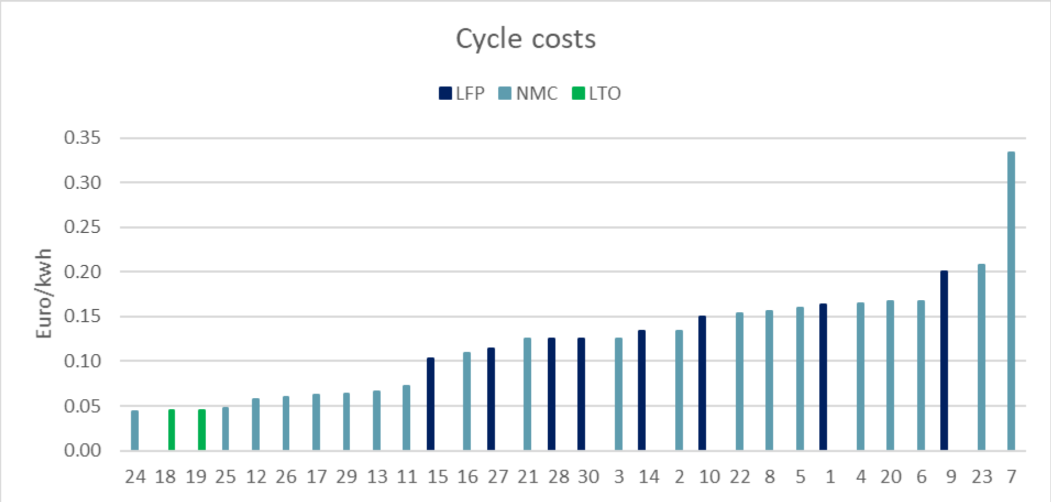

Figure 4 Costs per cycled kWh in Euro/kWh

Figure 5 shows the systems costs of each battery system compared to the cycle costs. The battery system with the lowest cycle costs are the LTO systems, which have one of the highest system costs.

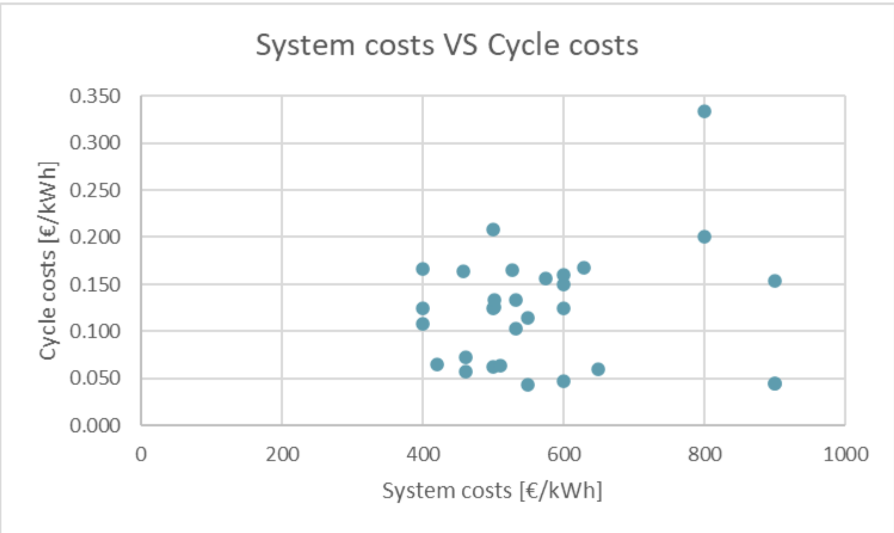

Figure 5 System costs compared to costs per cycled kWh

The highest score for cycle costs is defined as everything at a lower cost compared to the system with the lowest cycle costs and therefore everything below €0.04 per kWh. The battery systems which have cycle costs below €0.07 per kWh are considered as heavy duty battery systems, as those are more cost efficient for applications with a large number of cycles. Then there is a cluster of battery systems with a cycle costs between €0.07 and €0.15 per kWh, which is considered as an average range. The remaining battery systems have a cycle costs between €0.15 and €0.21 per kWh, except for one system. This is considered as a below average range for cycle costs. Everything above a cost of €0.21 is considered to be expensive and results in the lowest score for cycle costs.

Cycle costs	
Score	**Range**
1	> €0.21
2	> €0.15 – €0.21
3	> €0.07 - €0.15
4	€0.04 - €0.07
5	< €0.04

Table 3 Scoring ranges for cycle costs

3.2 Energy

The energy density of the different battery systems is analyzed by comparing the gravimetric specific energy and volumetric specific energy for each battery system. Besides the overall energy density also the cell to module weight and volume ratio is investigated. Only a limited amount of suppliers provided the information about the cell weight and volume.

The gravimetric and volumetric specific energy are compared based on cell chemistry, cell shape and system design. The specific energy is determined for the battery system only, so not taking required service space or battery room height into account. Figure 6, Figure 7 and Figure 8 below show the comparison between the volumetric and gravimetric specific energy of all battery systems.

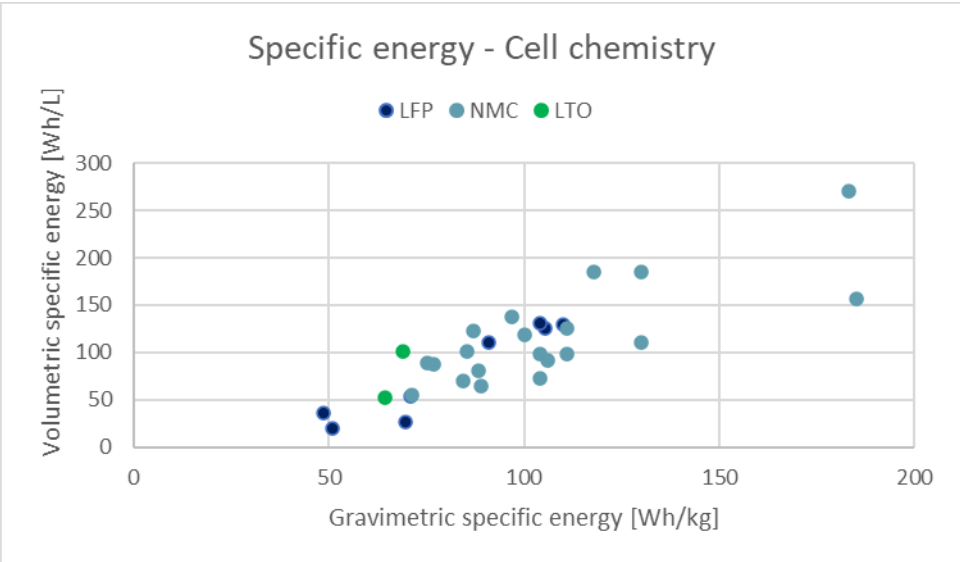

Figure 6 Gravimetric and volumetric energy density per cell chemistry

Based on the used cell chemistry it is clear from the figure above that NMC cells generally result in a higher specific energy, both gravimetric as well as volumetric. The LTO have a relatively low specific energy, although the system design can have a large influence on the volumetric specific energy as shown by the LTO systems, which are based on the same cells. There are several LFP based systems which score similar to most NMC based systems, however, there are two systems that have a significantly lower specific energy, especially volumetric, which are both LFP based.

Average energy density	Gravimetric [Wh/kg]	Volumetric [Wh/L]
NMC	107	116
LFP	81	79
LTO	67	76

Table 4 Average energy density per cell chemistry

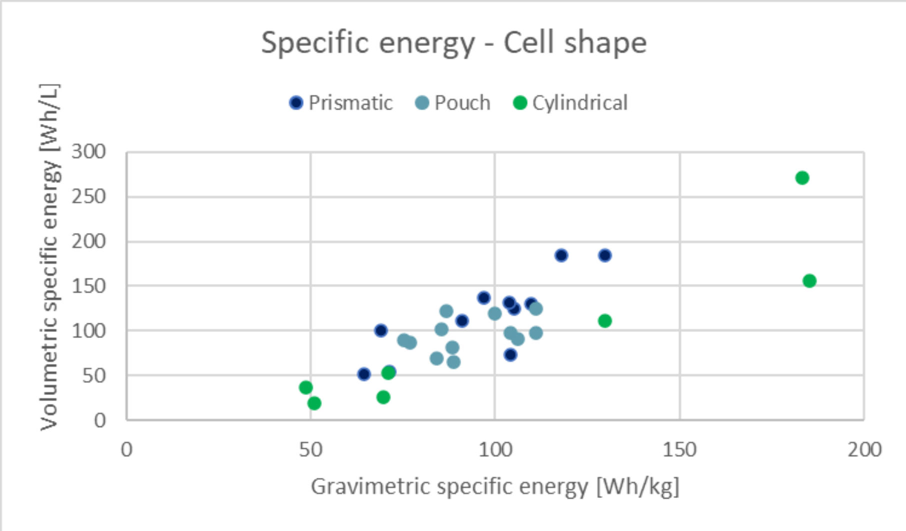

Figure 7 Gravimetric and volumetric energy density per cell shape

Based on the figure above, the systems with cylindrical cells result in both the lowest as well as the highest specific energy. The two systems with the lowest specific energy have very large cylindrical power cells and the systems with a very high specific energy have very small cylindrical energy cells. This is assumed to cause the large difference in energy density. It is also noticeable that although pouch cells have the largest energy density at cell level, they require more support for integration in a battery system and therefore at a system level the energy density is lower. The cylindrical cell based systems have a higher gravimetric energy density compared to their volumetric energy density and most prismatic cell based systems have a higher volumetric energy density compared to their gravimetric energy density. This shows that cylindrical cells are more likely to result in a light weight battery system, but prismatic cells are more likely to result in a battery systems which requires less volume for the same capacity.

Average energy density	Gravimetric [Wh/kg]	Volumetric [Wh/L]
Prismatic	97	117
Pouch	93	96
Cylindrical	105	96

Table **5** Average energy density per cell shape

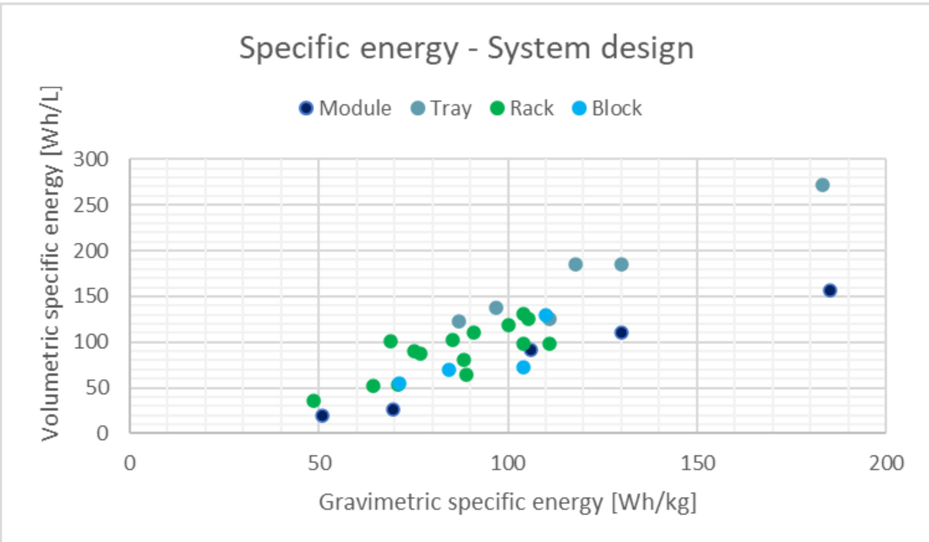

Figure 8 Gravimetric and volumetric energy density per battery system design

The tray design systems have the highest average energy density, both gravimetric and volumetric. The module design systems also score relatively high on gravimetric energy density, but preform less on volumetric energy density. This analysis is performed on battery system level, however, the rack based systems and especially the block based systems usually have additional systems integrated within the battery system, such as cooling systems, ventilation or safety systems. Therefore the comparison on system design is not completely unbiased.

Average energy density	Gravimetric [Wh/kg]	Volumetric [Wh/L]
Module	108	81
Tray	121	171
Rack	86	90
Block	92	82

Table 6 Average energy density per system design

3.2.1 Gravimetric specific energy

The gravimetric energy density ranges from 49 Wh/kg to 185 Wh/kg. In Figure 9 it shows that LFP and LTO based systems usually result in a lower energy density compared to NMC based systems.

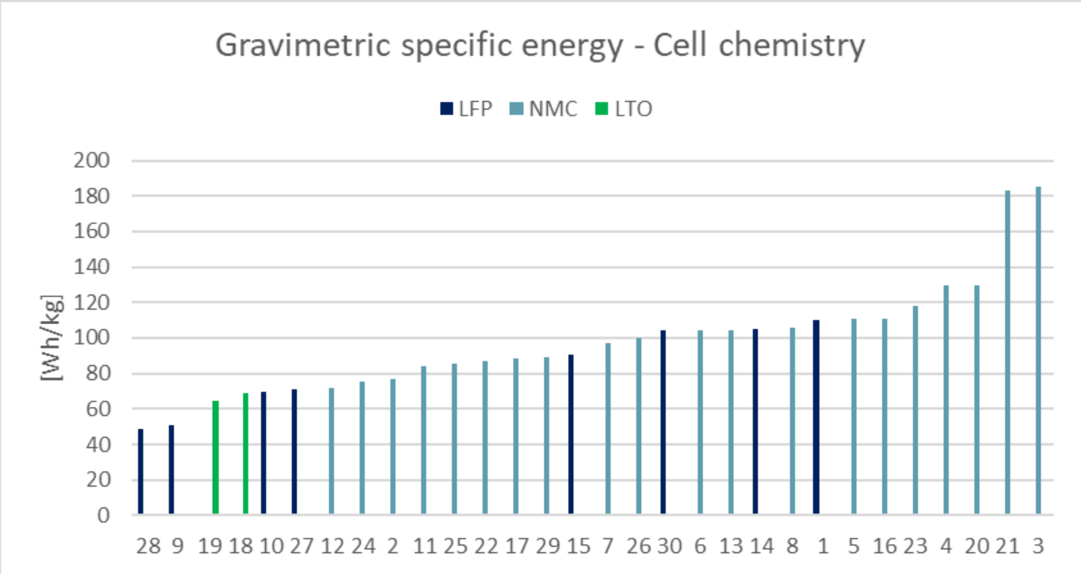

Figure 9 Gravimetric energy density per cell chemistry

However, the types of cells used in these systems are not only varying in cell chemistry, but also in specifications. Therefore the energy density if compared to the maximum continuous discharge C-rates of the systems in Figure 10. From this figure there are 3 different types of battery systems identified: High energy, Medium energy and High power. The battery systems with a maximum C-rate up to 1C are considered to be high energy systems. Above 1C and up to 3C are considered to be medium energy systems and above 3C are considered to be high power systems.

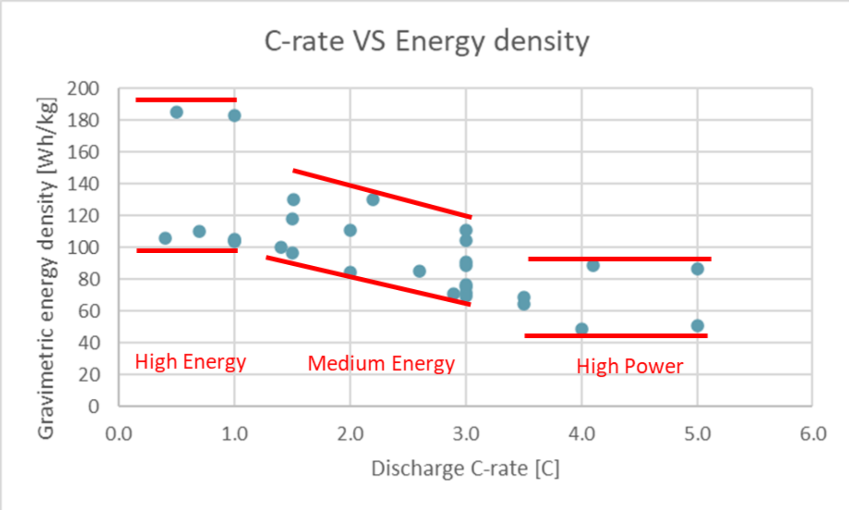

Figure 10 Overview of energy density and discharge C-rates for different types of batteries

The 3 different types of battery systems also perform differently on energy density, which can be related to the maximum continuous discharge C-rate. The average of all energy densities can be expressed by a second order polynomial: (2.6*[C-rate]^2)-30*[C-rate]+151. This polynomial is used to determine the score for gravimetric energy density, as shown in Figure 11 and Table 7.

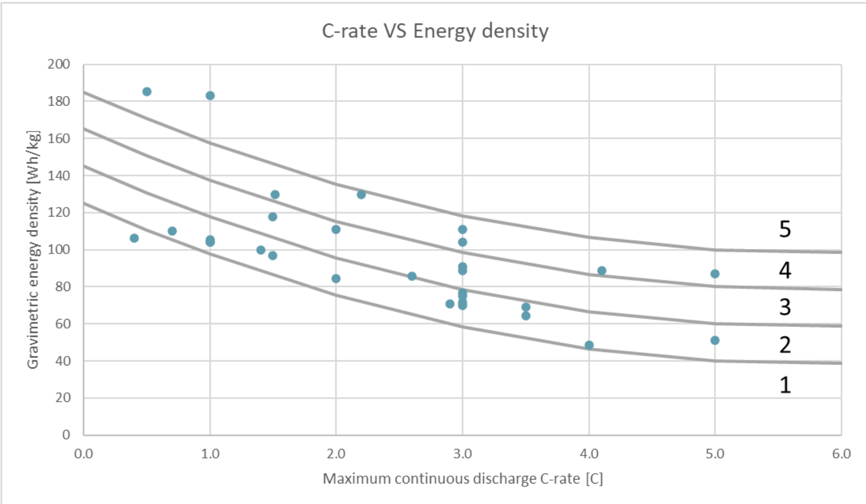

Figure 11 Scoring range for gravimetric specific energy

Gravimetric specific energy [Wh/kg]		
Score	Lower range	Upper range
1	-	≤ 2.6*[C-rate]^2-30*[C-rate]+125
2	> 2.6*[C-rate]^2-30*[C-rate]+125	≤ 2.6*[C-rate]^2-30*[C-rate]+145
3	> 2.6*[C-rate]^2-30*[C-rate]+145	≤ 2.6*[C-rate]^2-30*[C-rate]+165
4	> 2.6*[C-rate]^2-30*[C-rate]+165	≤ 2.6*[C-rate]^2-30*[C-rate]+185
5	> 2.6*[C-rate]^2-30*[C-rate]+185	-

Table 7 Scoring ranges for gravimetric energy density

3.2.2 Volumetric specific energy

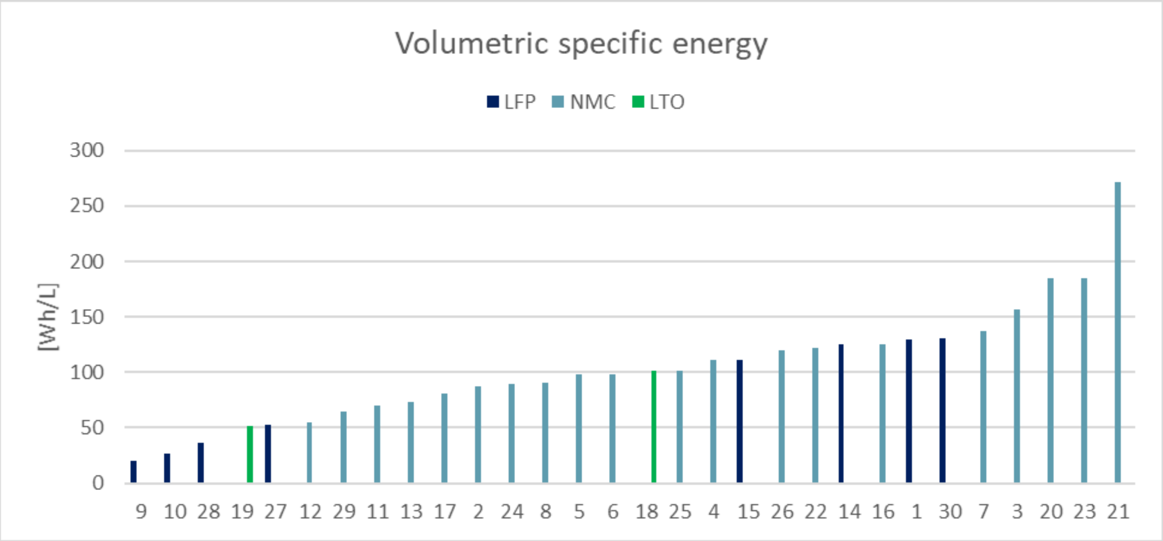

Figure 12 Overview of volumetric specific energy per cell chemistry

The volumetric specific energy is expressed in Wh/L and ranges between 20 Wh/L and 271 Wh/L. Similar to the gravimetric energy density, the volumetric energy density shows a dependency on the maximum continuous discharge C-rate, as shown in Figure 13. The same method for determining the scores is therefore used as well. Only the height of the range limits have been adjusted to the range values for the volumetric energy density, as shown in Table 8.

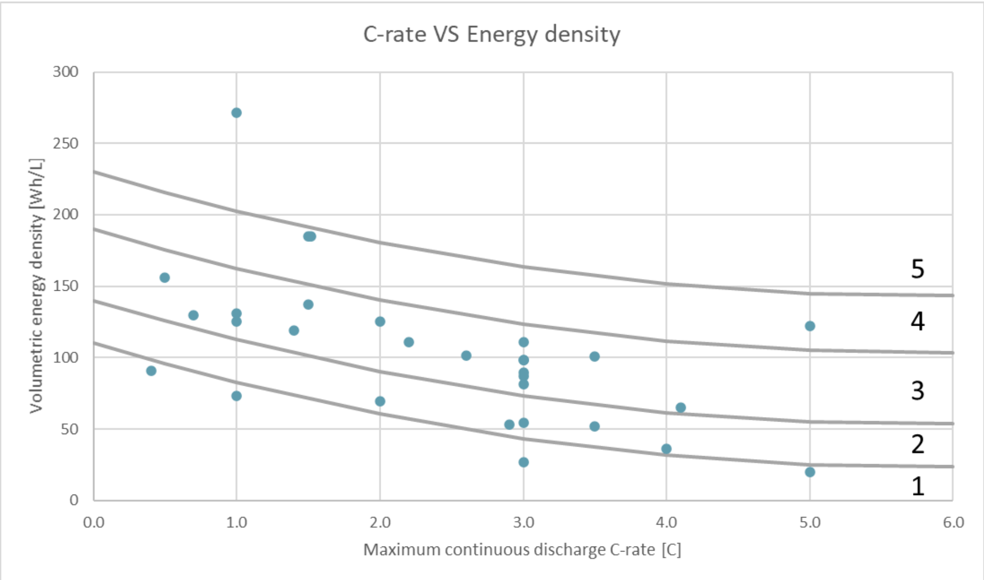

Figure 13 Scoring range for volumetric specific energy

Volumetric specific energy [Wh/L]		
Score	Lower range	Upper range
1	-	≤ 2.6*[C-rate]^2-30*[C-rate]+110
2	> 2.6*[C-rate]^2-30*[C-rate]+110	≤ 2.6*[C-rate]^2-30*[C-rate]+140
3	> 2.6*[C-rate]^2-30*[C-rate]+140	≤ 2.6*[C-rate]^2-30*[C-rate]+190
4	> 2.6*[C-rate]^2-30*[C-rate]+190	≤ 2.6*[C-rate]^2-30*[C-rate]+230
5	> 2.6*[C-rate]^2-30*[C-rate]+230	-

Table 8 Scoring ranges for volumetric energy density

3.2.3 Cell to module weight ratio

Only from 9 out of 30 battery systems the cell weight is provided by the system suppliers. Therefore it is not possible to show a complete overview of the impact of system design on the cell to module weight ratio. Based on the available information the average cell to module weight ratio is 1.7. This means that the average weight of a battery module is 1.7 times heavier compared to the combined weight of all the cells inside. The lowest cell to module weight ratio is 1.1 and the highest is 2.6. In Figure 14, Figure 15 and Figure 16 the cell to module weight ratio is compared to the cell capacity based on cell chemistry, cell shape and system design. Unfortunately there is not enough information available to determine if there is a relation between the cell to module weight ratio based on these three aspects.

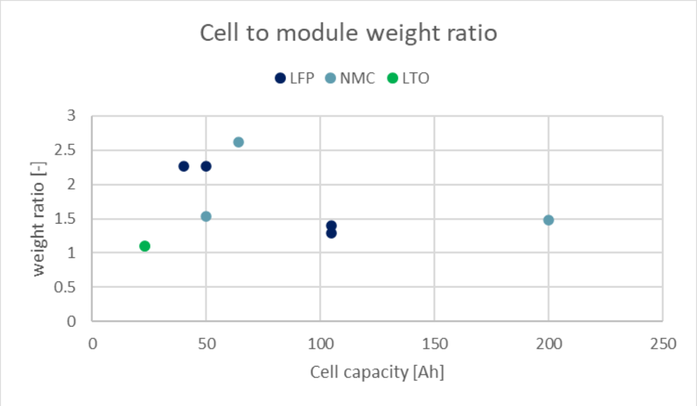

Figure 14 Cell to module weight ratio per cell chemistry

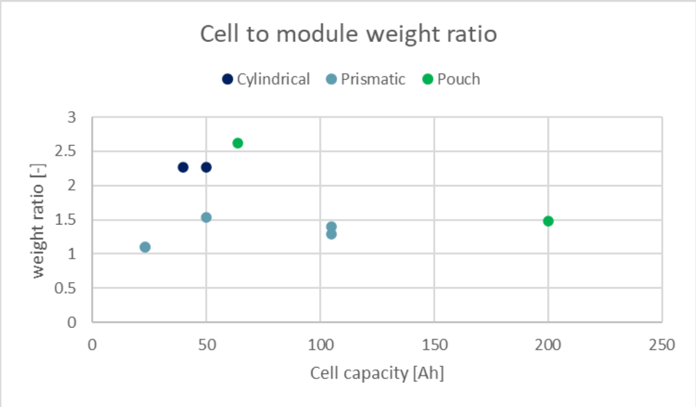

Figure 15 Cell to module weight ratio per cell shape

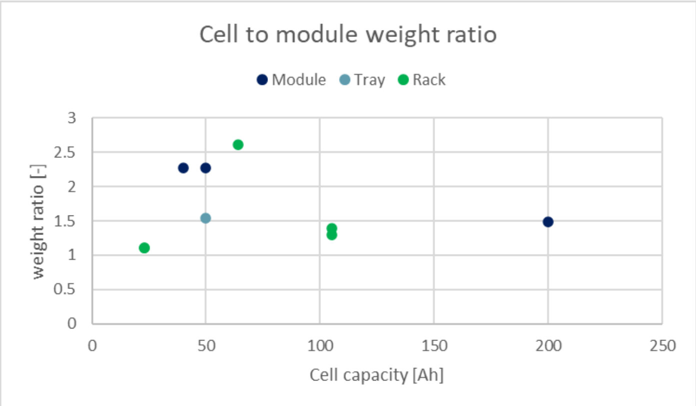

Figure 16 Cell to module weight ratio per system design

Based on the available information the current lowest and highest cell to module weight ratios are defined as limits for the highest and lowest score. A low cell to module weight ratio is considered as a positive property, resulting in a light weight overall battery system. The difference between the lowest of 1.1 and the highest of 2.6 is equally divided over the 3 remaining scores, resulting in the scoring ranges as shown in the table below.

Cell to module weight ratio	
Score	**Range**
1	> 2.6
2	>2.1 – 2.6
3	>1.6 – 2.1
4	1.1 – 1.6
5	< 1.1

Table 9 Scoring ranges for cell to module weight ratio

3.2.4 Cell to module volume ratio

Only from 12 out of 30 battery systems the cell volume is provided by the system suppliers. Therefore it is not possible to show a complete overview of the impact of system design on the cell to module volume ratio, as similar is the case with the cell to module weight ratio. Based on the available information the average cell to module volume ratio is 2.7. This means that the average volume of a battery module is 2.7 times larger compared to the combined volume of all the cells inside. The lowest cell to module volume ratio is 1.4 and the highest is 3.8. In Figure 17, Figure 18 and Figure 19 the cell to module volume ratio is compared to the cell capacity based on cell chemistry, cell shape and system design.

In contrary to the cell to module weight ratio, for the volume ratio it seems that there are some trends visible. However, due to the small set of datapoints, these conclusions should be taken with caution. The trend regarding cell chemistry that can be identified is that it looks like the NMC cells have in general a higher cell to module ratio compared to LFP and LTO cells.

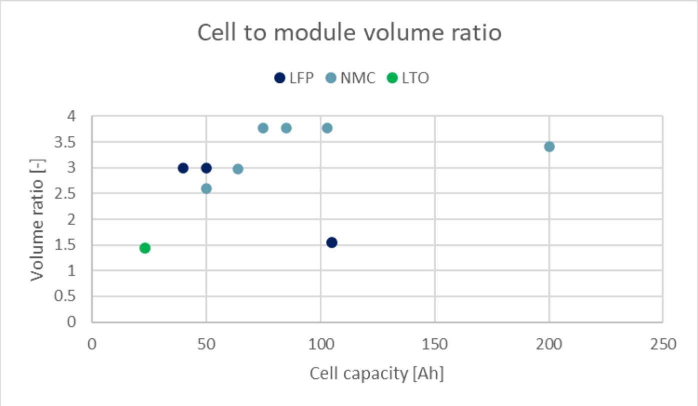

Figure 17 Cell to module volume ratio per cell chemistry

Regarding the cell shape, the pouch cells seem to have a higher cell to module volume ratio compared to the cylindrical cells and especially compared to the prismatic cells.

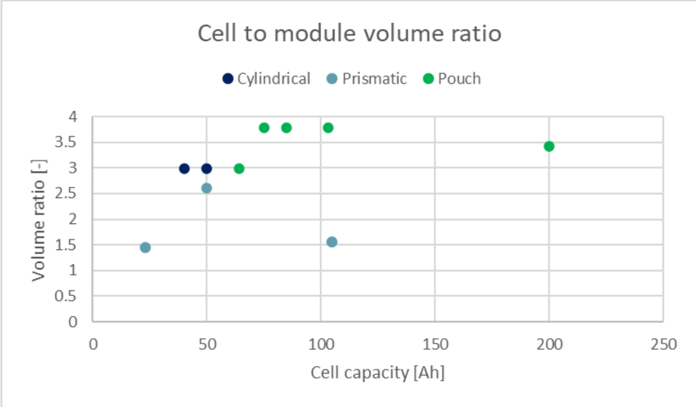

Figure 18 Cell to module volume ratio per cell shape

Regarding the system design there is no clear trend identified from Figure 19.

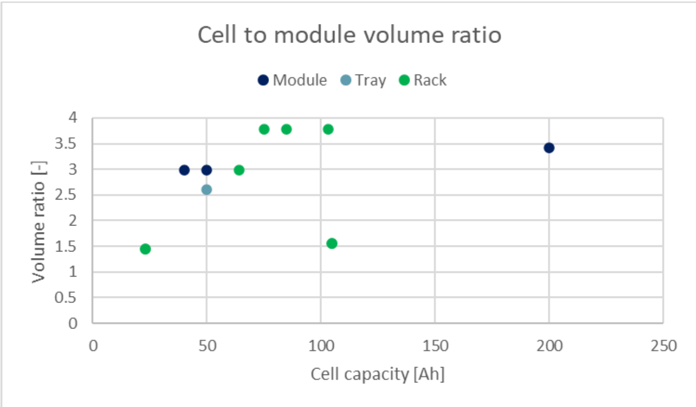

Figure 19 Cell to module volume ratio per system design

A similar approach is used to determine the scores like with the weight ratio. Therefore the limit for the lowest score is the highest cell to volume ratio of 3.8 and the limit for the highest score is the lowest cell to volume ratio of 1.4. The remaining three scores are defined by dividing the remaining range in three equal parts, resulting in the table below.

Cell to module volume ratio	
Score	**Range**
1	> 3.8
2	>3.0 – 3.8
3	>2.2 – 3.0
4	1.4 – 2.2
5	< 1.4

Table 10 Scoring ranges for cell to module volume ratio

3.3 Power

The power density of marine battery systems is analyzed by comparing the gravimetric and volumetric specific power as well as the maximum continuous C-rates for charging and discharging of the batteries. Unlike for the energy density, the power density and C-rates are investigated separate from each other as there can be a difference in requirements for gravimetric power density, volumetric power density and power per installed battery capacity (C-rate). In the three figures below the gravimetric and volumetric specific power is compared based on cell chemistry, cell shape and system design.

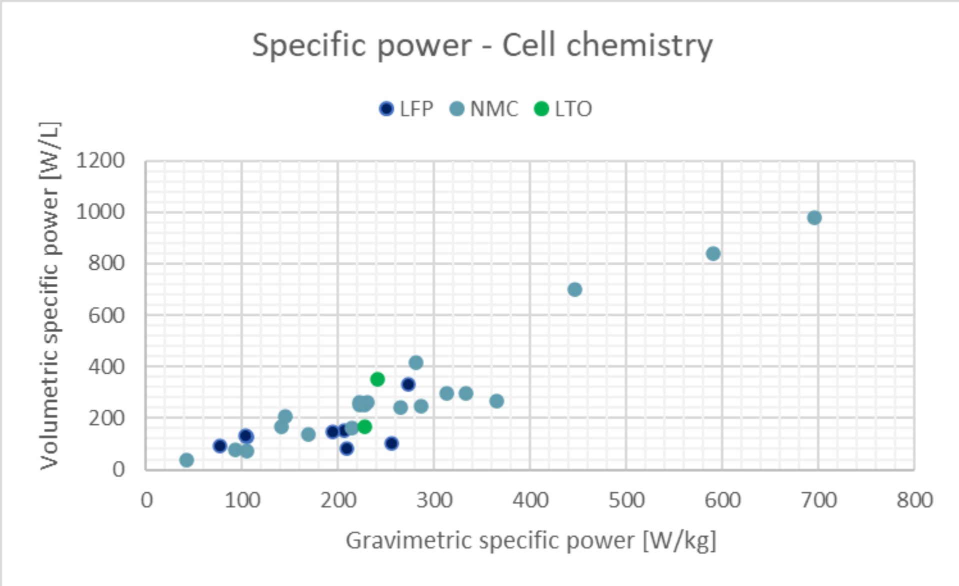

Figure 20 Gravimetric and volumetric power density per cell chemistry

There are 3 systems with NMC cells which have the highest volumetric as well as gravimetric power density. NMC based batteries score in general above average regarding power density. The overall average gravimetric specific power is 243 W/kg and for volumetric specific power this is 261 W/L. Although LTO cells are considered as high power cells, based on their C-rates, the performance of the battery systems using LTO cells is a bit below average for power density. The systems using LFP cells score overall worst on their specific power, especially when it comes to volume.

Average power density	Gravimetric [W/kg]	Volumetric [W/L]
NMC	269	308
LFP	178	145
LTO	234	260

Table 11 Average power density per cell chemistry

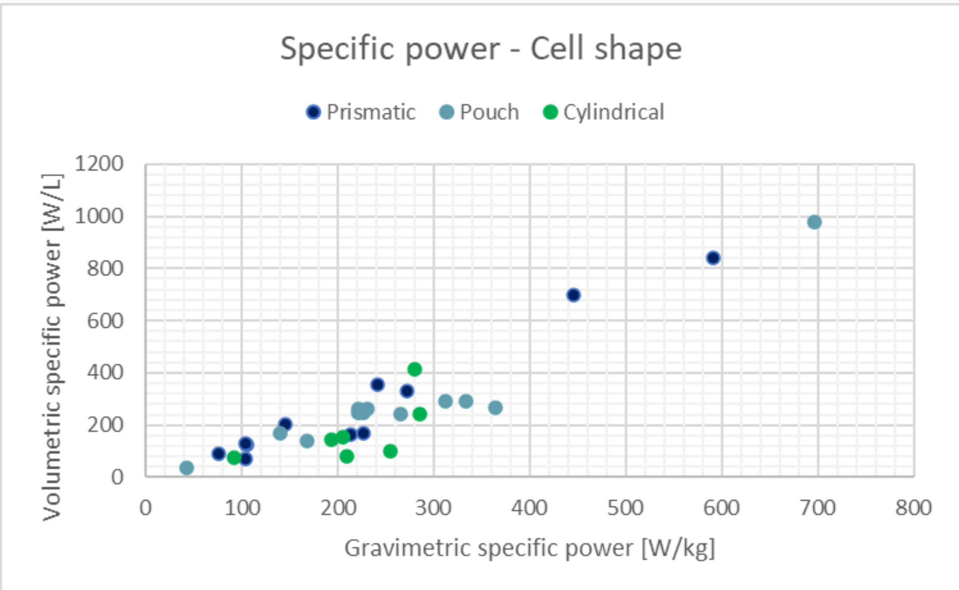

Figure 21 Gravimetric and volumetric power density per cell shape

Based on cell shape it can be said that cylindrical cells score worst when it comes to gravimetric specific power, but especially volumetric. Pouch cells on average score the highest on gravimetric power density. Prismatic cells on average score the highest on volumetric power density.

Average power density	Gravimetric [W/kg]	Volumetric [W/L]
Prismatic	230	289
Pouch	269	287
Cylindrical	218	174

Table 12 Average power density per cell shape

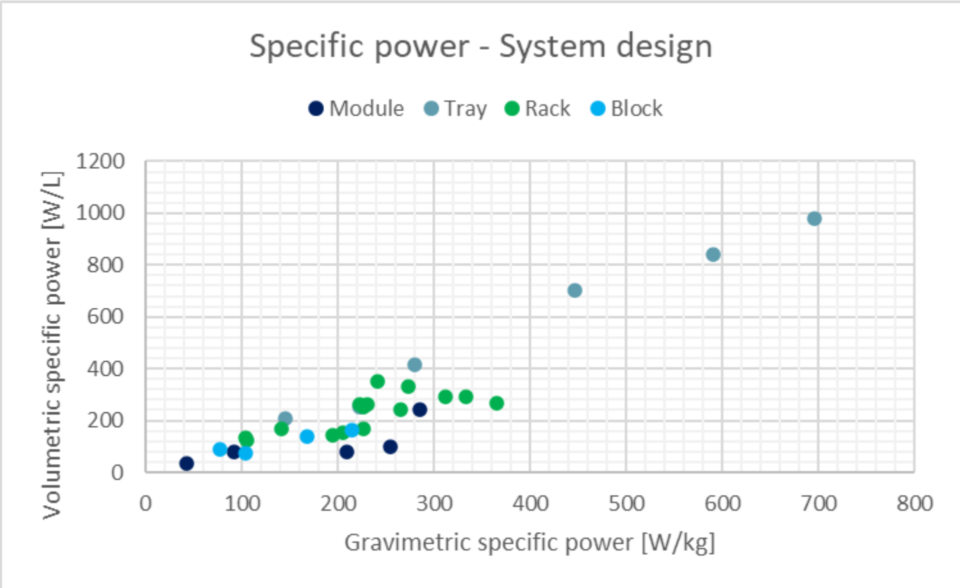

Figure 22 Gravimetric and volumetric power density per system design

The block based systems generally score worst on the specific power. This is expected as these systems are mainly designed for large, high energy applications and therefore don't require much power. More surprising is the performance of the module based systems, which score particularly bad on the volumetric specific power. The tray based systems score significantly higher on both gravimetric as well as volumetric power density compared to the other system designs.

Average power density	Gravimetric [W/kg]	Volumetric [W/L]
Module	177	108
Tray	398	565
Rack	230	230
Block	141	116

Table 13 Average power density per system design

3.3.1 Gravimetric specific power

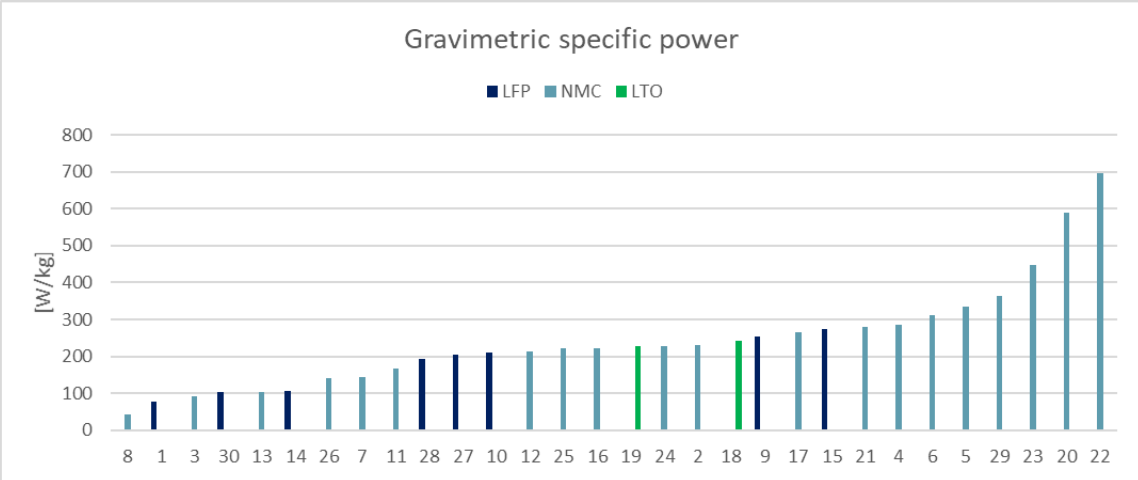

Figure 23 Overview of gravimetric power density

The gravimetric specific power ranges from 42 W/kg to 696 W/kg. The average specific power of all systems combined is 243 W/kg. The average score is therefore determined to be the range between 200 W/kg and 300 W/kg. The next steps are 150 W/kg below and above this range. The lowest score is therefore everything below 50 W/kg and the highest score is everything above 450 W/kg.

Gravimetric specific power [W/kg]	
Score	**Range**
1	< 50
2	50 – 200
3	> 200 - 300
4	> 300 – 450
5	> 450

Table 14 Scoring ranges for gravimetric power density

3.3.2 Volumetric specific power

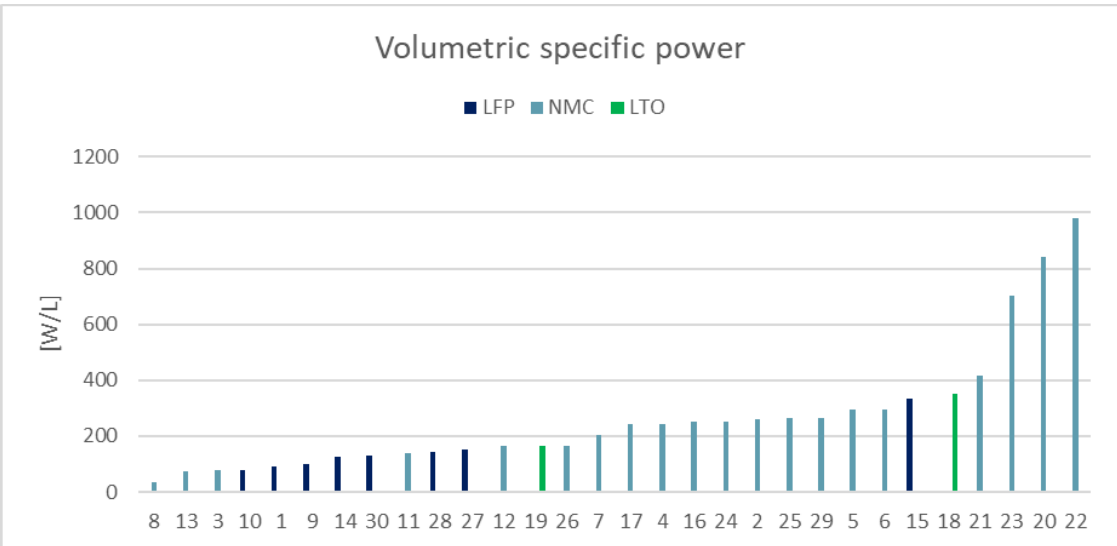

Figure 24 Overview of volumetric power density

The volumetric specific power ranges from 36 W/kg to 978 W/kg. The average specific power of all systems combined is 261 W/kg. Because the total spread is larger compared to the gravimetric specific power, the average score is therefore determined to have a larger range between 150 W/kg and 350 W/kg. The next steps are 100 W/kg below and above this range. The lowest score is therefore everything below 50 W/kg and the highest score is everything above 450 W/kg.

Volumetric specific power [W/L]	
Score	**Range**
1	< 50
2	50 – 150
3	> 150 – 350
4	> 350 – 450
5	> 450

Table 15 Scoring ranges for volumetric power density

3.3.3 Discharge C-rates

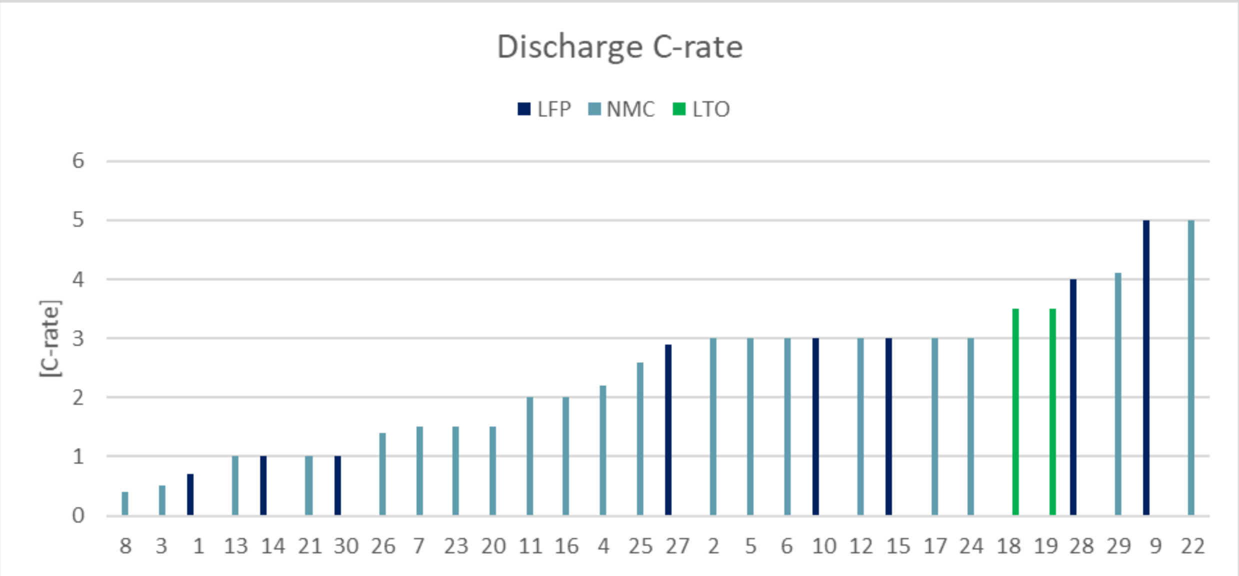

Figure 25 Overview of discharge C-rate per cell chemistry

The maximum continuous discharge C-rates range from 0.4C to 5C, with an average of 2.4 considering all systems. Everything below the lowest C-rate of 0.4C is considered as the lowest possible score. Everything higher than the highest C-rate of 5C is considered as the highest score. The remaining scores are determined based on the High energy, Medium energy and High power batteries as discussed in section 3.2.1.

Discharge C-rate [C]	
Score	**Range**
1	< 0.4
2	0.4 – 1
3	> 1 – 3
4	> 3 – 5
5	> 5

Table 16 Scoring ranges for maximum continuous discharge C-rate

3.3.4 Charge C-rates

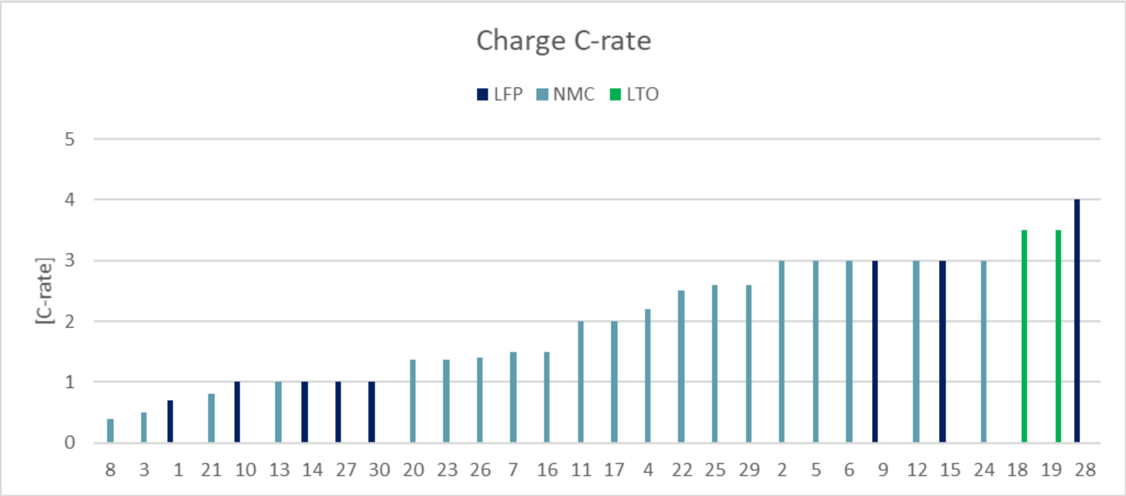

Figure 26 Overview of charge C-rate per cell chemistry

The maximum continuous charge C-rates range from 0.4C to 4C, with an average of 2.0 considering all systems. The charge C-rate of 20 out of 30 battery systems is equal to the discharge C-rate, however, for 10 systems the charge C-rate is lower than the discharge C-rate. Everything below the lowest C-rate of 0.4C is considered as the lowest possible score. Everything higher than the highest C-rate of 4C is considered as the highest score. The remaining scores are determined based on the High energy, Medium energy and High power batteries as discussed in section 3.2.1.

Charge C-rate [C]	
Score	**Range**
1	< 0.4
2	0.4 – 1
3	> 1 – 3
4	> 3 – 4
5	> 4

Table 17 Scoring ranges for maximum continuous charge C-rates

3.4 Lifetime

The battery lifetime is determined by its cycle life and calendar life. The cycle life is mainly dependent on the DoD and C-rates of the performed cycles. The calendar life is mainly dependent on the temperature and average SoC of the batteries. The actual lifetime of a battery system on board of a vessel is difficult to determine beforehand because of the variations in operations and cycles that the batteries will perform. To evaluate the lifetime of different battery systems the number of cycles that can be performed at 80% DoD, at 1C and 25 degrees Celsius is requested from the battery suppliers.

3.4.1 Cycles

Although a constant cycle of 80% DoD at 1C and 25 degrees Celsius is in most marine applications not a realistic operational profile for the batteries, it is used as a measure because of the availability of data to be able to make a fair comparison between the different battery systems.

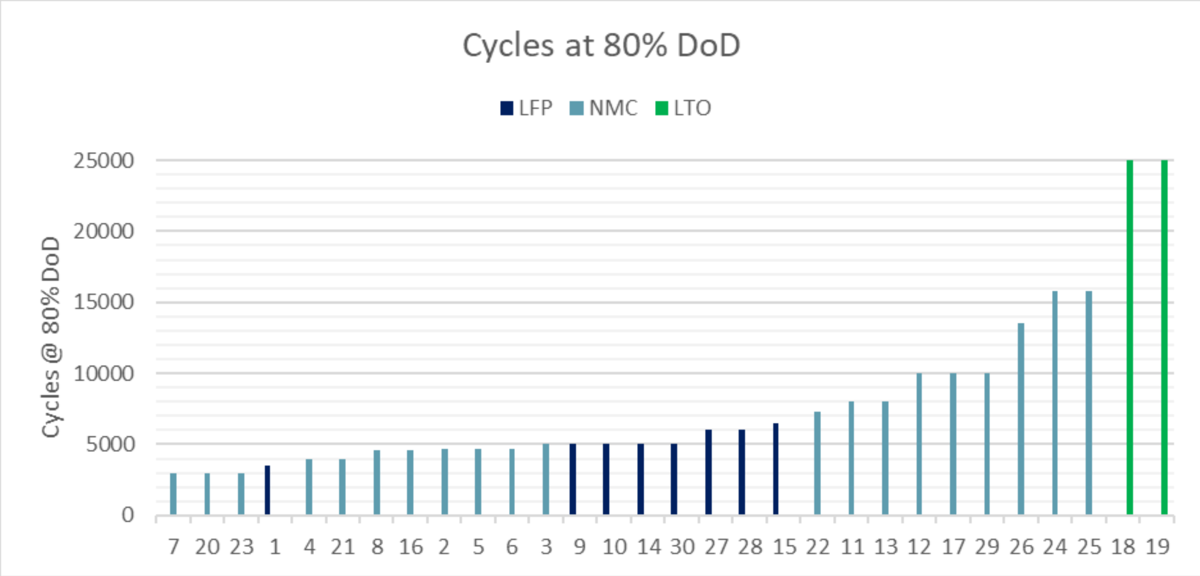

Figure 27 Number of estimated cycles at 80% DoD

The battery systems using LTO cells promise the largest number of cycles (25000). The battery systems with the most amount of cycles after that promise 15700 cycles. Therefore the highest score is determined to be for battery systems with more than 16000 cycles. The second highest score is based on the small cluster of battery systems which can perform more than 10000 cycles. The lowest score is based on the batteries which can perform less than 1 cycle per day for a 10 year design lifetime, resulting in 3650 cycles. The remaining two scores are divided in approximately an equal number of cycles, therefore the limit between a score of 2 and 3 is 7000 cycles.

Number of cycles [@80%DoD]	
Score	**Range**
1	< 3650
2	3650 – 7000
3	> 7000 – 10000
4	> 10000 – 16000
5	> 16000

Table 18 Scoring ranges for number of cycles at 80% DoD

3.4.2 Maximum design life

The design life of a battery system depends on multiple variables such as temperature, number of cycles, depth of discharge and C-rates. The expected design life of a battery system is usually based on an estimation of the operational profile and the number of cycles the batteries will make. In practice the actual cycles that the battery will be making and the temperatures inside the battery room will vary from this estimation. However, the lifetime calculation is needed to determine the commercial viability of a battery powered vessel or to choose the type and size of battery system that will be installed. Although most vessels have an expected lifetime of 25 up to 40 years, this is currently not achievable for the battery system. Therefore a design life has to be determined for the batteries, after which it is acceptable from a commercial or operational point of view to replace the battery system for a new one. Currently this design life is usually determined at approximately 10 years for most types of battery powered vessels.

The suppliers of the marine battery systems have been asked what the maximum design life is that they would consider to offer if the use of the battery system would be significantly low, so it will not affect the battery lifetime, for instance one 10% DoD cycle per month. The suppliers of 19 out of the 30 battery systems investigated here have provided an answer to this. For the other 11 systems it is not known. See the results in Figure 28 below.

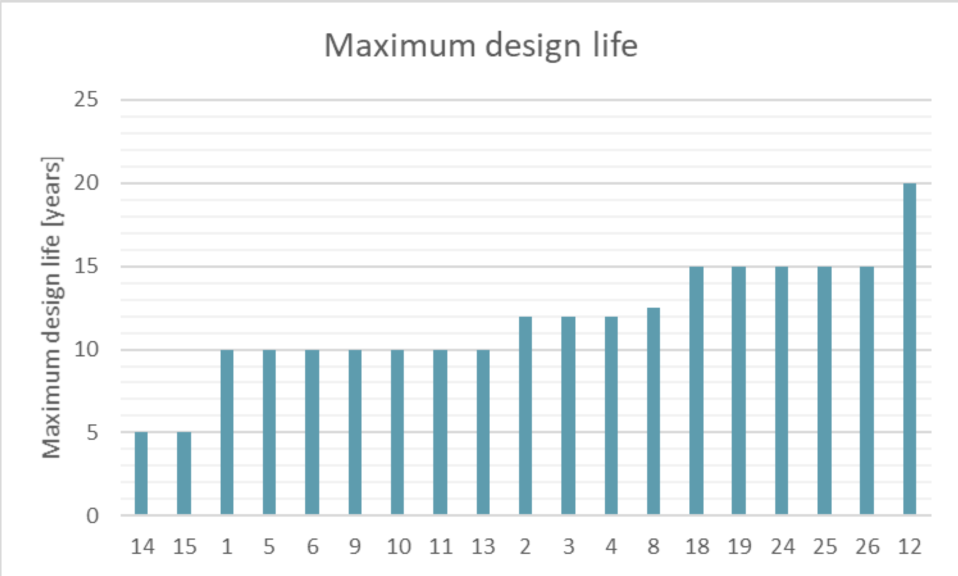

Figure 28 Maximum design life in years

The lowest maximum design life which was offered by a supplier was 5 years. The highest maximum design life which was offered by a supplier was 20 years. On average the maximum design life is 12 years. In Figure 29 the comparison between the maximum design life in years and the estimated number of cycles at 80% DoD is shown. The suppliers which can promise a lifetime of 15 years or higher also offer more cycles at 80% DoD compared to the other battery systems.

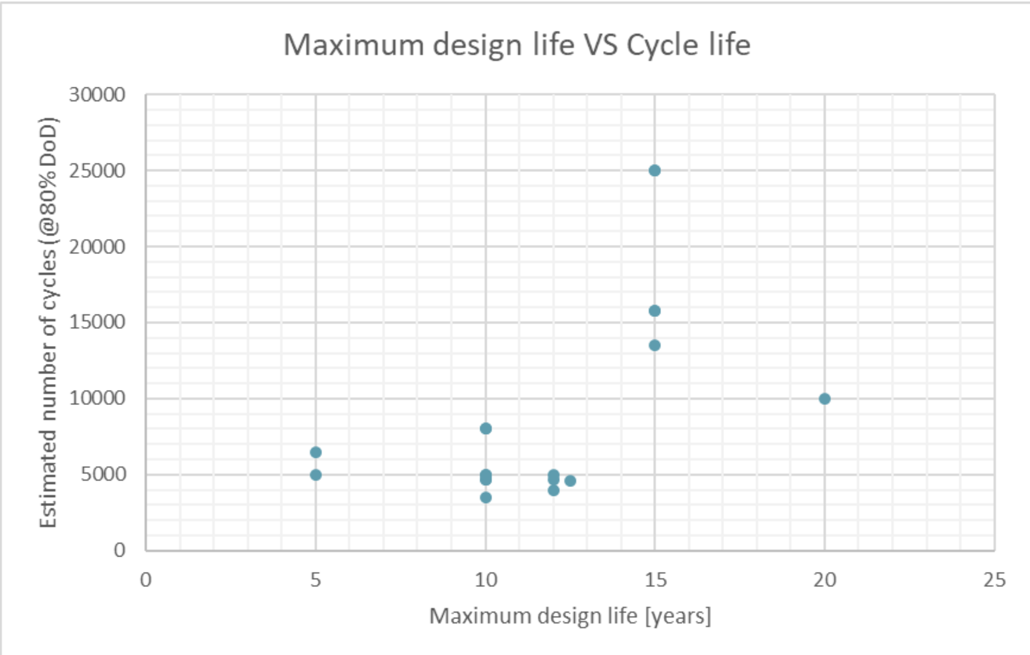

Figure 29 Maximum design life compared to estimated number of cycles at 80% DoD

The most common design life requirements for marine batteries is 10 years and therefore if the maximum design life is below this it is determined to result in the lowest score. Because the average maximum design life is 12 years, between 10 and 12 years it is determined to result in a score of 2 points. From 12 to below 15 is assumed as an average score for maximum design life and from 15 to 20 is considered above average. A design life of more than 20 years is considered as the highest possible score.

Maximum design life [years]	
Score	**Range**
1	< 10
2	10 – <12
3	12 – <15
4	15 – 20
5	> 20

Table 19 Scoring ranges for maximum design life

3.5 Thermal management

The thermal management of marine battery systems can be arranged through forced air cooling or through liquid cooling. In general liquid cooling is more effective, but air cooling is lighter and assumed to be cheaper. Also, cooling liquid and electricity doesn't mix well and in the past accidents have happened where a cooling liquid leakage resulted in a fire on board of a battery powered vessel. However, there are now also systems on the marine battery market which have a liquid cooling system which cools the battery cell so effective that it is physically impossible for the cells to ignite into a thermal runaway, as long as the cooling system is active. Of the 30 battery systems in this study there are 10 which only come as an air cooled system, 14 only come as a liquid system and 6 systems can be either air cooled or liquid cooled.

The cooling system requirements are analyzed based on the required cooling capacity, according to the percentage heat rejection at a 1C discharge, and based on the required inlet temperature of the cooling medium, either air or liquid. For the heat rejection it is assumed the lower the heat rejection, the higher the efficiency of the batteries and the smaller the required investment on the cooling system for the batteries. A low inlet temperature can require a significant cooling system, which can be costly, large and heavy. In Figure 30 the average required inlet temperature and the percentage heat rejected by the batteries at a 1C discharge are compared to each other. The data from only 16 out of 30 battery systems in this document was available for comparison of the cooling systems.

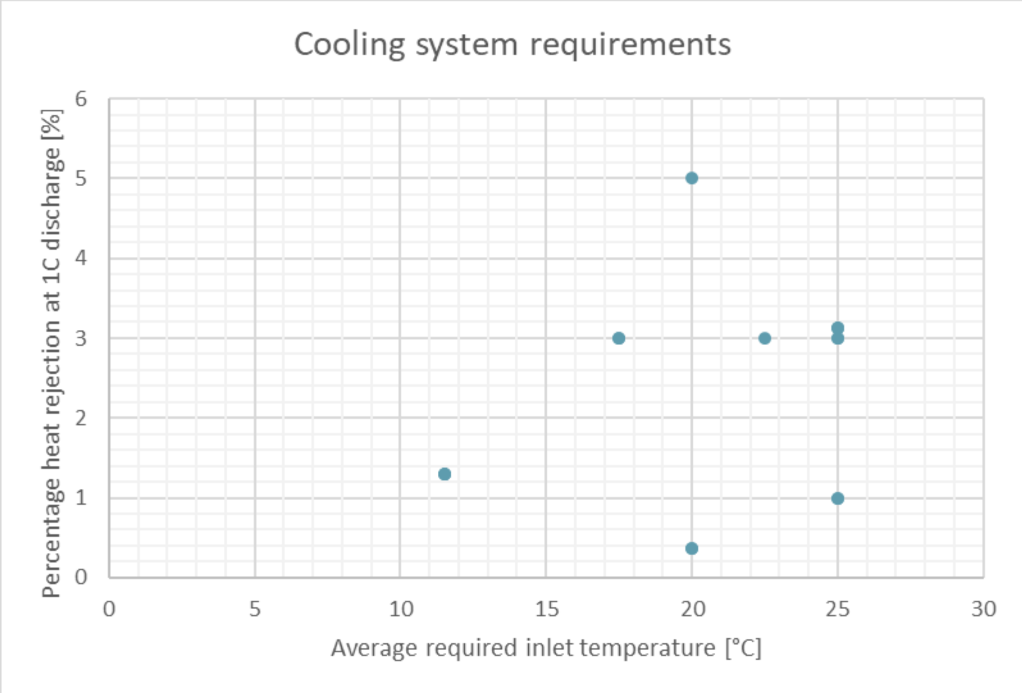

Figure 30 Overview cooling requirements

3.5.1 Heat rejection

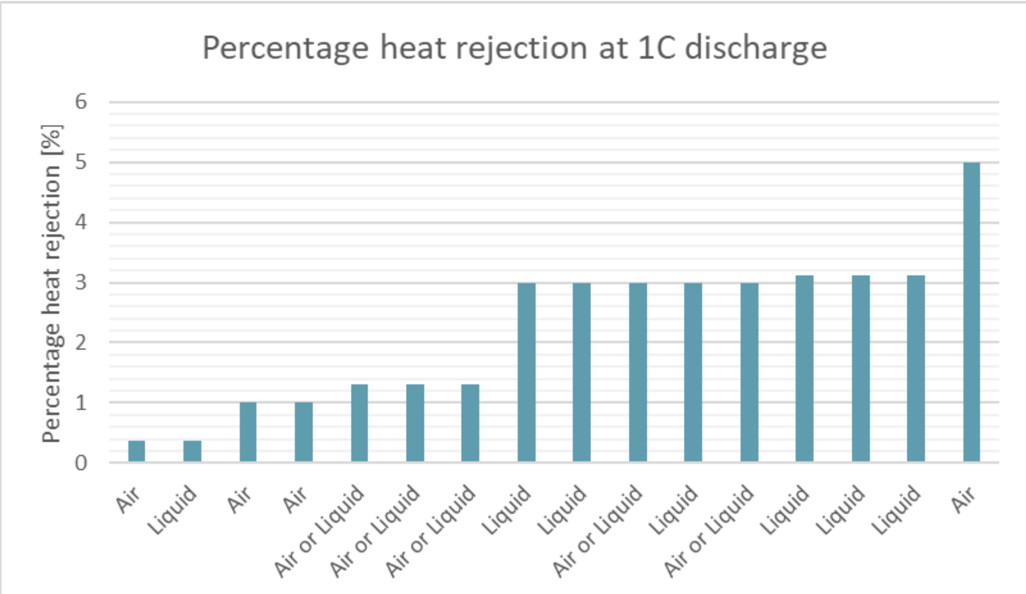

Figure 31 Heat rejection at 1C discharge

The heat rejection from the batteries at a 1C discharge rate is compared for 16 battery systems. The heat rejection of these battery systems ranges from 0.36% up to 5%. The average heat rejected at 1C is 2.2%. Therefore the average score is for the battery systems with a heat rejection between 1.5% and 2.5%. The remaining scores are determined by steps of 1% up and down. Resulting in a top score for the battery systems with a heat rejection below 0.5% and the lowest score for battery systems with a heat rejection higher than 3.5%.

Heat rejection at 1C [%]	
Score	Range
1	> 3.5%
2	> 2.5% – 3.5%
3	> 1.5% – 2.5%
4	0.5% – 1.5%
5	< 0.5%

Table 20 Scoring ranges for heat rejection at 1C discharge

3.5.2 Inlet temperature

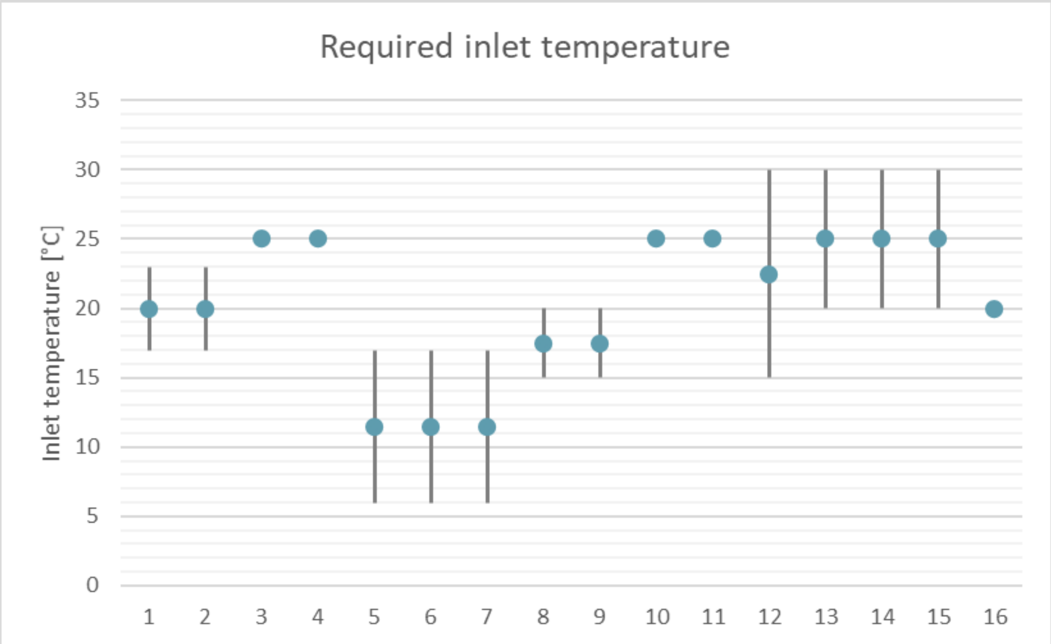

Figure 32 Required inlet temperature (average, minimum and maximum)

The required inlet temperature of the cooling medium has a large influence on the cooling system. The lower the required inlet temperature, the more energy will be required to cool the cooling medium. Therefore the overall efficiency of the battery system will go down. Although a low temperature will improve the lifetime of the batteries, it will be ideal to achieve the longest possible lifetime with as little energy spend on cooling as possible. The idea behind the determination of the scores for heat rejection are therefore based on a higher score for a higher required inlet temperature as it will require less energy from the cooling system and likely a smaller cooling installation as well. The requirements from different suppliers vary significantly. Figure 32 shows the average required inlet temperature and the minimum and maximum allowed inlet temperature, if this has been provided by the supplier. The inlet temperature requirements do not seem to be affected by the type of cooling system, air or liquid, as for the systems with both options the inlet temperature requirements are the same. The average required inlet temperature is approximately 20°C. The lowest requirements demand for a temperature between 6°C and 17°C, resulting in an average of 11.5°C. The highest inlet temperature required is 25°C. Above 25°C battery lifetime is known to reduce significantly and therefore this is also considered to be the max.

Required inlet temperature [°C]	
Score	**Range**
1	< 15°C
2	15°C – <18°C
3	18°C – <22°C
4	22°C – <25°C
5	25°C

Table 21 Scoring ranges for required inlet temperature

3.6 Safety

The safety of each battery system is determined by the cell chemistry, thermal runaway propagation measures, the amount of gas released in case of a thermal runaway, the requirements for a ventilation system and the specified IP rating of the battery system. Not all the specifications regarding the safety features are known for all battery systems. Therefore a calculation has been made based on the available information to determine an overall safety score for each battery system in section 3.6.6.

3.6.1 Cell chemistry

The materials used for the battery cells determine the thermal stability of the cell. Different cell chemistries therefore result in different temperatures at which a thermal runaway is initiated. The main three cell chemistries for Lithium-ion batteries in the marine sector are NMC, LFP and LTO. Of these three chemistries LFP has the highest thermal stability, meaning that a thermal runaway is most difficult to induce for this type of battery cell and therefore are considered to be the safest technology on the marine market at this moment. The NMC and LTO cells have similar cathode material, however the anode material is what distinguishes the LTO cells. LTO cell have a higher thermal stability compared to NMC cells. Therefore a score of 2 is determined for NMC type of cells, LTO cells result in a score of 3 and LFP cells result in a score of 4. The lowest score is determined for cells with a thermal stability similar to NCA cells, where a thermal runaway can de initiated at even lower temperatures compared to NMC. The score of 5 is determined for future types of cells which do not suffer from thermal runaways.

Cell chemistry	
Score	**Range**
1	NCA, or similar thermal stability
2	NMC, or similar thermal stability
3	LTO, or similar thermal stability
4	LFP, or similar thermal stability
5	No thermal runaway possible

Table 22 Scoring ranges for cell chemistry regarding safety

3.6.2 Thermal runaway propagation

The event of a thermal runaway is the most critical when performing a risk analysis for a marine battery system. The impact of a thermal runaway is for a large part determined by the level at which a thermal runaway is isolated. There are two acceptable levels considered by classification societies, as can be read in [2], cell level or module level. With cell level propagation isolation a thermal runaway of one cell does propagate to any of the surrounding battery cells. Module level propagation isolation is when a thermal runaway of one cell can propagate to other cells within the battery module, but cannot propagate to other modules in the battery system. There also are battery systems where a thermal runaway can propagate to multiple cells, but not to the complete module. Although this is not an official level of propagation isolation according to class, it is considered in this analysis as an intermediate step between cell level and module level, multiple cell level. The lowest score is for battery systems which do not have any propagation measures included. Cell level propagation isolation can be achieved with active measures as well as passive measures. Active propagation isolation can be achieved by cooling of the battery cells, which prevents the thermal runaway to occur. However, if the cooling system malfunctions, the cell level propagation isolation is no longer applicable. Therefore the highest scoring solution is for battery systems with passive cell level propagation isolation. Within these battery systems a thermal runaway of one cell will not propagate to any surrounding cells under any circumstances as all measures are passive and cannot fail.

Thermal runaway propagation	
Score	**Range**
1	No propagation measures
2	Module level
3	Multiple cell level
4	Cell level – active
5	Cell level – passive

Table 23 Scoring ranges for thermal runaway propagation measures

3.6.3 Gas release

One of the main hazards of battery cells going into thermal runaway is the explosive and toxic gas that is released by the cell. This gas should not be allowed to build up in a confined space such as a battery room as this can lead to dangerous situations. More gas release in case of a thermal runaway results in a less safe battery system, as there will be a bigger chance of creating an explosive atmosphere when more gas is being released and more measures will need to be taken to handle all this gas in a safe way. The amount of gas released in a thermal runaway is determined in Liters at a temperature of 25°C and under normal atmospheric pressure. Out of the 30 battery systems in this analysis, from 18 of the battery systems this information has been provided by the battery suppliers. The smallest amount of gas released in a thermal runaway is approximately 0.75 L, the largest amount is 800 L and on average 118 L of gas is released in case of a thermal runaway.

Thermal runaway gas release [L]	
Score	**Range**
1	> 500 L
2	200 L - 500 L
3	100 L - < 200 L
4	5 L – < 100 L
5	< 5 L

Table 24 Scoring ranges for thermal runaway gas release

3.6.4 Ventilation system

The gas released as discussed in section 3.6.3 needs to be ventilated out of the battery room. There are three main types of ventilation systems considered for marine batteries: open ventilation, half open ventilation and closed ventilation. If the amount of gas is relatively small it is considered possible as a safe option to have an open ventilation system. In an open ventilation system the gases released by the batteries in case of a thermal runaway are vented directly into the battery space after which external EX-fans remove the gases form the battery space and out of the vessel. If the volume of gas released in a thermal runaway is relatively large, an open ventilation system is considered unsafe and it can occur that additional EX classed housing is required for the battery system. This is considered as the least safe ventilation option. In a half open ventilation system the gases are directed into a ventilation ducting which is connected to the cooling system which recirculates the air back into the battery space. The ventilation ducting is required to have gas detection and upon detection of gas an EX-fan is required to activate to remove the gases from the ducting and measures need to be in place to ensure that the gases cannot be recirculated into the cooling system and battery space. The closed ventilation system has a ventilation ducting for thermal runaway gases which is independent from the cooling air. With a closed ventilation system the gases from a thermal runaway can only go into one direction and that is through the ducting and outside of the vessel. This is currently considered as the safest type of system on the market. The highest score is considered therefore for future system which might not need any type of ventilation system. The most common choice of ventilation system is closed ventilation as it heavily reduces the required additional safety measures inside the battery space, making it easier for integration.

Thermal runaway ventilation	
Score	**Range**
1	Additional EX housing required
2	Open ventilation
3	Half open ventilation
4	Closed ventilation
5	No ventilation required

Table 25 Scoring ranges for thermal runaway gas ventilation

3.6.5 IP rating

In the recent period there have been several accidents on board of vessels with battery systems installed which were caused by short circuiting of the batteries due to water ingress in the battery space. Also accidents can occur when by accidents the batteries are short circuited, which partially can be prevented by a high IP rating as well. Therefore a high IP rating is considered as an additional safety feature in this analysis. The highest rating of IP 69 means that the housing is completely closed, also against dust, and is completely watertight, even with a humidity above 90%. As dust and humidity can cause failures inside a battery system, the IP rating of 69 is determined to result in the highest score in this analysis.

Additionally, a high IP rating also allows for a water-based fire extinguishing system to be installed in the battery space. The main goal for extinguishing fires related to batteries is to cool down the environment, to prevent the remaining batteries to go into thermal runaway. Water-based extinguishing systems are more effective in cooling the environment compared to inert gas type of extinguishing systems. However, for safe use of a water-based fire extinguishing system a minimum IP rating of at least IP X6 is recommended. For the second highest score it is determined that IP 56 is the lowest requirement, as the housing will be completely closed for intrusion by any size of object. The average score is determined for battery systems which are protected from objects 0f 2.5 mm in diameter and are protected from splashing water from any direction. Therefore IP 34 or higher results in a score of 3. A score of 2 is determined for battery systems which can't be accidentally touched by a finger and are protected from spraying water, meaning IP 23. Everything below IP rating 23 is considered to result in the lowest score of 1.

40% of the analyzed battery systems have an IP rating of 67, which is the highest occurring IP rating. The lowest achieved IP rating by one of the battery systems is IP 22.

IP rating	
Score	**Range**
1	Lower than IP 23
2	IP 23 or higher
3	IP 34 or higher
4	IP 56 or higher
5	IP 69

Table 26 Scoring ranges for IP rating

3.6.6 Safety score

The total safety score of all 30 battery systems is calculated by adding all the scores on the individual subjects and dividing it by the number of subjects. For not all battery systems it is known how much gas will be released in case of a thermal runaway. Therefore the score for those battery systems is determined by the remaining 4 subject, while the other scores are calculated using all 5 subjects. The lowest safety score achieved by a battery system is 2.25. the average score is 3.37 and the highest safety score is 4.20. The tray based systems score the lowest on safety, with an average of 2.8. the modules are third with an average of 3.3. Rack and block based systems score the highest with an average of 3.6. Most rack and block based systems have additional integrated safety features, which results higher score regarding safety.

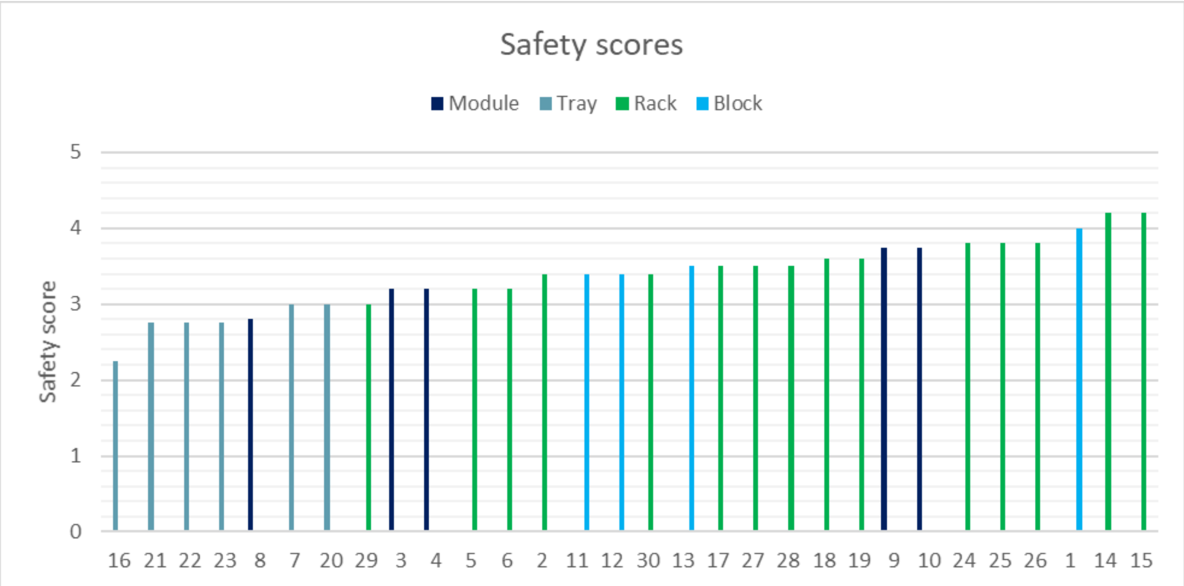

Figure 33 Overview of overall safety scores per battery system

Be aware that a low safety score does not mean that a battery system cannot be installed in a safe way on board of a vessel. It is a measure of how much effort is required to design to safety systems surrounding the batteries. Therefore it is still possible to install the battery system with a score of 2.25 on board of a vessel and have the vessel approved by a class society. However, this system will require more safety measures on board of the vessel to achieve the required level of safety according to class.

3.7 Mechanical integration

The mechanical integration of marine battery systems is investigated by analyzing the flexibility and ease of installing batteries in battery spaces which can vary significantly in dimensions and layout depending on the size and type of vessel. Three factors have been identified to play a role in the flexibility of installing batteries on board of a ship: the smallest building block, height optimization and the required service space.

3.7.1 Smallest building block

The smallest building block of a battery system is the smallest part which can be placed individually and independent of others. Battery spaces on board of ships come in many different shapes and sizes and small building blocks help for an optimal fit of the batteries. In Figure 34 the overview is shown of the smallest building block per Liter for all of the compared battery systems. The block based systems are designed as large blocks and therefore obviously have the largest building blocks.

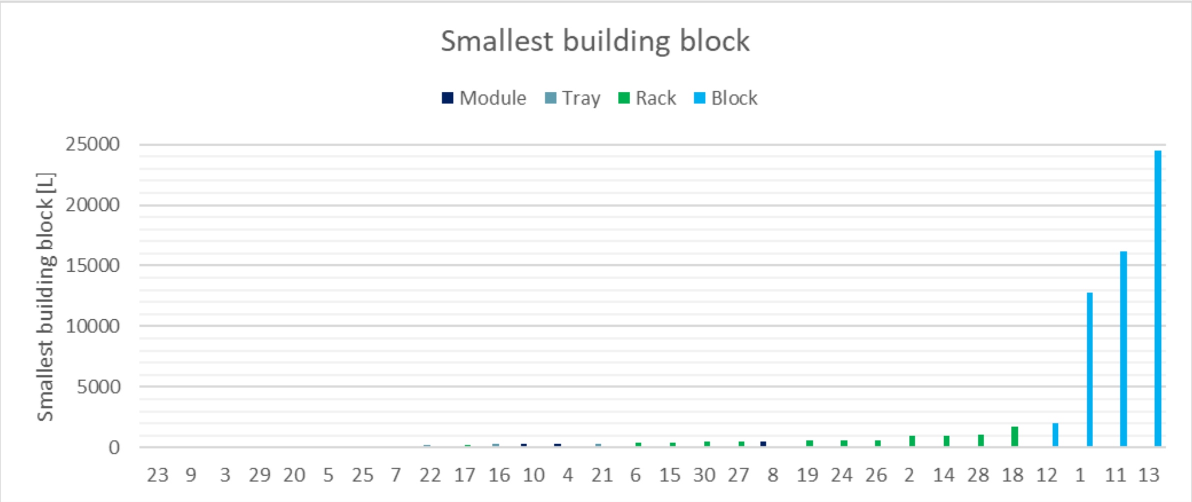

Figure 34 Overview of smallest building block per battery system

For a better overview the 3 largest block based systems have been removed from the graph in Figure 35. The tray based systems have the smallest building blocks with an average of 200 L. The module based battery systems have a slightly larger average volume of 254 L. The rack based systems have an average volume of 605 L for their smallest building block. The block based systems have an average of 13837 L for their smallest building block. The average volume of the smallest building block of all battery systems together is 2230 L.

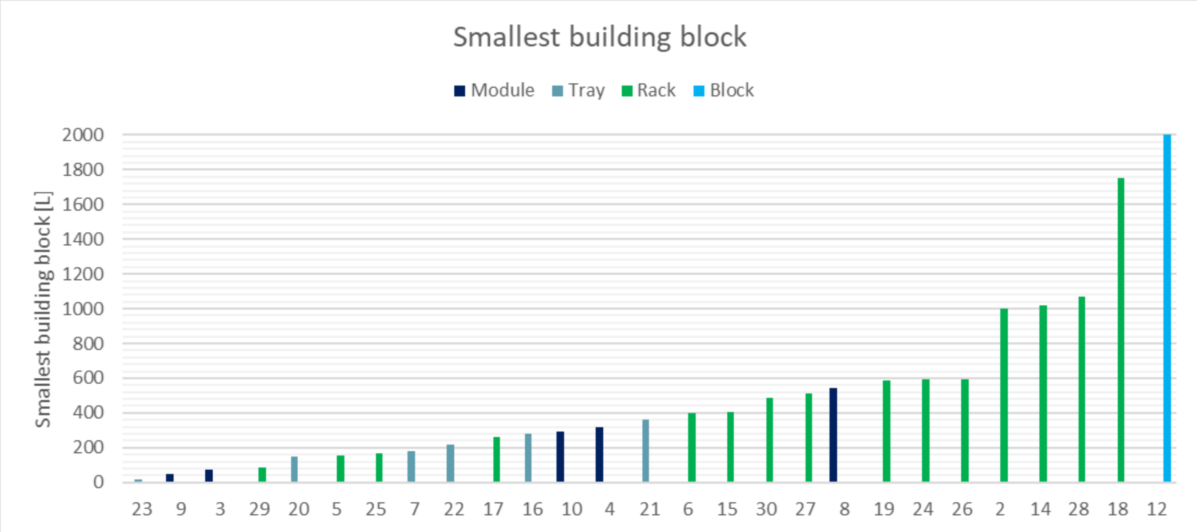

Figure 35 Smallest building block per battery system, excluding 3 largest systems

Considering that the block based systems are the only systems that have a smallest building block which is larger than the average, this average is considered as the threshold for the lowest score. The average score of 3 is determined for the battery systems which have a smallest building block with a volume between 200 L, the average of the tray based systems, and 600 L, the average of the rack based systems. The top score is determined at everything below 100 L, because the module, tray and rack based systems with the smallest building blocks all perform below this point.

Smallest building block [L]	
Score	**Range**
1	> 2230 L
2	> 600 L – 2230 L
3	> 200 L – 600 L
4	100 L – 200 L
5	< 100 L

Table 27 Scoring ranges for smallest building block

3.7.2 Height optimization

The volumetric energy density of a battery system by itself can be significantly smaller compared to the energy density of the complete battery space. Although for the vessel, the size of the battery space can have a large impact. There is no standard height for a battery space. Therefore it can be that a battery system which fits perfectly on one vessel, does not optimize the available volume of the battery space on another vessel. It is investigated what the minimum and maximum height for each battery system are. The difference between this minimum and maximum is then determined as the measure of flexibility in height optimization of the battery system. With a large difference between the minimum height and the maximum height, the battery system can be optimized for all different kind of heights for battery spaces. Some battery systems do not have a maximum possible height, for those systems a maximum height of 3.5 meters is assumed.

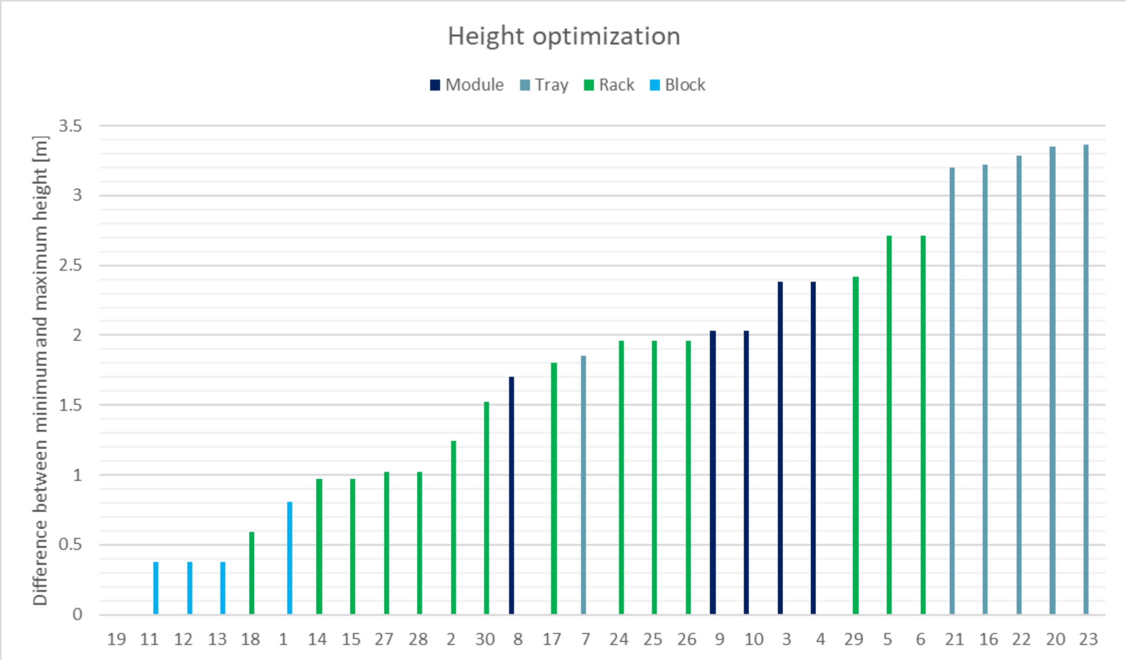

Figure 36 Difference between maximum and minimum height per battery system

There is one rack based battery system which is only available in one height which can't be customized. Therefore this system has 0 m as result for height optimization. This is considered as the lowest possible score. The lowest average is for the block based systems at 0.5 m. The rack based systems have an average of 1.5 m and the module based systems have an average of 2.1 m. The highest average is for the tray based systems at 3.0 m. The total average of all systems combined is 1.8 m. The limit between the score of 2 and 3 is determined to be in between the average of the block based systems and the rack based systems, at 1.0 m. The score of 3 is based on the height optimization up to the average of all systems combined, 1.8 m. The highest score of 5 is determined for all battery systems with a height optimization above the average of the tray based system, so above 3.0 m.

Height optimization [m]	
Score	**Range**
1	0 m
2	> 0 m – 1.0 m
3	> 1.0 m – 1.8 m
4	> 1.8 m – 3.0 m
5	> 3.0 m

Table 28 Scoring ranges for height optimization

3.7.3 Service space

Similar to the optimization in height of the battery system, the required floor surface of the battery system is also an important factor determining the energy density of the battery space. The required floor space is mainly determined by footprint of the battery system, but the service space plays an important role in this. Service space is needed for installation and maintenance of the battery system, however, this space is not effectively used for energy storage. To achieve an energy density as high as possible within a battery space, the service space area should be as small as possible compared to the footprint of the batteries.

The dimensions of the battery space have a large influence on how well the battery system can be optimized to fit within the available floor surface. It can be very beneficial to install two rows of batteries across from each other, so they can both utilize the same floor area as service space. This would then be the most optimal way of installing a specific battery system. Therefore the required service space in percentage of the footprint of the battery system is determined for the most optimal way of placing of the battery system.

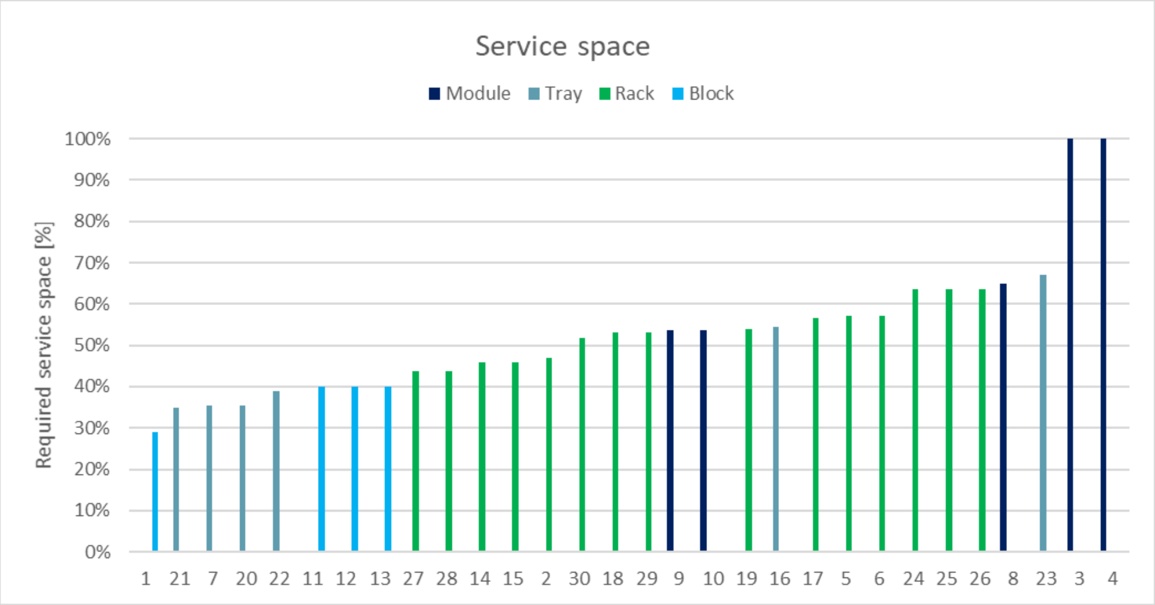

Figure 37 Overview of required service space per battery system

The average required service space over all battery systems is 53%. The battery system which can be optimized on floor surface the most has a required service space of 29%. The battery system with the most required service space compared to the footprint of the batteries needs 100% of service space, meaning that half of the battery space will be filled with air and not energy storage. The lowest service space requirements are for the block based systems at 37% on average. This is the main idea behind block based systems and is what makes them interesting, especially for larger vessels. On second place come the tray based systems, with an average of 44%. Third are he rack based systems with 53% and fourth are the module based systems with an average of 74%.

The lowest score is determined for everything above the average of the module based systems, considering these systems have the highest average of 74%. The highest score is determined for everything below the highest average, which is the average of the block based systems, 37%. The remaining scores are determined by the averages of the module and rack based systems.

Service space [%]	
Score	**Range**
1	> 74%
2	53% - 74%
3	44% - <53%
4	37% - <44%
5	< 37%

Table 29 Scoring ranges for required service space

3.7.4 Integration flexibility

The three scores for smallest building block, height optimization and required service space are combined into one final score for rating the flexibility of a battery system regarding mechanical integration. The battery systems with the highest integration flexibility can be integrated in the most optimal way independent of the shape and size of the battery room. This makes the battery system deployable for as many different ship types as possible, while achieving the highest energy density on battery space level.

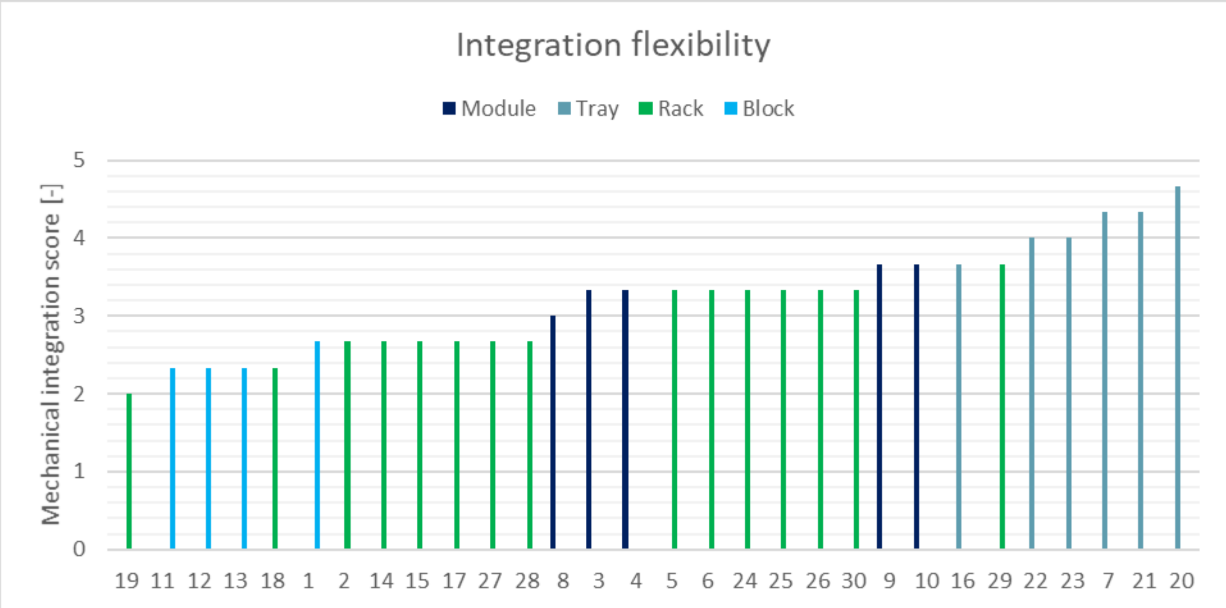

Figure 38 Overview of overall scores for integration flexibility per battery system

On average score for integration flexibility is 3.2, with a lowest score of 2.0 and a highest score of 4.7. The battery systems which score the lowest on integration flexibility are the block based systems with an average score of 2.4. The rack based systems score a bit higher with an average of 2.9. In second place come the module based systems with an average of 3.4 and the highest average score is for the tray based systems with an average of 4.2.

3.8 Electrical integration

As discussed in section 2.9 the voltage requirements for a fixed bus are based around a 700Vdc and 1000Vdc level. Ideally for a battery system it has to be possible to adjust the nominal voltage to match the requirements for a 700Vdc and a 1000Vdc bus. However, in the case of a floating bus the voltage requirements are determined by all components connected to the bus and this can vary significantly from case to case. Therefore the possibility of a battery system to adjust its nominal voltage level to fit the system's requirements is considered to be an added value to the performance of the system, so it can be applied in a multitude of differently designed propulsion systems. However, it is not only the voltage range that is important. A higher voltage level will require a smaller current to achieve the required power and therefore it will always be beneficial to design the battery system to have a voltage level as high as possible within the system's limits. The maximum voltage, voltage window, voltage range and voltage step are used to determine the electrical performance. Additionally, during installation it is considered safer to have as few connections to be made as possible, which is the fifth characteristic evaluated on the subject of electrical integration.

3.8.1 Maximum nominal voltage

A higher nominal voltage results in lower currents. Therefore it is considered to be positive if a battery system can be designed to match the highest nominal voltage within the limits of the electrical system. In Figure 39 the maximum possible nominal voltage of all battery systems is shown.

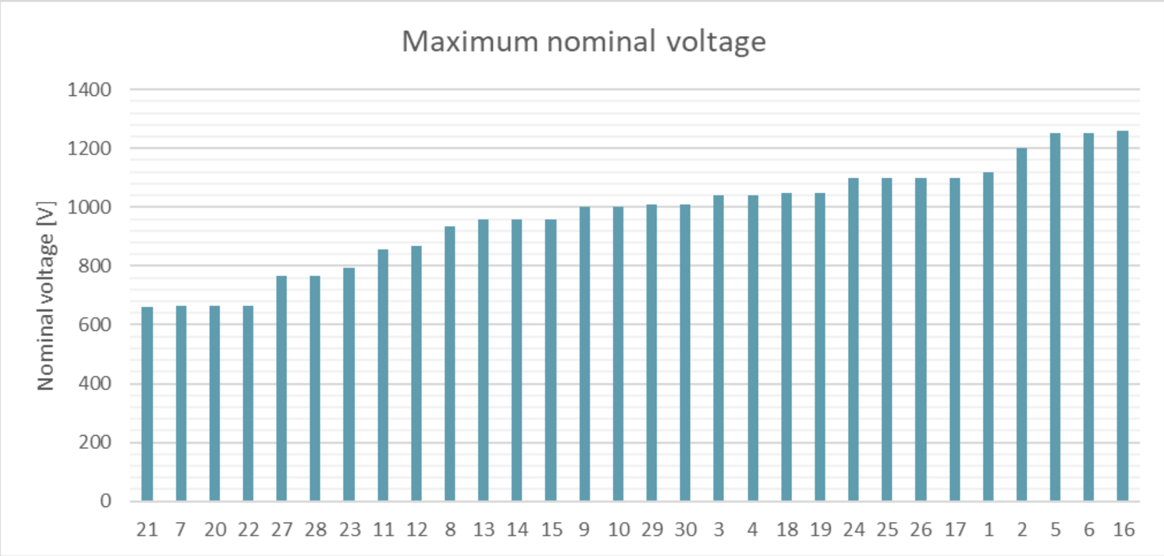

Figure 39 Overview of maximum nominal voltage per battery system

The average maximum nominal voltage of all systems combined is 973V. The highest nominal voltage is 1258V and the lowest nominal voltage is 662V. The nominal voltage is between 12% and 18% lower than the maximum voltage, depending on the type of cells being used. On average this is assumed to be 15% for simplification. 700V is the minimum requirement from a fixed bus voltage point of view. Therefore a maximum nominal voltage of 15% below 700V is assumed to be the minimum requirement and everything below that level of approximately 600V is considered as the lowest score. Similar for the voltage level of 1000V for a fixed bus, the limit for the second lowest score is 850V, as it is 15% below 1000V. The average score is determined to be from 850V up to 1000V and the score of 4 is determined from 1000V up to the current maximum of 1258V nominal voltage. The highest score is considered for future battery systems which might be able to go above 1258V.

Maximum nominal voltage [V]	
Score	**Range**
1	< 600 V
2	600 V – 850 V
3	>850 V – 1000 V
4	>1000 V – 1258 V
5	> 1258 V

Table 30 Scoring ranges for maximum nominal voltage

3.8.2 Voltage window

The voltage window is determined by the difference between the voltage at 100% and at 0% SOC. The difference in percentage between the minimum voltage and the maximum voltage is used to determine the score for the voltage window.

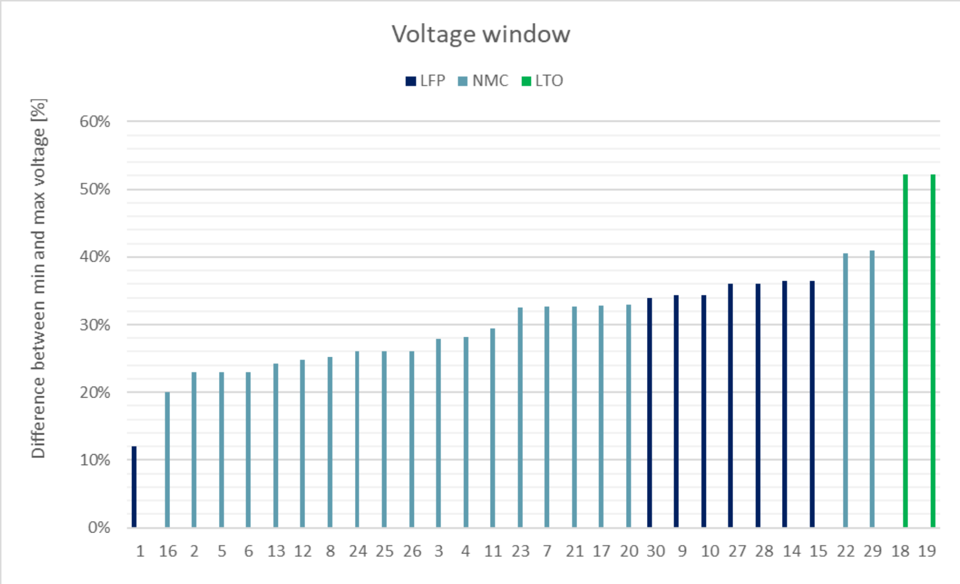

Figure 40 Difference between minimal and maximal voltage in %

On average the maximal voltage is 31% higher compared to the minimal voltage. The battery system with the smallest difference has a maximal voltage which is 12% higher compared to the minimal voltage. The largest difference between the minimal and maximal voltage is 52%. In general the NMC based systems have a smaller difference between the minimal and maximal voltage, except for one system with LFP cells which has the smallest difference. The LTO cells have the largest difference between the minimal and maximal voltage.

Voltage window [%]	
Score	**Range**
1	> 50%
2	40% – 50%
3	30% – < 40%
4	20% – < 30%
5	< 20%

Table 31 Scoring ranges for voltage window (difference between maximum and minimum voltage)

3.8.3 Voltage range

Figure 41 shows the overview of the range of the minimum and maximum, nominal voltages for all battery system in this analysis, sorted on the difference between the minimum and maximum, the range. As mentioned, a larger nominal voltage range is considered to be beneficial for the design flexibility and application of the battery system in different propulsion system designs.

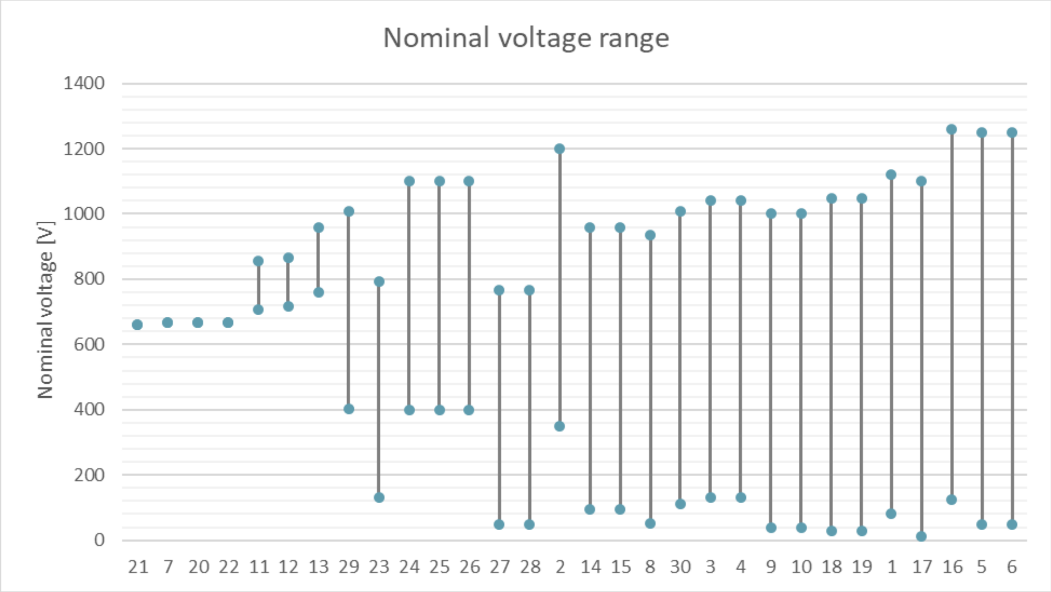

Figure 41 Overview of nominal voltage range per battery system

As the maximum nominal voltage is already discussed in section 3.8.1, here only the absolute range of the nominal voltage is compared, independent of the minimum and maximum.

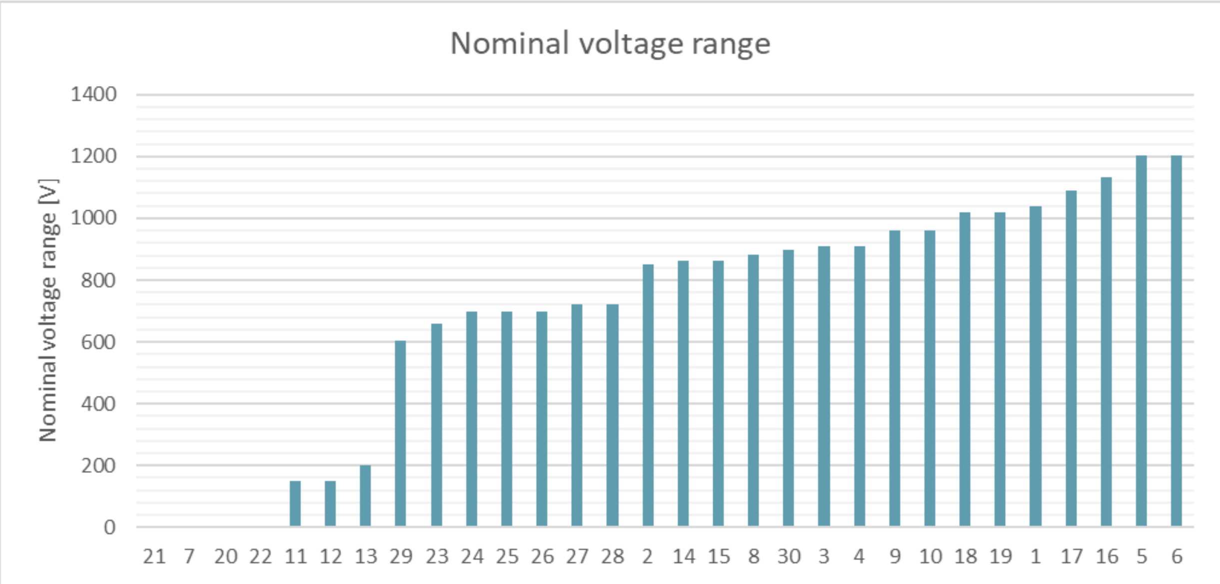

Figure 42 Overview of absolute nominal voltage range per battery system

There are 4 battery systems in the comparison that do not have a variable nominal voltage and there are 3 battery systems with a nominal voltage range below 200V. The battery systems with the highest variability in nominal voltage have a difference of 1202V in minimum and maximum nominal voltage. The average voltage range calculated over all 30 battery systems is 704V. Not taking the 4 battery systems into account which do not have a variable nominal voltage, the average is 812V. Without the 3 battery systems with a voltage range below 200V as well, the average voltage range is 896V. The lowest score is determined for the battery systems which do not have a variable voltage. The second lowest score is determined for the battery systems which have a voltage range up to 600V. Then the average score is linked to the average of 812V, not taking the 4 non variable battery systems into account. A voltage range of 1000V or higher is considered to result in the highest score.

Voltage range [V]	
Score	**Range**
1	0 V
2	0 V – 600 V
3	>600 V – 812 V
4	>812 V – 1000 V
5	> 1000 V

Table 32 Scoring ranges for voltage range

3.8.4 Voltage step

The flexibility of a battery system to adjust the nominal voltage to the requirements of the electrical system on board of the ship is determined by the voltage step at which the nominal voltage can very between the minimum and the maximum value. A smaller voltage step results in a higher flexibility.

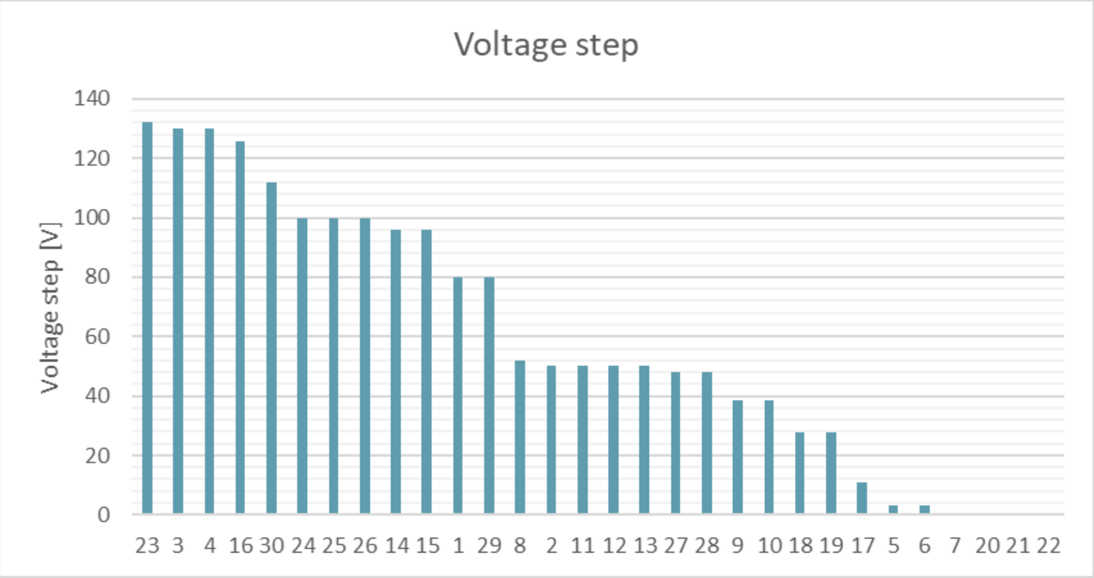

Figure 43 Overview of voltage step per battery system

There are 4 battery systems which do not have a variable nominal voltage. Therefore the lowest score is related to the battery systems with a voltage step of 0V. The largest voltage step is 132V and the smallest voltage step is 3V. The average voltage step over all battery systems is 59V, which is determined as the limit for the average score of 3. A voltage step above 100V is considered for a below average score. Between 59V and 10V is considered as above average. A voltage step below 10V is determined to result in the highest score.

Voltage step [V]	
Score	**Range**
1	0 V
2	> 100 V
3	>59 V – 100 V
4	10 V – 59 V
5	< 10 V

Table 33 Scoring ranges for voltage step

3.8.5 Power connections

Every power connection that has to be made during installation of the battery system on board of the vessel is a potential hazard due to human error or mechanical error. Therefore the installed capacity per power connection is analyzed by comparing the embedded energy per battery module, resulting in a specific capacity in kWh per power connection.

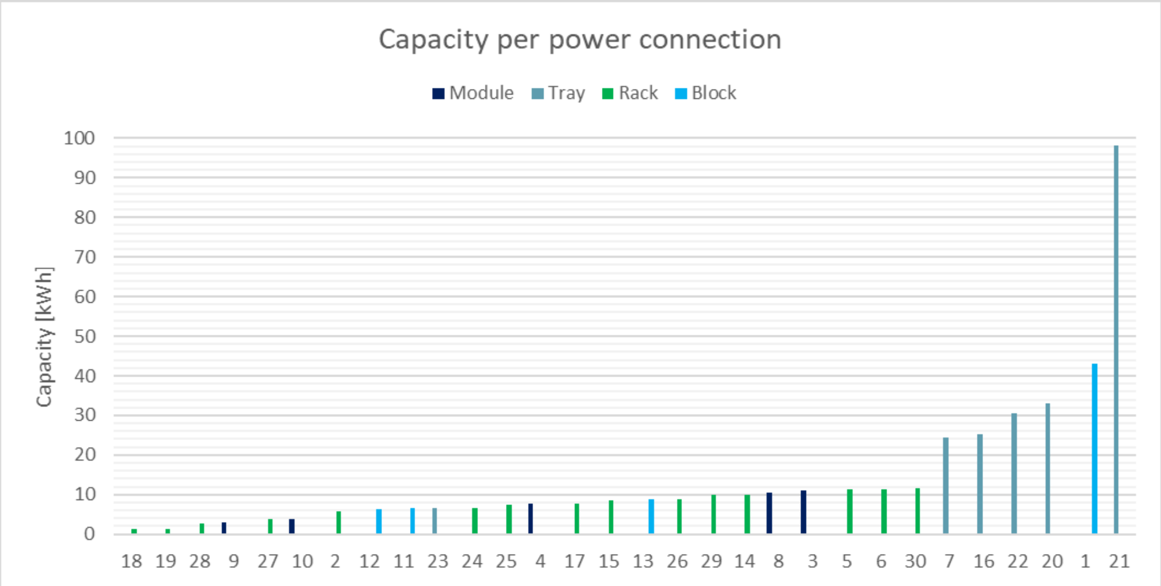

Figure 44 Overview of capacity in kWh per module

The system with the highest amount of power connections per installed energy has a capacity of 1.2 kWh per module. The system with the least amount of power connections per installed energy has a capacity of 98 kWh. The average capacity per module is 14 kWh, therefore the average score is determined between 10 and 20 kWh. The module and rack based systems have the lowest average capacity per module of 7 kWh. Therefore the score of 2 is determined for the range of 5 to 10 kWh. Below 5 kWh per module is therefore the lowest score. The block based systems have an average capacity per module of 16 kWh and the tray based systems have an average embedded energy of 36 kWh. The above average score of 4 is therefore determined for the range from 20 to 50 kWh. Above 50 kWh per module results in the highest score of 5.

Capacity per module [kWh]	
Score	**Range**
1	< 5 kWh
2	5 kWh – < 10 kWh
3	10 kWh – < 20 kWh
4	20 kWh – 50 kWh
5	> 50 kWh

Table 34 Scoring ranges for capacity per module

3.8.6 Electrical integration score

The total score for the electrical integration is based on the 5 factors as described above, the maximum nominal voltage, voltage window, voltage range, voltage step and the capacity per module. A high overall score for electrical integration indicates that a battery system is flexible in its design to fit into different types of vessels and electrical propulsion systems.

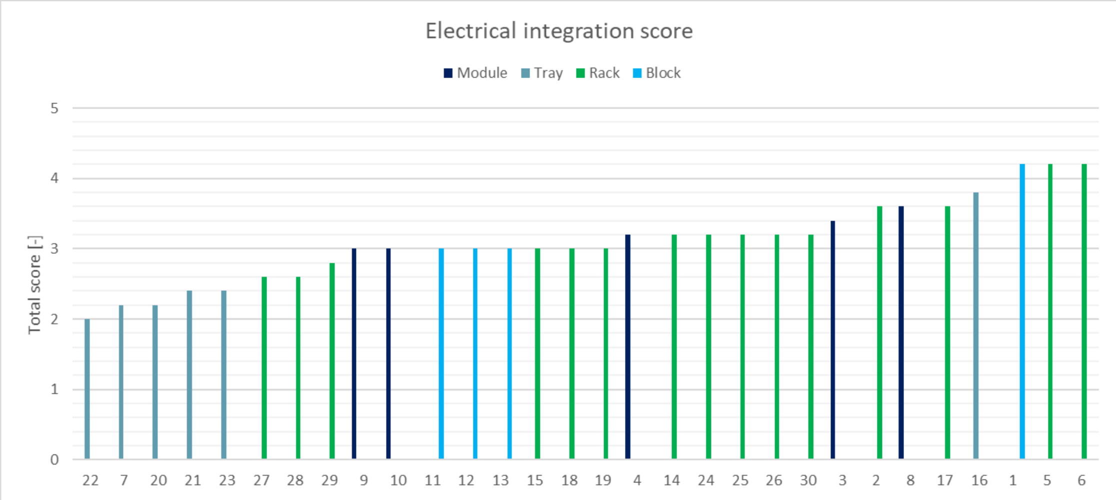

Figure 45 Overview of overall score for electrical integration

The average score for electrical integration is 3.1. The lowest average score is for the tray based systems, with an average of 2.5. The module and rack based systems have an average score of 3.2 and the highest score is for the block based systems with an average of 3.3. The averages of the block, module and rack based systems are close to each other. Only the tray based systems have a significantly lower average score. This is caused by the fact that most tray based systems do not have a variable voltage range.

3.9 Battery Management System

The battery management systems are rated based on 3 different categories: BMS architecture, cell balancing and BMS sensors. Each of the topics consists of multiple subcategories. Not all of the information on these subcategories is available for some of the battery suppliers. Therefore the subcategories are used together to determine 1 score for each category, normalized for the number of subcategories for which information was available. Therefore a comparison can be made between different battery systems even without all information available for all systems.

Also, some subcategories only have two options as possible outcome. The battery systems can score only a 2 or a 4 on these subcategories, relating to below average and above average. This allows for these subcategories to be taken into account in the same rating system based on the score 1 to 5.

3.9.1 BMS architecture

The BMS architecture is rated on 3 subcategories: the number of strings that can be connected in parallel per BMS, the power consumption per BMS and the internal redundancy of the BMS, as explained in section 2.10.

The number of strings that can be connected in parallel can vary from 1 to unlimited. As for every BMS a connection with the PMS, EMS or AMCS of the vessel is required for communication, it is assumed that a larger number of strings connected in parallel results in a system which can be upscaled more easily without increasing the complexity of integration and installation on automation level. The highest score is for the unlimited number of parallel connections. The lowest score is for the systems with a complete BMS on system level per string. On average it is possible to connect between 8 and 12 strings in parallel per BMS.

Strings in parallel per BMS	
Score	**Range**
1	1
2	> 1 - < 8
3	8 – 12
4	> 12
5	Unlimited

Table 35 Scoring ranges for number of strings in parallel possible per BMS

The power consumption per BMS is assumed to be a measure of efficiency of the battery system. A BMS can be responsible for powering different amounts of strings and a string can have a different capacity depending on the type of system and specific system design. Therefore the power consumption per BMS is calculated per kWh of battery capacity for which the BMS is responsible. Because the design of most battery systems can be quite flexible in number of strings per BMS and the installed capacity per string, these numbers are based on estimates for a 1000V system and the numbers can be varying compared to the power consumption of the BMS in reality, depending on the actual system design. The BMS with the lowest power consumption has a consumption of 0.04 W per installed kWh. The BMS with the highest power consumption has a consumption of 1.82 W per installed kWh. On average the power consumption of the BMS is calculated at 0.91 W per installed kWh. The scores are based on this distribution. Therefore, a consumption above 1.82 W/kWh equals a score of 1 and a consumption below 0.04 W/kWh results in a score of 5. Between 1.82 and 0.04 is divided in 3 equal parts, matching the remaining scores.

Power consumption BMS per kWh [W/kWh]	
Score	**Range**
1	> 1.82
2	1.23 – 1.82
3	0.63 – <1.23
4	0.04 – <0.63
5	< 0.04

Table 36 Scoring ranges for power consumption per BMS per installed kWh

Integrated redundancy within the BMS is for marine battery systems an important requirement. A single failure inside the BMS should not be able to cause the battery system to be disconnected during operation and therefore most of the marine battery systems have a redundancy function integrated into the BMS. Because for the redundancy only the options yes or no are identified as possibility, a system can either score 4 points for 'yes', having a redundancy function integrated into the BMS, or 2 points for 'no', not having a redundancy function integrated into the BMS.

Redundancy function integrated in BMS	
Score	**Range**
2	No
4	Yes

Table 37 Scoring ranges for redundancy function BMS

3.9.2 Cell balancing

The cell balancing functionality of the BMS is rated on 4 subcategories as explained in section 2.10. Balancing can be performed passive or active, the process can be started automatically or manually, the accuracy of the determining the unbalance of cell voltages and the balancing current, which determines the speed of the process.

Cell balancing as explained in section 2.10 can be a passive or active process. With passive balancing energy is dissipated and therefore less efficient. Passive balancing results in a score of 2 and active balancing results in a score of 4.

Passive or active balancing	
Score	**Range**
2	Passive
4	Active

Table 38 Scoring ranges for passive or active cell balancing

Most battery systems start the balancing function automatically based on several conditions. However, it also occurs that the crew is required to initiate the balancing function when the unbalance of the cells becomes too large. An automatic start is preferred as it reduces the amount of time the battery cells can be unbalanced and a manual required start increases the responsibilities for the crew.

Automatic or manual start of balancing	
Score	**Range**
2	Manual
4	Automatic

Table 39 Scoring ranges for manual or automatic start of cell balancing

Most balancing functions are initiated based on a difference in cell voltage of several mV. The smaller this difference is, the larger the accuracy of the balancing function and the more balanced the system will be. The battery system with the lowest accuracy starts balancing at a difference of 20 mV between two battery cells. The system with the highest accuracy starts balancing at a difference of 1.5 mV between two battery cells. These are therefore determined to be the limits for the lowest and highest score respectively. The average accuracy is around 10 mV, resulting in the distribution of scoring ranges as shown below.

Balancing accuracy [mV]	
Score	**Range**
1	>20
2	>12.5 – 20
3	>7.5 – 12.5
4	1.5 – 7.5
5	< 1.5

Table 40 Scoring ranges for balancing accuracy

The speed of the balancing process is mainly depending on the current with which the cells can be balanced. A higher balancing current results in a faster balancing process. The battery system with the highest balancing current can balance the cells at 3A. The lowest balancing current is 105 mA and on average, based on the available information, the balancing current is around 1A. However, this does not say anything relevant because of the different sizes of the battery cells. Therefore the balancing current is divided by the capacity of the cell in Ah, resulting in a balancing current in mA/Ah. The scores are determined based on the ranges in mA/Ah as shown below. Below 5 mA/Ah results in the lowest score and above 20 mA/Ah results in the highest score. Then the remaining 3 scores are equally divided between that with steps of 5 mA/Ah.

Balancing current [mA/Ah]	
Score	**Range**
1	< 5
2	5 – <10
3	10 – <15
4	15 - <20
5	≥ 20

Table 41 Scoring ranges for balancing current

3.9.3 BMS sensors

The functionality of the sensors of the BMS is rated on 3 subcategories as explained in section 2.10: the number of cells per voltage sensor, the number of cells per temperature sensor and if the battery system has an integrated thermal runaway exhaust gas sensor.

A lower number of cells per voltage sensor is assumed to result in a higher safety of the battery system as a failure on cell level can be noticed with a higher accuracy. Based on the available information there are only 3 different options: 2 cells per voltage sensor, 1 cell per voltage sensor or 2 sensors per 1 cell. Having more than 2 sensors per battery cell is considered to be ineffective, therefore there are only 4 scores possible, from 1 to 4. The highest score of 4 is for the systems with 2 sensors per 1 battery cell, so 0.5 cells per sensor. The score of 3 is determined for the systems with 1 cell per sensor. The score of 2 is determined for the systems with 2 cells per sensor. The lowest score of 1 is determined for the battery systems with more than 2 cells per voltage sensor.

Number of cells per voltage sensor	
Score	**Range**
1	> 2
2	2
3	1
4	0.5

Table 42 Scoring ranges for number of cells per voltage sensor

Similar to the voltage sensors, a lower number of cells per temperature sensor is assumed to result in a higher safety. The system with the highest number of battery cells per temperature sensor has 14 cells per sensor. The system with the lowest number of battery cells per temperature sensor has 0.5 cells per sensor, so 2 sensors per every battery cell. Resulting in an additional layer of redundancy. This is assumed to be the maximum, as more temperature sensors per battery cell is considered to be ineffective. On average, based on the available information, there are 4 cells per temperature sensor. This resulted in the distribution of scoring ranges as shown in the table below.

Number of cells per temperature sensor	
Score	**Range**
1	> 14
2	10 - 14
3	4 - 10
4	1 - < 4
5	< 1

Table 43 Scoring ranges for number of cells per temperature sensor

A thermal runaway is one of the highest risks to be considered for a battery system. Before and during a thermal runaway gases are released by the battery cells. Although voltage and temperature measurements can notice a thermal runaway as well, gas detection is often considered necessary as additional safety function for marine battery systems. Based on the detection of these gases the ventilation system of the battery space can be activated to remain a safe environment on board of the vessel. Most battery systems do not have an integrated gas detection sensor. Therefore it is the responsibility of the ship designers and builders to integrate this within the battery space. This leaves the possibility for flaws in the battery space design. Also, most of the available gas detection sensors for open spaces such as a battery space require frequent maintenance and calibration of the sensors. This results in additional responsibilities for the crew of the vessel and more possibilities for system failures. Having a gas detection sensor integrated into the battery system is therefore considered to reduce the complexity of integrating a battery system on board of a vessel in a safe way.

Integrated gas sensor	
Score	**Range**
2	No
4	Yes

Table 44 Scoring ranges for integrated gas detection sensor

3.9.4 Overall BMS score

Not all information of all battery system suppliers was available for this research. This is taken into account for the calculation of the overall score for the battery management systems. The overview of the BMS score for all battery systems in this comparison is shown in Figure 46. The lowest score for the performance of a BMS is 2.0, the highest achieved score is 3.8. The average score for all systems combined is 3.1. There is no clear relation identified between the design of the system and the BMS score.

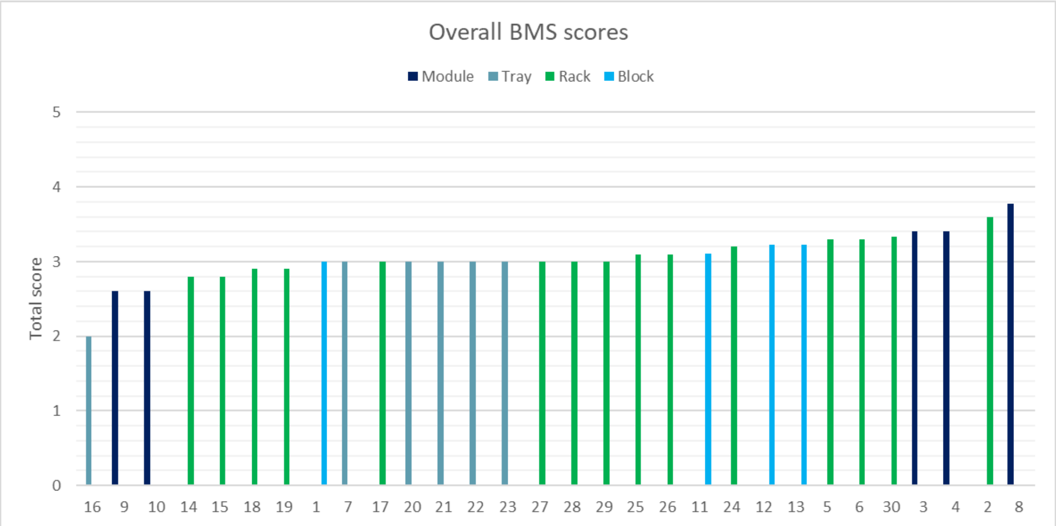

Figure 46 Overview of overall scores for BMS per battery system

4 Battery performance

The battery system performance is calculated based on the KPI rating system as described in chapter 3. This chapter provides the overview of all 30 battery systems and how they score compared to each other. First the overview is provided with equal weighting of all categories. The results are shown for the different cell chemistries and for the different types of system design. Then the scores are given varying weighting factors to show which systems perform better when different requirements play a more important role in the design of the battery system. Therefore the category under investigation is given a weight factor of 5, to increase the importance compared to the other categories. This is approached from 5 different assumptions, determining which battery systems have the highest overall performance if:

- overall costs are the most important factor
- energy is the most important factor
- power is the most important factor
- battery lifetime is the most important factor
- safety is the most important factor
- electrical integration flexibility is the most important factor

4.1 Cell chemistry performance

Figure 47 shows the comparison of the costs per cycled kWh and the overall performance score of all battery systems divided based on the used cell chemistry. The highest scoring battery systems have LTO cells, with an average score of 3.5. The systems based on NMC cells have an average score of 3.0 and the systems based on LFP cells have an average score of 2.7. Additionally the systems with the lowest costs per cycled kWh are either based on LTO cells or NMC cells.

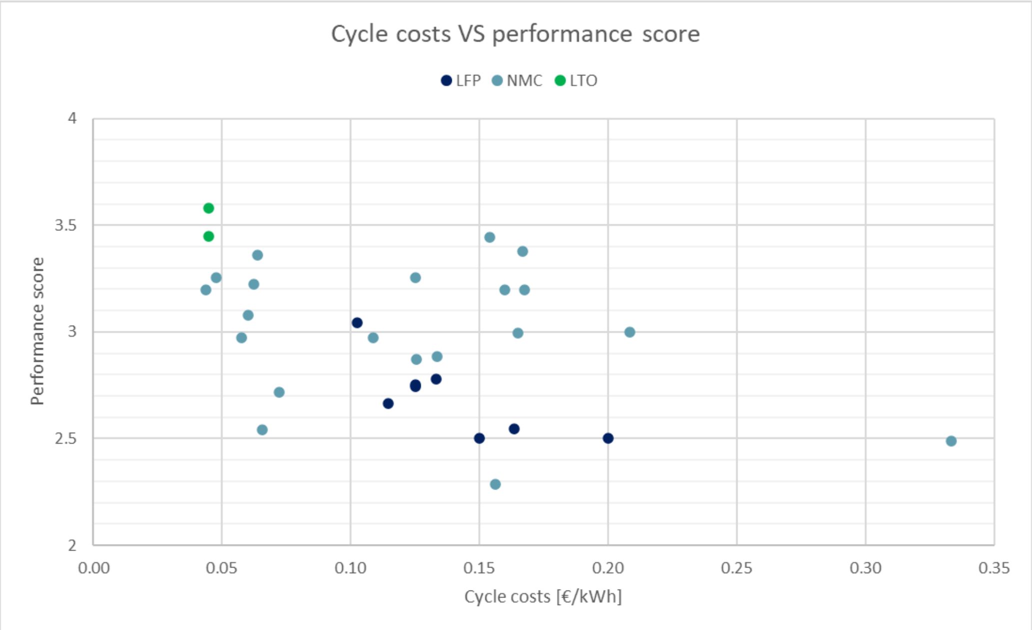

Figure 47 Costs per cycle compared to battery performance for different cell chemistries

4.2 Overall battery performance

The analysis of the overall performance score of all 30 battery systems shown in Figure 48. The average performance score for all battery systems combined is 3.0. The lowest scoring battery system has an overall performance of 2.3. The highest scoring battery system has an overall performance of 3.5.

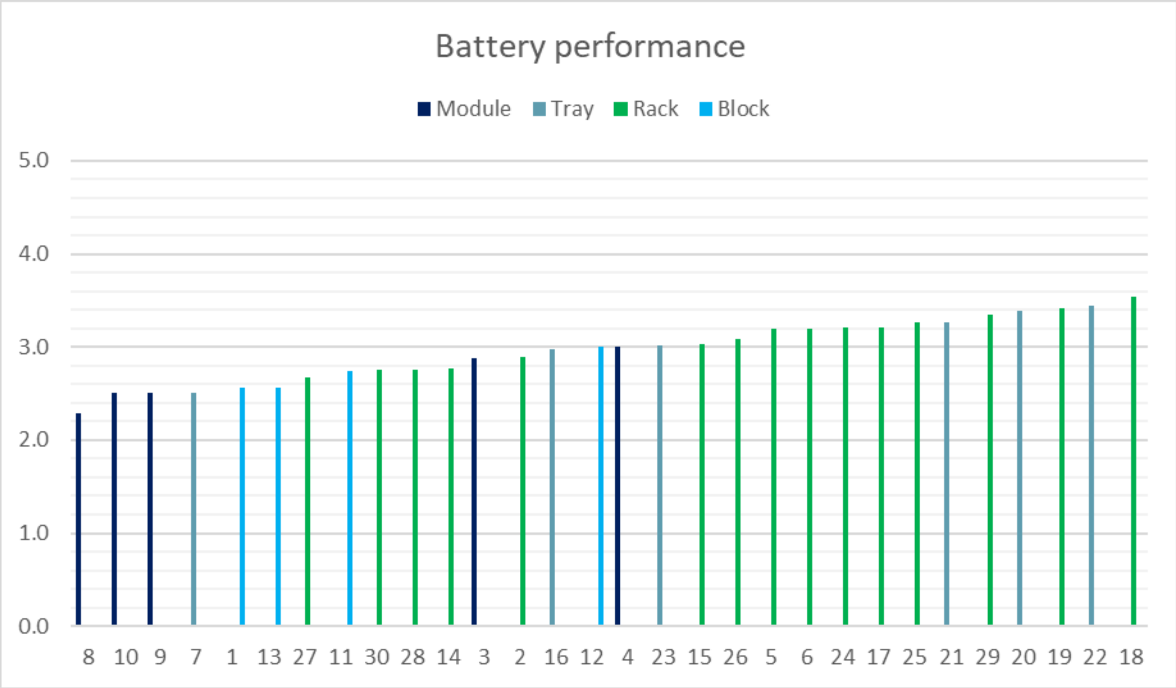

Figure 48 Overview of overall performance score per battery system

For each of the 4 different battery system designs the average, lowest and highest overall score is determined, shown in Table 45.The tray and rack based battery systems have the highest average scores of 3.1. However, the lowest and highest scores of the rack based systems are higher compared to the lowest and highest scores for the tray based systems. Therefore it is determined that rack based systems score the highest on overall performance and tray based systems are in a second place. Block based systems come in at a third place with an average of 2.7 and the module based systems have the lowest average score of 2.6.

	Module	Tray	Rack	Block
Average score	2.6	3.1	3.1	2.7
Lowest score	2.3	2.5	2.7	2.6
Highest score	3.0	3.4	3.5	3.0

Table 45 Overview of average, lowest and highest score per battery system design

4.3 Costs

The importance of the score for system costs and cycle costs is multiplied by 5 to see the effect on the overall performance of the different battery systems. This resulted in a change in score for most of the systems.

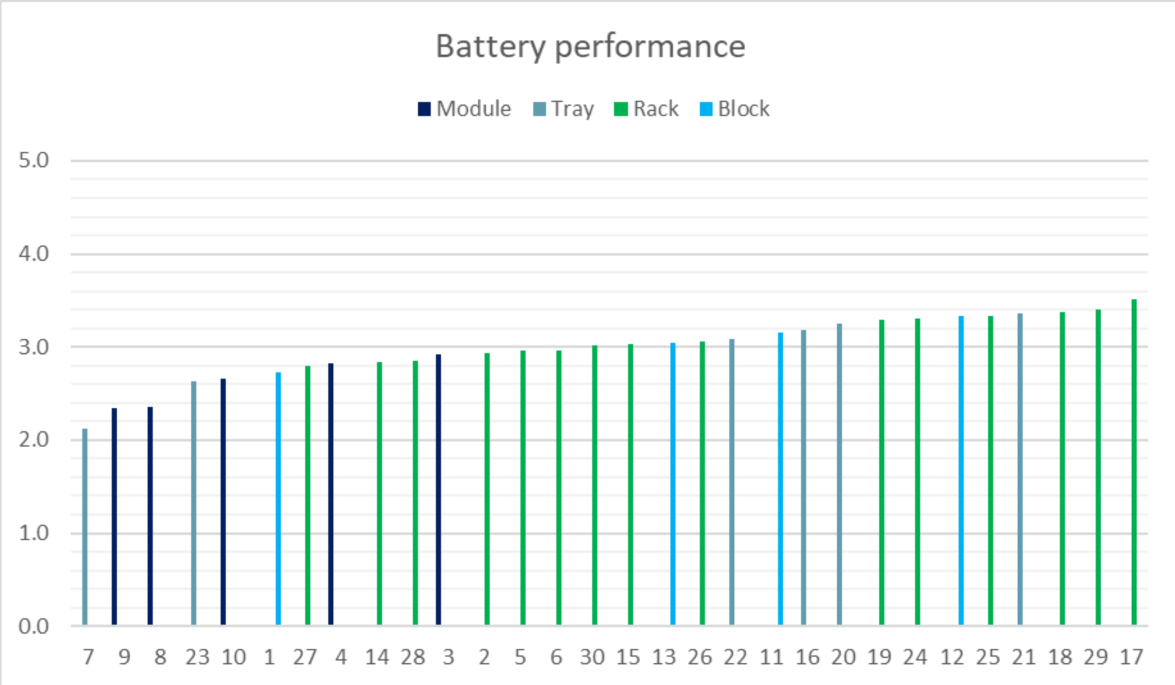

Figure 49 Overview of overall score per battery system with highest importance to costs

The largest negative change happened for the tray based systems, where the average score dropped by 0.2 and the lowest scoring system even score 0.4 points less. The module based systems only have a reduced top score and remain the lowest scoring battery system design. The largest positive change occurred with the block based systems, where the average increased by 0.4 points. This results in an average of 3.1, which is similar to the average score of the rack based systems. Although the lowest and highest scores for the block based systems also increased significantly, the racks based systems still score higher on the highest score.

	Module	Tray	Rack	Block
Average score	2.6	2.9 **(-0.2)**	3.1	3.1 **(+0.4)**
Lowest score	2.3	2.1 **(-0.4)**	2.8 **(+0.1)**	2.7 **(+0.1)**
Highest score	2.9 **(-0.1)**	3.4	3.5	3.3 **(+0.3)**

Table 46 Overview of average, lowest and highest score per battery system design with highest importance to costs

4.4 Energy

The score for the categories of energy and mechanical integration have been multiplied by a factor 5 to determine the best performing battery systems when a high overall energy density is required. This is not only depending on the energy density at battery system level, but also at battery space level. Therefore all the mechanical integration properties are taken into account as well.

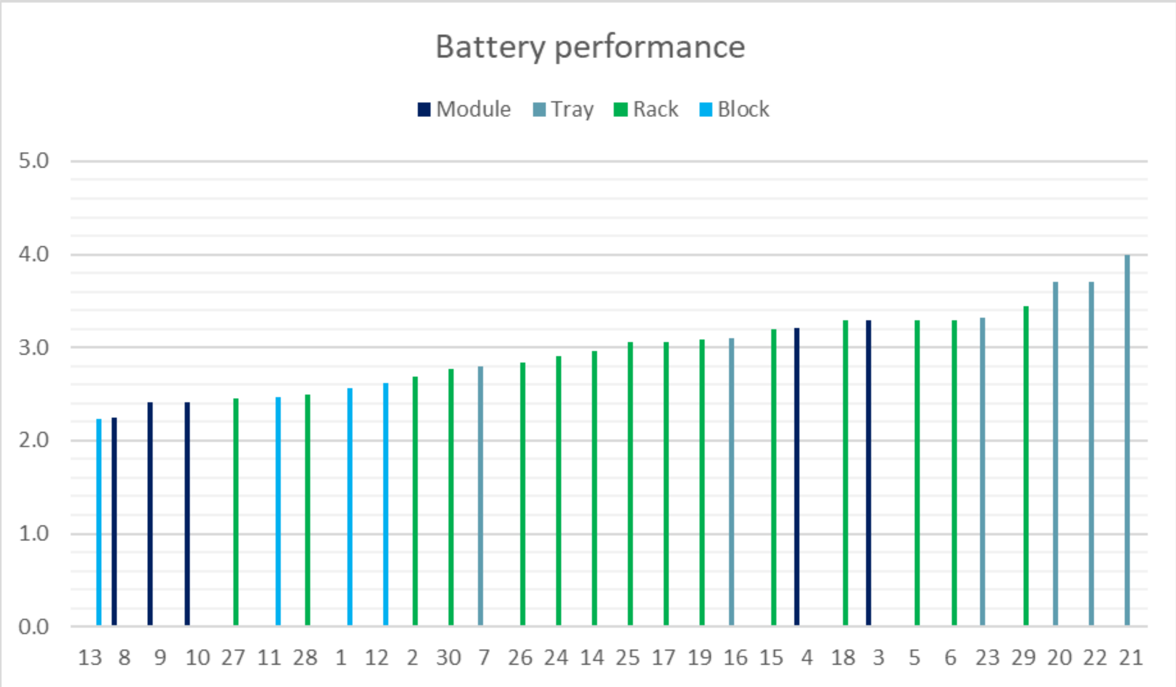

Figure 50 Overview of overall score per battery system with highest importance to energy

The result is that the block based systems decrease the most in points and score the lowest on average. Also the rack based systems decrease significantly on the average, lowest and highest scores, but these are still higher scores compared to the module based systems. The module based systems score slightly better when energy is important, especially the highest score increases significantly. The tray based systems score the highest and show the largest increase of all system scores when energy is an important factor.

	Module	Tray	Rack	Block
Average score	2.7 (+0.1)	3.4 (+0.3)	3.0 (-0.1)	2.5 (-0.2)
Lowest score	2.2 (-0.1)	2.8 (+0.3)	2.5 (-0.2)	2.2 (-0.4)
Highest score	3.3 (+0.3)	4.0 (+0.6)	3.4 (-0.1)	2.6 (-0.4)

Table 47 Overview of average, lowest and highest score per battery system design with highest importance to energy

4.5 Power

The score for the categories of power and thermal management have been multiplied by a factor 5 to determine the best performing battery systems when a high overall power density is required. This is not only depending on the power density or C-rates at battery system level, but also by the efficiency of the cooling system. At high power a battery will generate more heat, which will have to be cooled in an effective way. Therefore all the thermal management properties are taken into account as well.

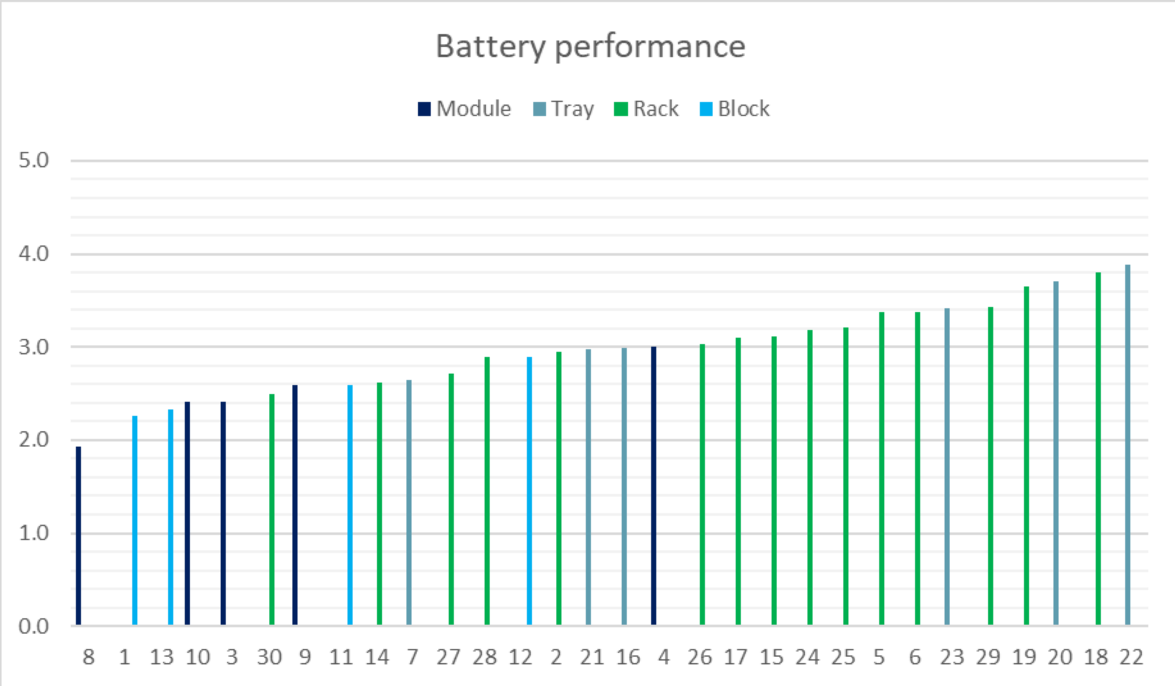

Figure 51 Overview of overall score per battery system with highest importance to power

Based on high power requirements the block based systems score significantly lower. This is not surprising as most block bases systems are design as high energy systems for large vessels. The module based systems also score lower based on power and have the same average score compared to the block based systems. The rack based systems have a reduced lowest score and an increased highest score, which results in the same average. The largest improvement is shown for the tray based systems, which score the highest when it comes to high power requirements.

	Module	Tray	Rack	Block
Average score	2.5 **(-0.1)**	3.3 **(+0.2)**	3.1	2.5 **(-0.2)**
Lowest score	1.9 **(-0.4)**	2.6 **(+0.1)**	2.5 **(-0.2)**	2.3 **(-0.3)**
Highest score	3.0	3.9 **(+0.5)**	3.8 **(+0.3)**	2.9 **(-0.1)**

Table 48 Overview of average, lowest and highest score per battery system design with highest importance to power

4.6 Lifetime

Battery lifetime is approached from the number of cycles which can be performed at 80% DoD and the maximum design life in years of a battery system. When this is determined as the highest importance by multiplying these sub categories by a factor 5, the following is the result.

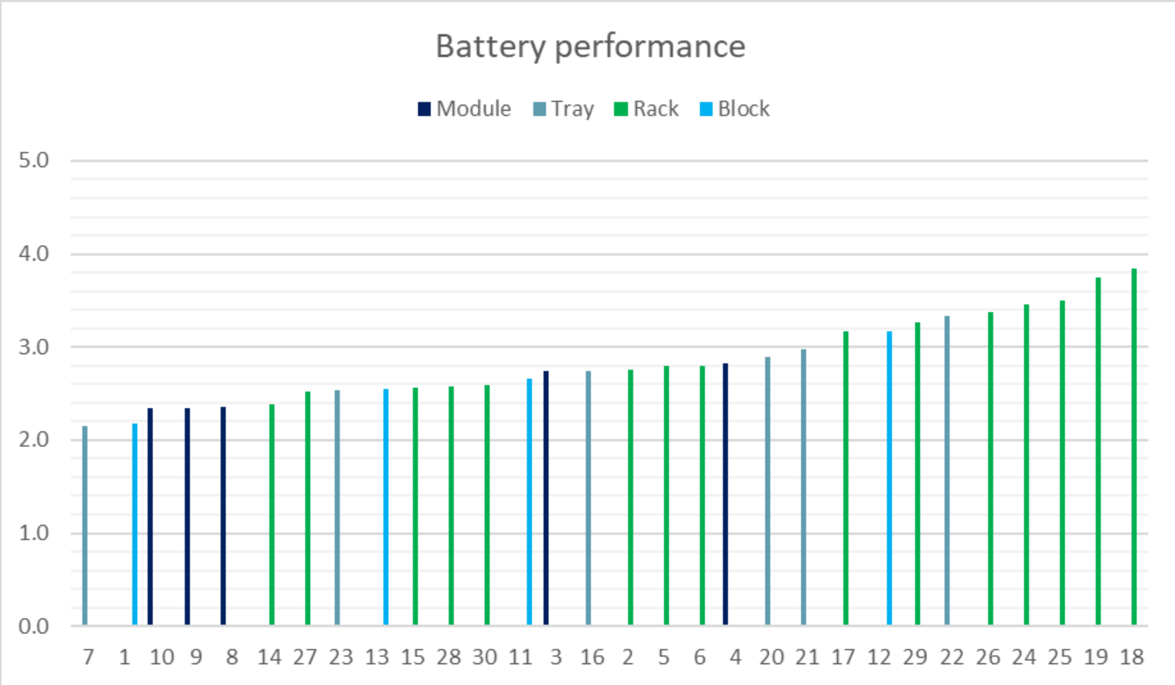

Figure 52 Overview of overall score per battery system with highest importance to lifetime

Almost all scores for almost all battery systems go down. Only the highest scoring rack and block based systems increase, but all the averages go down as well as the lowest scores. The rack based systems remain the system design with the highest average score, followed by the tray based systems. Then the block based systems follow in third place and the module based systems in fourth place. The lifetime is mainly dependent on the type of battery cell chemistry and therefore the system design is usually not of importance. Only for a few NMC based systems which can achieve high cycle life or calendar life due to efficient cooling of the cells as well as the LTO based systems, the lifetime scores above average. Therefore if lifetime is an important factor, these specific systems stand out significantly, but this is unrelated to system design.

	Module	Tray	Rack	Block
Average score	2.5 (-0.1)	2.8 (-0.3)	3.0 (-0.1)	2.6 (-0.1)
Lowest score	2.3	2.1 (-0.4)	2.4 (-0.3)	2.2 (-0.4)
Highest score	2.8 (-0.2)	3.3 (-0.1)	3.8 (+0.3)	3.2 (+0.2)

Table 49 Overview of average, lowest and highest score per battery system design with highest importance to lifetime

4.7 Safety

The fifth category which is investigated is safety and the importance of all the subcategories in the safety category are multiplied by a factor 5.

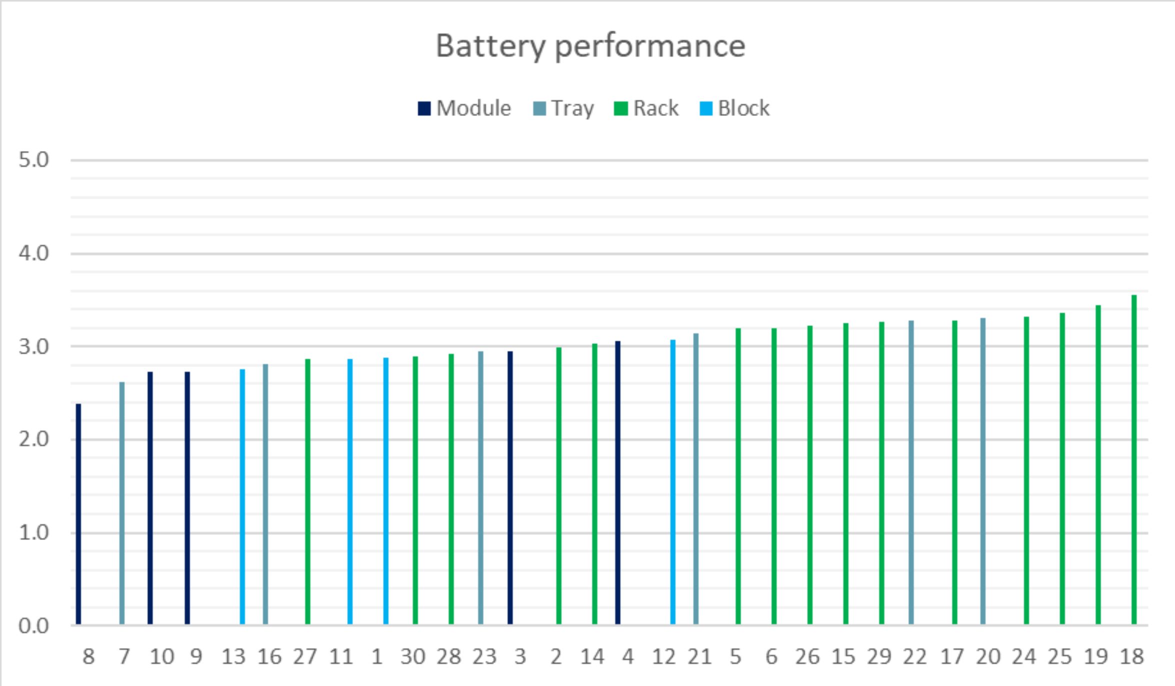

Figure 53 Overview of overall score per battery system with highest importance to safety

The overall score for the module, rack and block based systems increased. The rack based systems score the highest. The tray based system still has the second highest average score, however it does decrease when safety is important. From the rack and block based systems the integrated safety features result in this increase when safety is more important. For the module based systems it is assumed that due to the lack of these integrated safety features, the basic safety is already considered in the basic design of the module. Tray based systems overall require the most additional measures in the battery space to create a safe installation on board the vessel.

	Module	Tray	Rack	Block
Average score	2.8 (+0.2)	3.0 (-0.1)	3.2 (+0.1)	2.9 (+0.2)
Lowest score	2.4 (+0.1)	2.6 (+0.1)	2.9 (+0.2)	2.8 (+0.2)
Highest score	3.1 (+0.1)	3.3 (-0.1)	3.6 (+0.1)	3.1(+0.1)

Table 50 Overview of average, lowest and highest score per battery system design with highest importance to safety

4.8 Electrical integration flexibility

The flexibility of different types of battery system designs is investigated by multiplying the scores for electrical integration by a factor 5.

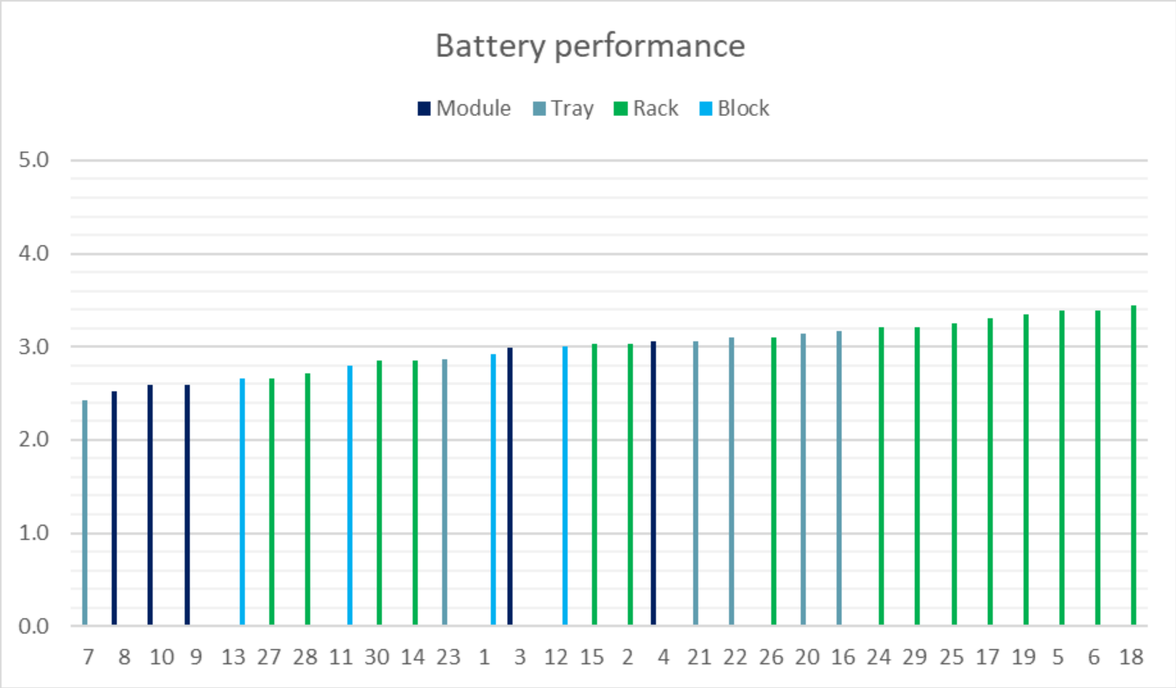

Figure 54 Overview of overall score per battery system with highest importance to electrical integration

The result is that the tray based systems score significantly lower. This is expected as most tray based systems are not flexible in their output voltage. The module based systems increase the most, but still score the lowest average. For the rack based systems only the highest score decreased, but overall still has the highest score. The block based systems have an increased lowest and average score, but the highest score remains the same.

	Module	Tray	Rack	Block
Average score	2.8 (+0.2)	3.0 (-0.1)	3.1	2.8 (+0.1)
Lowest score	2.5 (+0.2)	2.4 (-0.1)	2.7	2.7 (+0.1)
Highest score	3.1 (+0.1)	3.2 (-0.2)	3.4 (-0.1)	3.0

Table 51 Overview of average, lowest and highest score per battery system design based on electrical integration

5 Conclusions and Recommendations

This chapter described the conclusions of the research performed in this document and the recommendations for the system design of the HESS development in the continuation of the SEABAT project.

5.1 Conclusions

In total 33 different battery properties are used to determine the overall score of the battery systems. Although not all information from all battery systems was available, the large number of inputs is assumed to be sufficient to make the effect of the missing data minimal.

5.1.1 Battery types

In Deliverable 2.1 "Application matrix" the three basic requirements for battery selection are determined according to the figure below and these are the required energy, power and the number of cycles that have to be performed. These three basic requirements lead to three types of batteries which are specialized on these three topics:

- High energy batteries
- High power batteries
- Heavy duty batteries (large number of cycles)

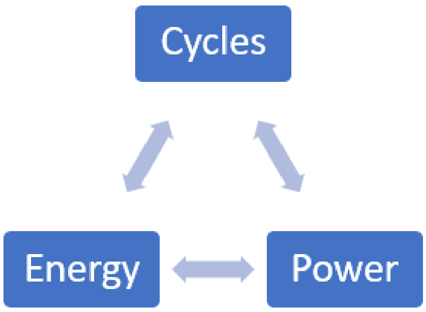

Figure 55 Basic battery requirements

A closer look at the relation between the maximum continuous discharge C-rate and the gravimetric energy density reveals another group of battery systems, the medium energy batteries as discussed in section 3.2.1.

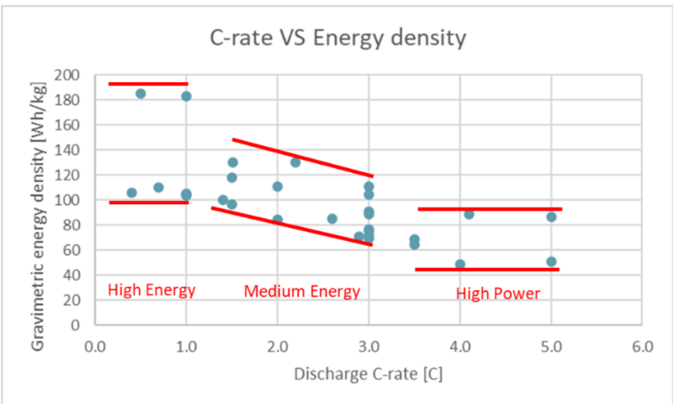

Figure 56 Overview of battery types

The heavy duty batteries distinguish themselves by the number of cycles they can perform at a DoD of 80%. Figure 57 below shows that there is a clear relation between the number of cycles that a battery can perform and the normalized costs per cycled kWh, although the system costs can vary significantly. The group of heavy duty batteries is therefore determined by the normalized costs per cycled kWh below 0.07 €/kWh. Currently the systems with the lowest normalized costs per cycled kWh are at approximately 0.04 €/kWh.

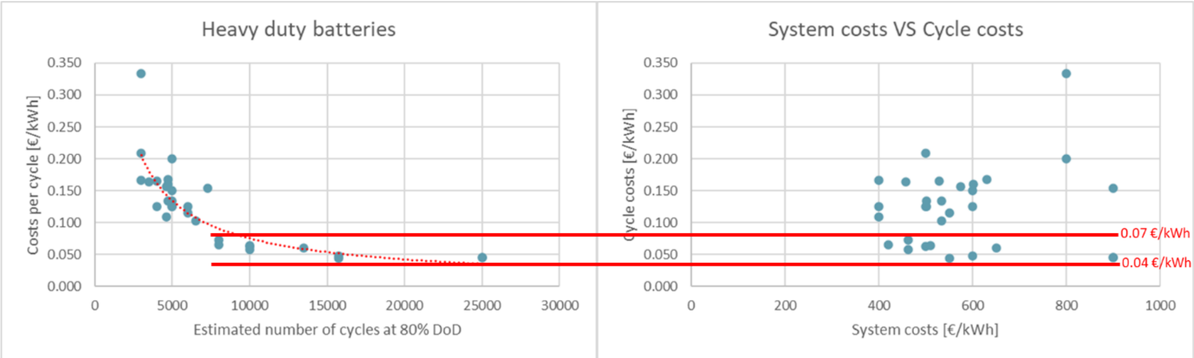

Figure 57 Determination of heavy duty battery types

The requirements for heavy duty batteries are based on different specifications compared to the high energy, medium energy and high power batteries and therefore it can be that a specific battery system can be classified as a heavy duty battery as well as one of the other types. Therefore in total there are six different basic types of battery systems defined, as shown in the figure below.

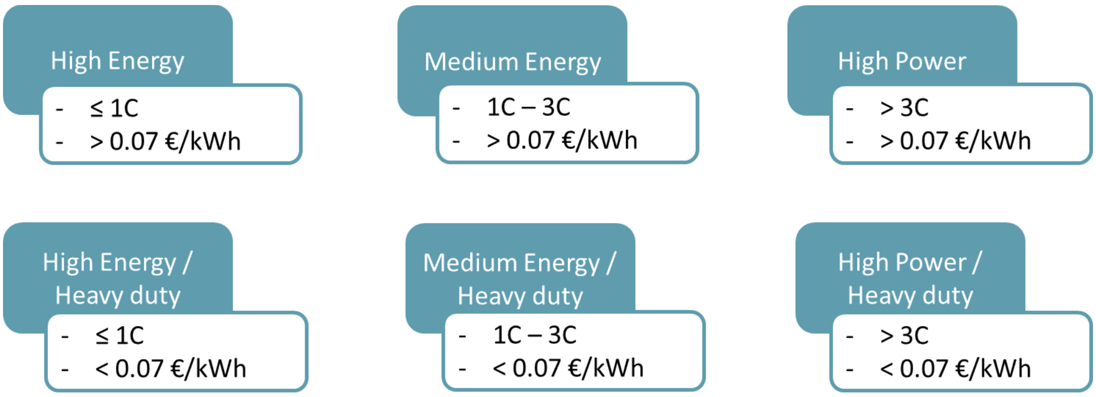

Figure 58 Overview of types of battery systems and their performance

5.1.2 Cell chemistry

Most of the marine battery systems are based on NMC cells. If we look at the overall score the LTO based systems have the highest result of 3.5 on average. The NMC cells have the second highest average score of 3.0. LFP based systems have the lowest average score of 2.7. In Figure 59 the comparison is made between the costs per cycle kWh and the overall performance score of the battery system. For the highest scores in combination with the lowest cycle costs the LTO based systems score best, followed by the NMC based systems.

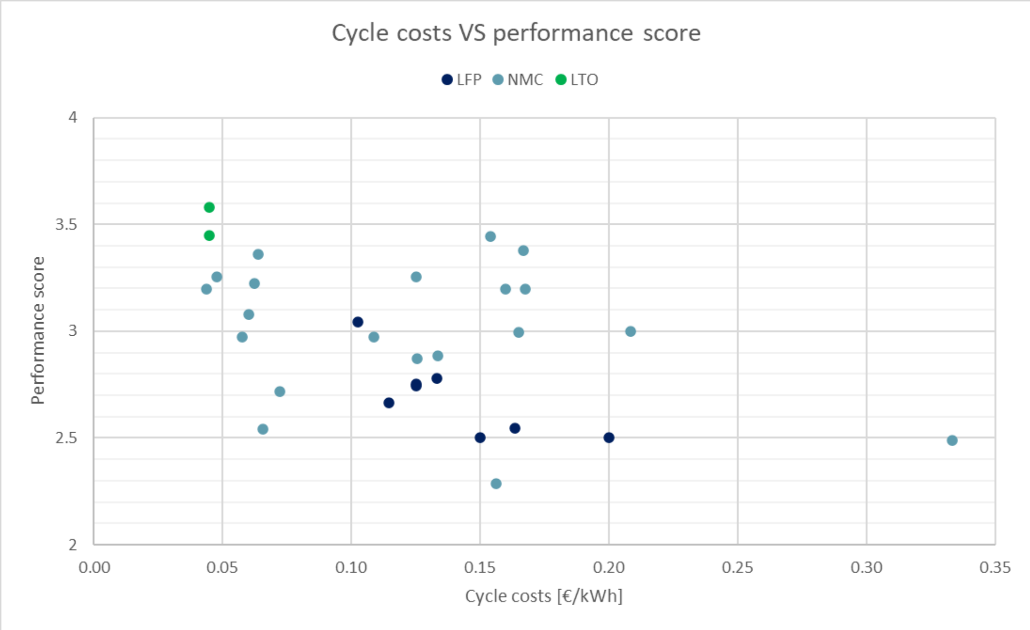

Figure 59 Costs per cycle compared to battery performance for different cell chemistries

5.1.3 Costs

The system costs and cycle costs are compared in Figure 60 per battery type.

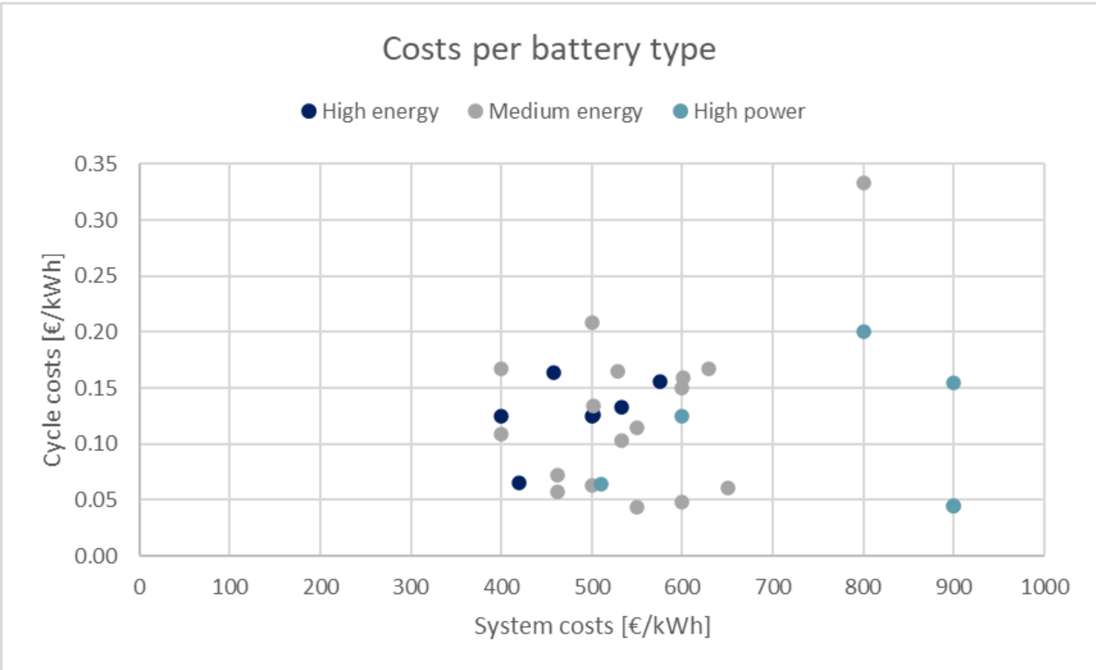

Figure 60 System costs compared to cycle costs per battery type

The lowest, average and highest system costs as well as cycle costs are shown in Table 52 for the high energy, medium energy and high power battery systems . On average the high energy battery systems have the lowest system costs and the high power battery systems have the highest system costs. The medium energy battery systems have the lowest average cost per cycled kWh.

Battery type	System costs [€/kWh] Low	Average	High	Cycle costs [€/kWh] Low	Average	High
High energy	400	484	575	0.07	0.13	0.16
Medium energy	400	545	800	0.05	0.11	0.20
High power	510	768	900	0.04	0.13	0.33

Table 52 Overview of average, lowest and highest system and cycle costs per battery type

5.1.4 Weight

The weight of the different types of battery systems is shown by the gravimetric energy and power density in Figure 61. Based on the energy density the high power battery systems are the heaviest and the high energy battery systems have the lowest weight. Based on the power density the high power battery systems have the lowest weight and the high energy battery systems are heaviest. It depends on the energy and power requirements of a vessel if a high energy or high power system is the best choice based on weight.

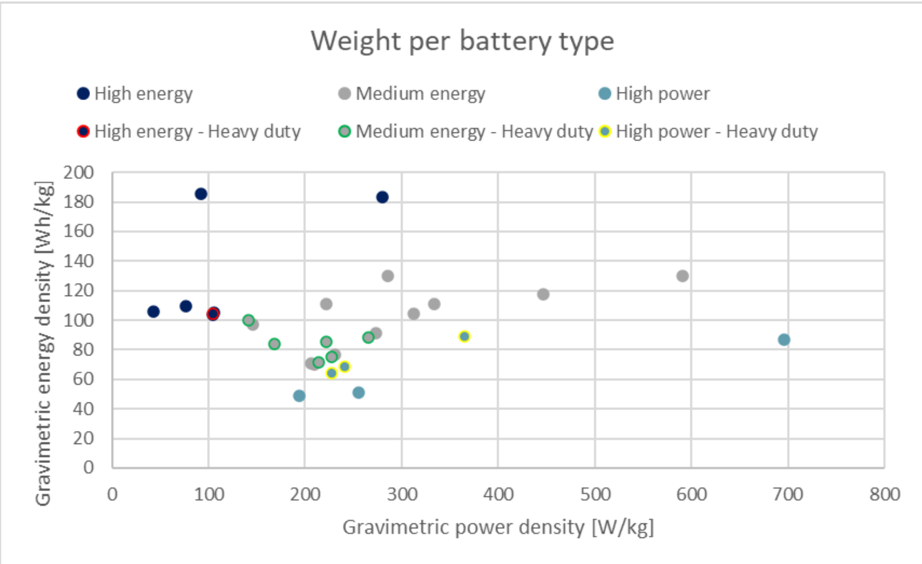

Figure 61 Overview of weight per battery type

Battery type	Gravimetric energy density [Wh/kg] Low	Average	High	Gravimetric power density [W/kg] Low	Average	High
High energy	104	128	185	42	115	280
Medium energy	70	95	130	141	264	591
High power	49	68	89	194	330	696

Table 53 Overview of average, lowest and highest weight per battery type

5.1.5 Volume

The volume of the different types of battery systems is shown in Figure 62 where the comparison is made between the volumetric power density and the volumetric energy density. The same results as with the weight of the different types of battery systems are valid for the volume.

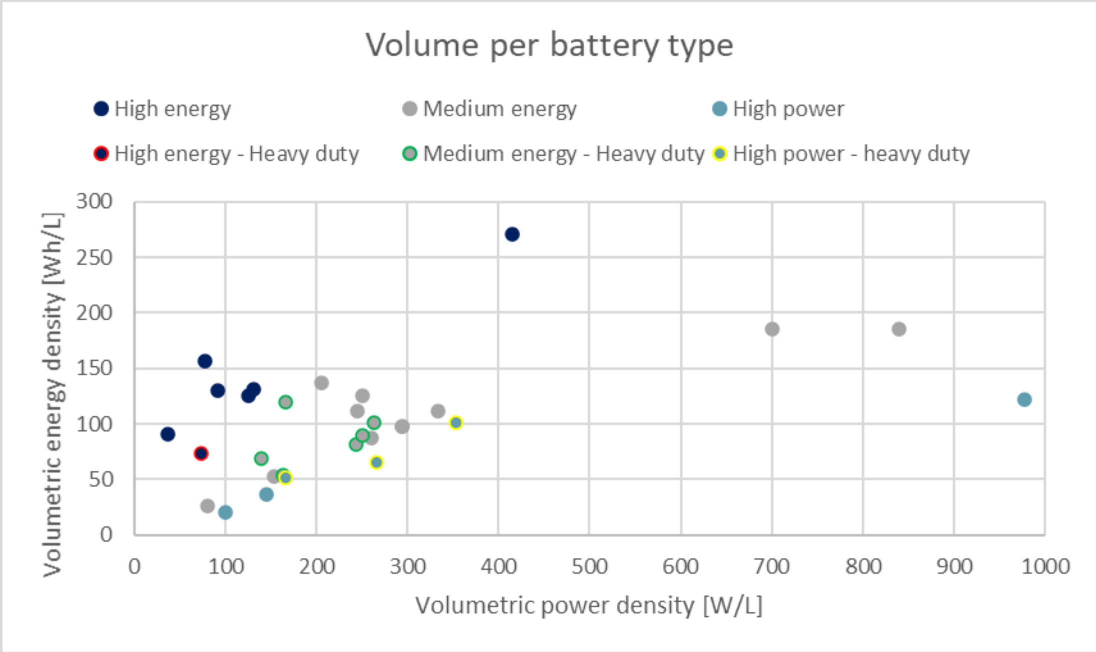

Figure 62 Overview of volume per battery type

The results are similar to the weight of the different types of battery systems. The high energy battery systems have the lowest volume based on energy density and the high power systems have the lowest volume based on power density.

Battery type	Volumetric energy density [Wh/L]			Volumetric power density [W/L]		
	Low	Average	High	Low	Average	High
High energy	73	140	271	36	136	415
Medium energy	27	102	185	80	287	840
High power	20	66	122	100	335	978

Table 54 Overview of average, lowest and highest volume per battery type

5.1.6 System design

There are four different types of marine battery system design identified: modules, trays, racks and blocks. Each type of design has several strong points and weak points which make them more applicable to different types of vessels. Table 55 shows the different battery system designs and how they score overall and when different requirements have a higher importance compared to others. Remarkable is that all four types of battery system designs have lifetime as a weak point. As discussed in section 4.6, the system design is not dependent on the system design and therefore this is also not taken further into account considering the weak points of the different designs.

	Overall	Costs	Energy	Power	Lifetime	Safety	Electrical
Module	2.6	2.6	2.7	2.5	2.5	2.8	2.8
Tray	3.1	2.9	3.4	3.3	2.8	3.0	3.0
Rack	3.1	3.1	3.0	3.1	3.0	3.2	3.1
Block	2.7	3.1	2.5	2.5	2.6	2.9	2.8

Table 55 Overview of average scores per battery system

The module based systems have the lowest overall score. The strong points of these systems are safety, energy and electrical integration flexibility. The weak point is power.
The tray based systems have together with the rack based scores the highest overall score. The strong points for the tray based systems are energy and power. Due to the shape factor of the tray, these types of systems can be fitted in a variety of different battery space shapes and sizes while achieve a high energy or power density over the volume of the battery space. The weak points of the tray based systems are costs, safety and electrical integration flexibility.

The rack based systems have the most stable overall score which varies the least depending on the different categories with the highest importance. The strong point for the rack based systems is safety. The weak point is energy.

The block based systems are in third place based on the overall performance score. The strong points are costs, safety and electrical integration flexibility. The weak points are energy and power. These types of systems are mainly designed to fit large vessels with large energy requirements. Therefore costs and safety are important, but the large battery spaces available on these types of vessels do not require much flexibility in the mechanical integration of the battery system on board.

5.2 Recommendations

The focus for the design of the HESS system should be on a high energy and a high power system. An overall medium energy battery system can be created by the HESS concept by combining the high energy batteries with the high power batteries to fulfill the requirements of the vessel.

The recommended system design is either a rack based system or a tray based system. The rack based systems have the most stable performance scores on all different categories, which result in a versatile and all-round applicable system. However with a tray based system design the highest performance on energy and power density can be achieved. Therefore if the decision for a rack based system is made it is recommended to focus on developing a versatile rack design with a high energy density. If the decision is made for a tray based system the focus should be to develop a system with a high safety performance, higher electrical integration flexibility and to do this keeping the costs for the system relatively low.

Regarding the costs for the battery system, to be competitive in the market, the high energy battery system should have a system costs around 400 €/kWh and cycle costs around 0.07 €/kWh. The high power battery system should have a system costs around 510 €/kWh and cycle costs around 0.04 €/kWh. This is only considering the costs for the battery system and not for any power conversion within the HESS. In WP 3 the total costs including power conversion needs to be considered, as this is where the HESS is assumed to be beneficial. However, none of the existing marine battery systems has power conversion included and therefore the requirements for this can't be defined based on the current systems.

The gravimetric energy density of the high energy battery should be around 185 Wh/kg and the volumetric energy density should be around 271 Wh/L. For the high power battery system this should be around 89 Wh/kg and 122 Wh/L. However the energy density of the complete battery room should be taken into account in the design choices of the battery system as well. Therefore the smallest building block of the battery system should be not too large, preferably below 100L. Also should the system be as flexible as possible in the height of the installation and should it be possible to optimize the height of the battery system according to the height of the battery space. Finally the required service space around the battery system should be minimized. A required service space below 37% of the footprint of the battery system is considered as the highest score on this topic.

The gravimetric power density of the high energy battery should be around 280 W/kg and the volumetric power density should be around 415 W/L. For the high power battery system this should be around 696 W/kg and 978 W/L. Besides this, the maximum continuous C-rates for these batteries should be around 1C for the high energy battery and around 5C or higher for the high power battery. With regards to cycle lifetime there is also a difference in high energy and high power batteries. In general the high power batteries need to be cycled more compared to the high energy batteries. Therefore it is recommended for the high power battery to aim for a cycle life above 16000 cycles at 80% DoD. For the high energy batteries it would be a high performance to have a cycle life above 5000 cycles at 80% DoD. Most marine battery systems are designed for a 10 year lifetime. This should be the minimum required design life for both the high energy and high power batteries, more will always be better. Because there will be different types of batteries in the HESS which will be used in a different way, the aging will also be different for the both battery types. Therefore it is also important to consider the possibility to replace battery modules at their EOL, while keeping the battery modules which are not at their EOL.

The thermal management system should be able to cool the batteries as efficient as possible. A heat rejection below 0.5% of the discharge power at 1C is considered the highest score, below 1.5% is considered above average. A required inlet temperature of the cooling medium is preferred to be around 25°C, between 22°C and 25°C is considered above average performance.

Regarding safety of the battery system it is recommended to have cell level thermal runaway propagation measures. The goal is to have as little gas as possible being released in case of a thermal runaway. An integrated gas exhaust ducting is strongly recommended for the removal of the gases released in a thermal runaway. This will reduce the complexity of the integration of the system on board of a vessel. The most important purpose for a fire extinguishing system in a battery space is the ability to cool, to prevent the fire from igniting the batteries. A water mist fire extinguishing system is assumed most effective in achieving this and to be able use a water mist system the battery system should have a minimum IP rating of 56, but preferably an IP rating of 67.

The output voltage of the battery system should at least be possible to supply a 700 Vdc and 1000 Vdc fixed DC-bus. However, for a higher flexibility and applicability to different types of electrical systems on various ship types is preferred to be able to adjust the voltage range of the battery system. A maximum nominal output voltage of 1000 Vdc is considered above average, 1258 Vdc or higher results in the highest score. A voltage range of 812 Vdc is considered above average. Above 1000 Vdc is considered as the highest score. A voltage step below 59 Vdc is considered above average, 10 Vdc or lower is considered as the highest score. The capacity per module of 20 kWh is above average, 50 kWh per module or higher results in the highest score.

The Battery Management System is preferred to be able to manage an unlimited amount of strings in parallel, more than 12 is considered above average. The BMS should have a power consumption of 0.63 W per installed kWh to perform above average and it should have an integrated redundancy function. The balancing of the battery cells should preferable be done actively and the process should be started automatically. A balancing accuracy of 7.5 mV is considered above average and 1.5 mV is considered as the highest performance. For a fast balancing process a 2000 mA balancing current is considered above average. The highest performance is a balancing function of 3000 mA or more. Each battery cell should have at least 1 voltage sensor, 2 sensors would be optimal for redundancy. If there is 1 temperature sensors for every 4 battery cells this would be an above average score, 1 sensor for every cell results in the highest score. An integrated gas detection sensor is considered as a strong point, as this improves the safety and the ease of integration on board of the vessel.

The analysis of current marine battery technology in this deliverable has been performed without taking power conversion into consideration. However, power conversion will be an important topic in the final design of the HESS and this will need to be considered in the comparison of a monotype battery system and the HESS to identify the actual possible benefits of a HESS.

6 Deviations from Grant Agreement Annex 1

There are no deviations with respect to Annex 1.

7 References

[1] SEABAT, "Roadmap for battery production," 2021.
[2] SEABAT, "D2.3 "Requirements document"," 2021.

8 Acknowledgements and disclaimer

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1	FM	FLANDERS MAKE
2	DAMEN	SCHEEPSWERF DAMEN GORINCHEM BV
3	FCSI	FINCANTIERI SI SPA
4	RINA	RINA SERVICES SPA
5	SOERMAR	FUNDACION CENTRO TECNOLOGICO SOERMAR
6	VARD	VARD ELECTRO AS
7	ABEE	AVESTA BATTERY & ENERGY ENGINEERING
8	IMECAR	IMECAR ELEKTRONIK SANAYI VE TICARET LIMITED SIRKETI
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Appendix A - Table of Abbreviations

#	Abbreviation	
1	SEABAT	Solutions for large batteries for waterborne transport
2	HESS	Hybrid Energy Storage System
3	C-rate	Charge or Discharge rate in kW/kWh
4	DoD	Depth of Discharge
5	SoC	State of Charge
6	kW	Kilowatt
7	kWh	Kilowatthour
8	BMS	Battery Management System
9	PMS	Power management System
10	EMS	Energy Management System
11	AMCS	Alarm Monitoring and Control System
12	NMC	Nickel Manganese Cobalt
13	LFP	Lithium Iron Phosphate
14	LTO	Lithium Titanate

Appendix B – List of tables

Appendix B – List of figures