EUROPEAN COMMISSION
HORIZON 2020 PROGRAMME - TOPIC H2020-LC-BAT-2020

Solutions for large batteries for waterborne transport

GRANT AGREEMENT No. 963560

D2.1 – Application matrix

Report details

Deliverable No.	SEABAT D2.1	
Deliverable Title	Application matrix	
Deliverable Date	28-08-2021	
Dissemination level	Public (PU)	
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Document History

Version	Date	Author	Remarks
V0.1	09/07/2021	S. ten Cate Hoedemaker (DAMEN)	First draft
V0.2	09/08/2021	S. ten Cate Hoedemaker (DAMEN)	Second draft
V1.0	29/08/2021	S. ten Cate Hoedemaker (DAMEN)	Final for submission

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 requirements for marine batteries can vary significantly for different types of vessels using the batteries for different types of applications. The goal for SEABAT is to develop a Hybrid Energy Storage System (HESS) which can combine the performance of two different types of battery technologies to optimize the battery systems to fulfil the requirements of a specific vessel. In the SEABAT project plan it is mentioned according to Figure 1 that using one specific type of battery system can result in oversizing of the battery system to fulfil both the energy and the power requirements. Another factor in this equation is the number of cycles which will be performed by the batteries. Two different approaches are used to determine which type of marine applications show the most potential for a HESS. First the energy, power and cycling requirements are used to determine the basic requirements of marine battery systems and to identify specific types of battery requirements independent of vessel type or type of battery application, this is considered the cycle analysis. The second approach is based on the theory of C-rate optimization, where two different types of batteries are combined in a HESS to match the C-rate requirements of an application exactly, to reduce the need of oversizing a monotype battery.

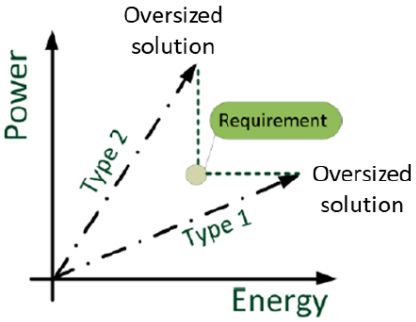

Figure 1 Oversizing of batteries due to vessel requirements

The operational requirements regarding C-rate and number of performed cycles daily are divided in 4 types A, B, C and D, based on the performance of marine battery systems currently on the market. A selection of battery powered vessels is investigated to determine which type of battery requirements are valid for two different types of cycles, primary cycles and secondary cycles. The primary cycles are defined as the nominal operations of the vessel. The secondary cycles are defined as the operations under non-standard circumstances which often require for a larger battery capacity compared to the primary cycles. The 34 selected vessels and their operational requirements are analyzed to identify different clusters of battery requirements, independently from vessel type or the type of application of the batteries.

		Number of cycles				
	Type	**A**	**B**	**C**	**D**	**Total**
C-rates	**A**	24%	2%	0%	2%	27%
	B	21%	7%	2%	2%	31%
	C	10%	7%	3%	10%	31%
	D	3%	2%	2%	6%	12%
	Total	57%	18%	6%	19%	

Table 1 Occurrence of battery types (C-rates: A=<1, B=1-3, C=3-6, D=>6) (Cycles: A=<1, B=1-3, C=3-7, D=>7 per day)

The result of the analysis is shown in the application matrix in Table 1, which shows the occurrence of different types of battery requirements for different types of vessel. This indicates the large variety of operational requirements for marine batteries and that a single type of battery will unlikely be able to fulfil all needs for all types of vessels. Finally it is determined which applications are most interesting as use case for the design process of the HESS. There are 6 different vessels selected to be used as input in WP 3 of SEABAT.

Contents

1 Introduction

The increase in adoption of battery technology in the marine market has introduced a new aspect of ship design: the sizing and selection of the right type of batteries for the right type of application. This aspect can be approached from two directions. (1) It is a new requirement for ship designers to have understanding of different types of battery technologies and how to integrate them on board of a vessel. This topic will be covered in this work package by deliverable 2.2, the KPI report and deliverable 2.3 the requirements document. (2) The other challenge is to determine the requirements from a vessel's perspective, focusing more on the operational profile of a vessel and matching this to the operational performance of specific types of battery systems. This topic is being discussed in this deliverable 2.1 the "application matrix".

In work package 1 of the SEABAT project the market evolution and potential within the next 5, 10 and 15 years is described [1]. Here the estimated number of vessels per type that will be delivered on the European market in the next 5, 10 and 15 years is described, as well as their potential for use of large battery systems. The largest groups in number of vessels to be delivered per year are considered to be fishing vessels, yachts and inland cargo vessels. However, the largest impact on the demand for marine battery systems is expected to come from large vessels, such as cruise vessels.

To determine the types of applications that can benefit from a Hybrid Energy Storage System (HESS), the types of vessels as discussed in deliverable 1.2 [1], are analyzed on their operational profiles and their operational requirements for batteries. First the types of vessels and types of marine battery applications need to be determined to achieve this. Then a method of comparing the types of applications based on their battery requirements is developed. This will result in an overview of the different types of vessels and their application of batteries in the application matrix.

The final goal of this deliverable is to determine the input required for work package 3 to define the operational requirements of the HESS which is to be designed in this project. This resulted in 5 vessels with different operational profiles which will be used by work package 3 as input for the simulation of the different considered topologies.

1.1 Purpose of the document

The purpose of this document is to create an overview of different vessels and their operational requirements for battery systems. This overview is used to identify clusters of different types of vessels which have the same type of requirements for their battery systems. A first guideline to marine battery selecting is created and the requirements which will be used as input for the successive deliverables and work packages in this project will be identified.

1.2 Document structure

In **Chapter 2** the approach of achieving the results in this task is described. First the scope of the research is described, followed by a summary of the different types of marine battery applications that have been selected and why they are relevant for the performed research. Then the basic requirements for the first step in battery sizing and selecting are discussed, which are the minimum requirements as input for designing a marine battery system. Finally, this chapter ends with the description of the two theories which are used to determine the need for a HESS onboard of a vessel and how this can be used for determining the most suitable use cases for work package 3 as input for the simulation models of the different topologies under investigation, cycle analysis and C-rate optimization.

The results of the cycle analysis are described in **Chapter 3**. In total 34 vessels and their operational requirements are gathered as input for this deliverable. In this chapter the analysis of these 34 vessels and their operational requirements for battery systems are described. Different types of applications are defined, resulting in the application matrix which shows how the different vessels compare to each other regarding battery requirements. The application matrix is followed by the description of how it is determined which applications are most feasible to benefit from a HESS on board.

The results of the C-rate optimization theory are described in **Chapter 4**. Here it is described how it is determined which vessels would benefit most from a HESS to use is for optimizing the C-rate to the exact value what is needed by the type of application.

The resulting selected applications which show most potential for installation of a HESS are presented in **Chapter 5**. Five applications are selected based on the cycle analysis and 1 application is selected based on the C-rate optimization theory. The operational profiles and basic battery requirements of these 6 applications are provided in this chapter.

The conclusion and recommendations of the results in this deliverable are discussed in **Chapter 6**. Here it is summarized what the main types of marine battery applications are and what should be focused on in work package 3 when design choices have to be made regarding the HESS which will be developed for the SEABAT project.

2 Approach

2.1 Scope

The scope is based on two aspects. Firstly, the types of vessels identified by work package 1 in deliverable 1.2 [1] are considered. Secondly the main types of electric topologies are discussed.

2.1.1 Vessel types

As described in deliverable 1.2 [1], all types of vessels no matter how large or small, can potentially benefit from a battery system on board. The benefit can be regarding cost savings by reduced fuel consumption or a reduction in maintenance costs for mechanical equipment but can also be regarding fulfilling local or global regulations regarding emissions. The largest demand for marine battery systems will come from:

- Ferries
- Offshore support vessels
- Cruise vessels
- Inland cargo vessels
- Yachts
- Fishing vessels

Other vessels such as tugs, patrol vessels and utility vessels can also potentially benefit significantly from the installation of a battery system on board, but due to the smaller number of vessels on the European newbuild market these vessels will have a smaller impact on the total battery demand. They are nonetheless considered in this task as well, to acquire a complete overview of the types of marine battery applications. Seagoing cargo vessels only apply for a small part of the European newbuild market and although they could also benefit from battery installations on board, they are not considered in this task, as they do not play an important role in the European marine battery market. In total 34 applications have been gathered by the SEABAT partners with shipbuilding experience. These applications are from the following ship types:

- 6 Ro-Ro ferries
- 4 Fishing vessels
- 4 Harbor tugs
- 4 Fast Crew Suppliers
- 2 Urban ferries
- 2 Waterbuses
- 2 Small tugboats
- 1 Fish carrier
- 1 Cruise vessel
- 1 Ferry
- 1 Trailing Suction Hopper Dredger (TSHD)
- 1 Shoal buster
- 1 Cable laying vessel
- 1 Patrol vessel
- 1 Fast ferry
- 1 Inland container vessel
- 1 Yacht

12 of the used applications have been built or are currently under construction. The other 22 vessels have been designed up to a certain level, but not (yet) built. For some of these vessels the battery design might not have been feasible, for others the tender was won by a competing shipyard.

There are vessel types that are not in this overview and this has two different reasons. The first reason is that for some vessels the energy demand for a battery system is significantly larger compared to the power or cycling requirements, with the result that a high energy battery system would be the only logical type of battery for these types of vessels. That is, if the installation of a battery system is feasible for propulsion at all. The second reason is that special attention has been paid to the type of operations for which the battery system is used on board the selected applications. The different types of possible combinations between full electric sailing, peak shaving, spinning reserve, load levelling and boost functions are all covered by the selected 34 applications. The same is valid for the different types of combinations in energy, power and cycling requirements. No additional applications could be identified which would add relevant information to this research. Therefore the 34 selected applications are considered to be relevant for the performed analysis and the number of applications is assumed to be sufficient to achieve reliable results.

Considering the results from [1] section 3.6 where the evolution of the battery market for marine applications is discussed, the largest market for marine batteries will remain as currently the ferry market. Therefore, the large variety of ferries in this study is considered relevant as well as necessary. Cruise vessels are also mentioned as large potential marine battery market. However, cruise vessels are expected to use batteries as the cruise vessel application considered in one of the 34 selected applications. The same is assumed for yachts, where batteries will mainly be used as large energy buffer and therefore the one used yacht application represents most of the yachting sector. Inland cargo vessels are also expected to become a large market for marine batteries. This application is also represented in the selection of vessels in this investigation, however, for inland cargo vessels battery swapping is considered as a promising development and therefore this type of application is less focused upon. In [1] there is also a large potential mentioned for the category “special vessels”. These types of vessels are covered by the fast crew suppliers, the TSHD and the cable laying vessel. Taking these considerations into account all potential applications for marine batteries are covered by the s34 selected applications used in this report.

2.1.2 Electric topologies

There are many different propulsion topologies applied in the marine sector currently. The design choices are usually based on the requirements for efficiency, redundancy, power availability or maneuverability of the vessel. Battery systems can be integrated in all types of propulsion topologies, in combination with current power sources such as diesel engines, as well as future sources such as fuel cells. A clearer overview of all different types of propulsion systems including batteries is provided by dividing them in three main groups:

- Fully battery powered
- Plug-in hybrid
- Hybrid

For a vessel to be fully battery powered it should fulfil three requirements:

- The vessel should have a demand in energy that can be realistically stored in a battery system on board considering weight, volume and costs. The functionality of the vessel should not suffer from the impact of installing a battery system.
- The vessel should have a fairly predictable operational profile, which is required to design the battery system to fulfil all the operational requirements of the vessel.
- The vessel should have access to a charging facility, which is easiest for vessels on a fixed route or that operates not too far from shore in the same area.

If a vessel fulfils all these three requirements it is feasible to have a fully battery powered propulsion system. If a vessel has a fairly predictable operational profile and access to a charging facility, but no practical energy requirements it is feasible for a plug-in hybrid propulsion system. If a vessel does not fulfil these requirements it can still potentially benefit from a battery system on board, but this will then be in a hybrid propulsion system.

The goal for the SEABAT project is to design and develop a HESS for fully battery powered vessels. Nevertheless, today the majority of the vessels are more prone to having a battery system installed in a hybrid or plug-in hybrid propulsion system. Future propulsion systems using fuel cells or alternative fuels, which will be used to reduce the emissions of the marine sector too, will also have a place for battery systems in different kinds of hybrid topologies. Hence, although the focus is on fully electrified vessels, it is important to also consider hybrid applications for the application matrix and not only focus on the fully battery powered vessels. Hybrid applications can be considered as additional applications for the SEABAT HESS that will expand the market potential and increase the application rate as well, without changing the technical core of the project.

2.2 Types of marine battery applications

Seven different applications of marine batteries are identified, which are described in this section.

2.2.1 Full electric

The most common assumed application for marine batteries is full electric propulsion. In this application the batteries supply the total load demand coming from the propulsion system as well as any other auxiliary systems on board of the vessel. This obviously is the type of application which is used for fully battery powered vessels, but it can also be part of the operational profile of a hybrid or plug-in hybrid vessel, if there is a fully electric mode defined.

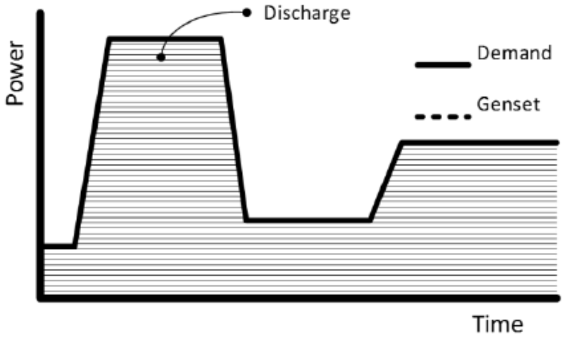

Figure 2 Full electric battery application

2.2.2 Load levelling

Load levelling is an application of batteries which is used to keep the load on the diesel engine or generator stable at one level by discharging the batteries when the demand is higher than the set load and charging the batteries when the demand is lower than the set load. This application is used to make the diesel engine or generator run at a more efficient load and to reduce the required maintenance, which can be increased by large load fluctuations.

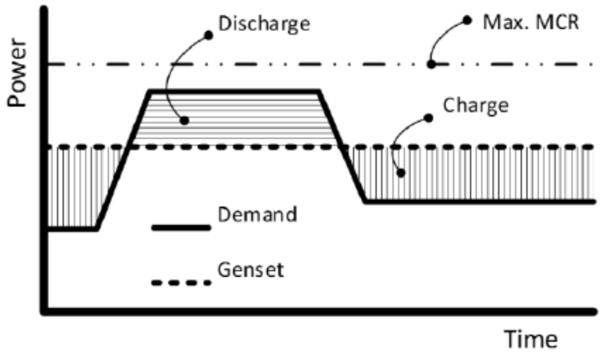

Figure 3 Load levelling battery application

2.2.3 Boost function

The boost function is an application where the batteries are used to increase (boost) the performance of a propulsion system by providing additional power to cover the peaks in demand. The batteries are charged when the demand is below a certain level again.

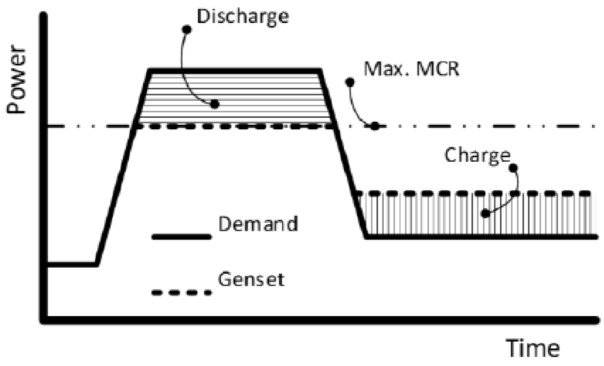

Figure 4 Boost function battery application

2.2.4 Spinning reserve

Vessels which require an additional level of power redundancy, constant or during specific types of operations, such as dynamic position, currently provide this redundancy by having more generators running than actually required. In the case that one of the generators has a black out, or power demand is suddenly significantly higher, the additional generator can step in and supply the load. This results in a waste of energy which is not being used and in an overall inefficient power system. This redundancy can also be achieved by adding a battery to the system, which can supply the load instantaneously when needed, without wasting energy when it is not needed. The spinning reserve application can result in fuel savings, emission reduction, a reduction in number of installed generators and maintenance costs and still provide the required safety and redundancy to the vessel's operations.

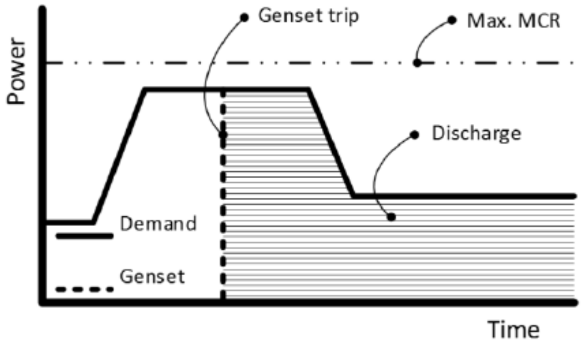

Figure 5 Spinning reserve battery application

2.2.5 Peak shaving

The peak shaving application uses the battery to take care of sudden peaks and fluctuations in power demand. This reduces the peaks in load demand on the diesel engine or generator, reducing the required maintenance. It can also be used as a bridging function between starting up of an additional generator.

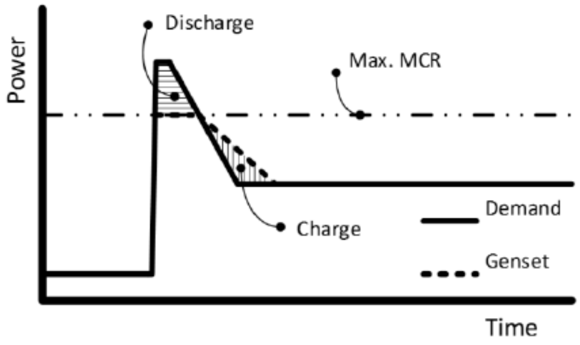

Figure 6 Peak shaving battery application

2.2.6 Load smoothing

The load smoothing application is comparable to the load leveling application. The battery system is used to keep the load on a diesel engine or generator at a stable level. The difference between load leveling and load smoothing is the frequency at which the loads fluctuate. Load smoothing is usually considered for load fluctuations at a frequency above 1 Hz.

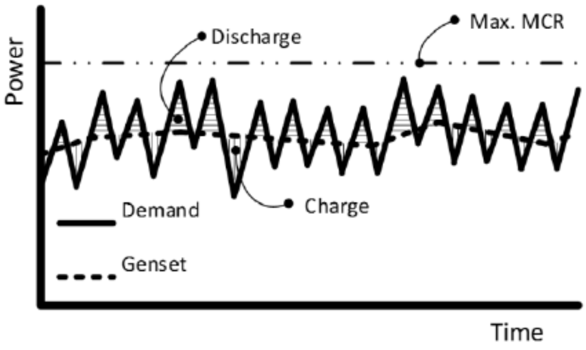

Figure 7 Load smoothing battery application

2.2.7 Ramp support

The ramp support application uses the battery system to increase the response time of a system. Batteries can almost instantaneously deliver power compared to diesel engines or generators. Therefore the response time of a diesel powered propulsion system can be improved significantly when adding a battery system.

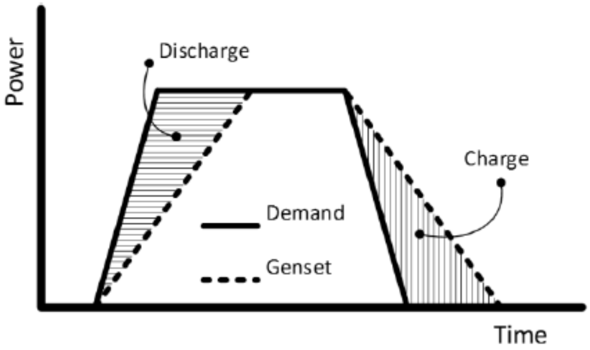

Figure 8 Ramp support battery application

2.3 Basic requirements

The basic operational requirements for batteries can be broken down into 3 parts, energy, power and the number of cycles. Therefore it should be determined how much energy in kWh is required for every operation, what is the maximum required charge and discharge power in kW and how many cycles will be performed daily, or annually if more suitable. These are considered to be the primary requirements for a battery system. The required power (kW) divided by the required energy (kWh) results in the C-rate. Typically, a certain battery technology is suited for one specific C-rate. The actual energy and power requirements then follow after proper scaling. Therefore, it is possible to further reduce the complexity by comparing only two different variables, i.e. the maximum required C-rates and the number of performed cycles.

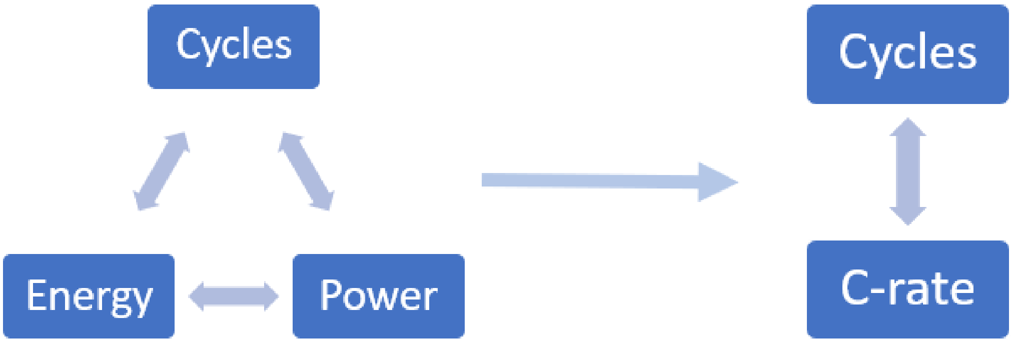

Figure 9 Basic requirements for battery sizing and selecting

The battery applications that have been defined in this document are based on required available energy, which for practical reasons and aging effects on the batteries can't be assumed to be 100% of the installed capacity of the batteries. Therefore the required energy is assumed to be 80% of the rated installed battery capacity, which is used for defining the C-rates as well as the performed number of cycles. In other words, the maximum required C-rates in this document all assume that the minimum required energy is 80% of the total installed capacity and the number of cycles that are performed daily are all based on cycles with a depth of discharge (DoD) of 80%.

2.4 Cycle analysis

The challenge in designing a battery powered vessel comes with sizing and selecting the right type of battery for the right type of application. As described above the 2 aspects of C-rates and number of performed cycles play an important role in this process. Each type of battery has a different combination of maximum C-rate and estimated number of cycles that can be performed until the end of life of the battery cells. However, the operational requirements of most vessels do not exactly fit to the specifications of the marine battery systems available on the market. Either the power demand of the vessel or the number of cycles can be too high to achieve a practical design life of the battery system. A common approach to deal with this problem is to oversize the battery system. This allows the batteries to deal with the highest required C-rates, because if the required power remains the same while the installed energy is increased, then the resulting C-rate on the batteries is reduced. Additionally, the DoD is reduced for every cycle, which results in a longer lifetime of the batteries.

The concept of a HESS is considered to be able to be sized more accurately to fit the demands in C-rates and number of performed cycles of the vessel, resulting in a more optimized battery system in costs, weight or volume as well as fulfilling the lifetime requirements. To determine which types of vessels and their application of batteries would potentially benefit the most from a HESS, different types of operational requirements which define the required type and size of the batteries are individually evaluated from each other and later compared for similarity. The 34 gathered battery powered vessels are therefore analyzed based on their operations from the point of view of the battery system to ensure that no difference is being made with requirements for full battery electric vessels or diesel-electric hybrid vessels. This is approached by dividing the different types of operations of a vessel in primary and secondary cycles in the cycle analysis.

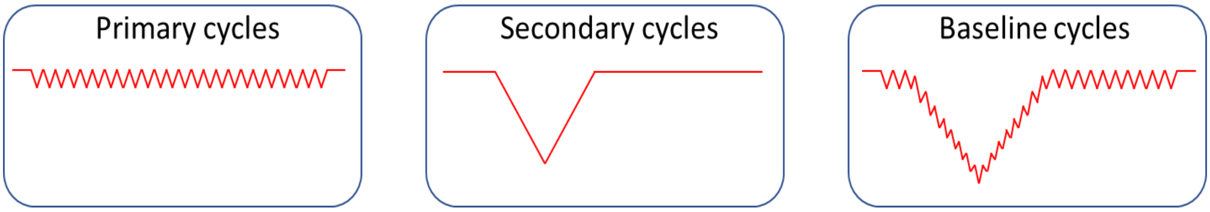

Figure 10 Required power for primary, secondary and baseline cycles vs time

Primary cycles are the most common types of cycles that a vessel will perform with the installed battery system, e.g. a ferry travelling between two ports. They represent the operational conditions at design level of the vessel. Secondary cycles are the operations performed with the batteries that are not according to the average design conditions. For instance when the environmental conditions are out of the ordinary, when an emergency operation has to be performed, or for example when the battery system is used for two different types of applications, such as load levelling and as spinning reserve. These secondary cycles can have a large influence on the requirements of the battery system, although they might not occur during most of the operations. Different vessels can have different reasons for requirements of their primary and secondary cycles. The battery requirements for the application are however based on the combination of both primary and secondary cycles. This combination is indicated by the baseline cycles and is required as input for the overall battery system performance. In most cases the primary cycles have a smaller energy requirement and a higher number of performed cycles, whereas the secondary cycles have larger energy requirements but a lower number of performed cycles. The goal of defining primary and secondary cycles is to find the right combinations of basic requirements (C-rates and number of performed cycles) and types of applications where a HESS can be beneficial for the overall battery system performance.

2.5 C-rate optimization

The second approach for identifying feasible applications for a HESS is based on C-rate optimization. All monotype battery systems only have one specific maximum continuous C-rate. As discussed in the SEABAT project description and shown by Figure 11, the specific requirements of a vessel often results in either an oversized power solution of an oversized energy solution. In the common case that the ratio between energy demand and power demand of a vessel does not fit the exact C-rate of an existing battery system, compromises must be made in the battery system design. This can result in oversized battery systems which are more expensive, heavier or larger than necessary.

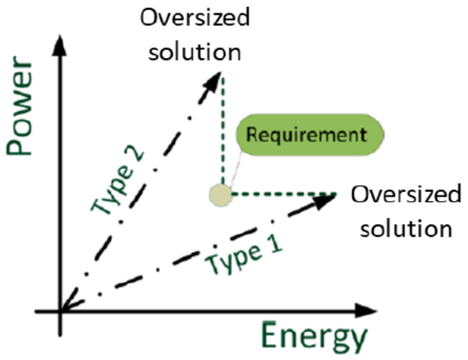

Figure 11 Oversizing of batteries due to vessel requirements

The applications which can benefit from a HESS are identified by comparing the C-rate requirements of the applications of the baseline cycles with the maximum continuous discharge C-rates of the battery systems currently on the marine market. The information about the battery systems currently on the marine market comes from [2].

3 Cycle analysis

In total 34 applications with batteries on different kinds of vessels have been gathered, as discussed in section 2.1.1. Then the primary types of cycles are discussed, followed by the secondary cycles. Then the requirements for batteries based on the primary and secondary cycles are analyzed. The application matrix is determined based on the requirements coming from this analysis and finally the applications which that can benefit from installing a hybrid battery system are discussed.

3.1 Primary Cycles

The primary cycles are the most common types of cycles for which the battery system is used. Therefore, the primary cycle is by definition the type of cycle which is performed more often compared to the secondary cycles. They are the base for the design of a battery system and usually are a good baseline for the lifetime calculation of the battery system.

3.1.1 C-rates

The required maximum C-rates for primary cycles range from 0.1C to 96C. Figure 12 below shows the complete overview on a logarithmic scale because of one application requiring 96C. Figure 13 shows the results without this outlier on a linear scale, to give a better overview of the different required C-rates.

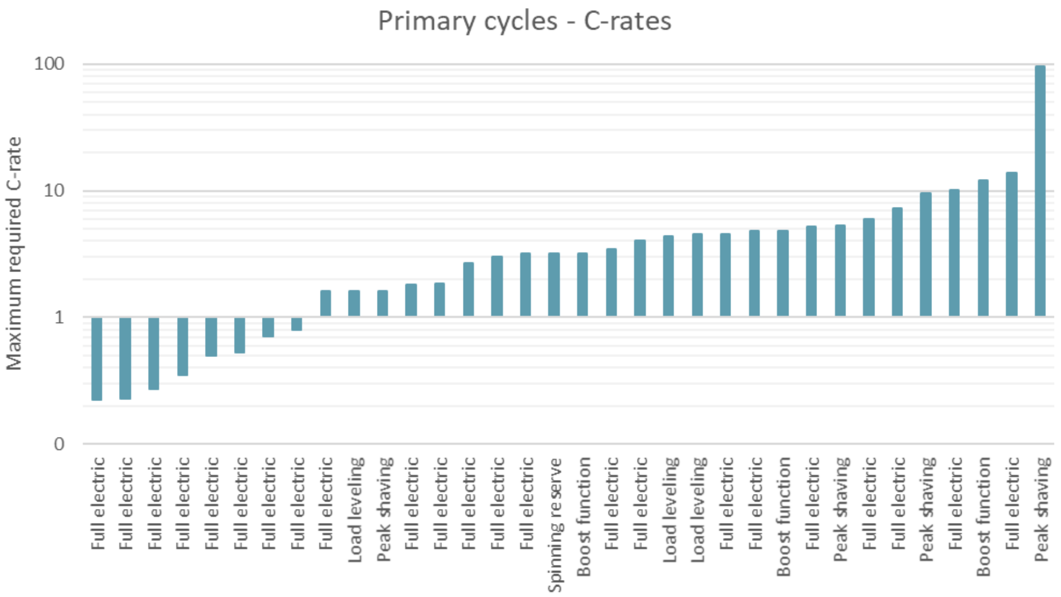

Figure 12 Maximum required C-rates for primary cycles (logarithmic scale)

Figure 13 shows the results without the application which requires 96C. The remaining applications range from 0.1C to 13.7C. The full electric applications of batteries are distributed all over the range of C-rates. The peak shaving and boost function applications are mainly located in the upper half of the C-rate range, as peaks typically appear occasionally (requiring less energy) but require sufficient power to have sufficient impact. The load levelling applications are located relatively lower because they typically work more continuously, hence requiring more energy rather than power.

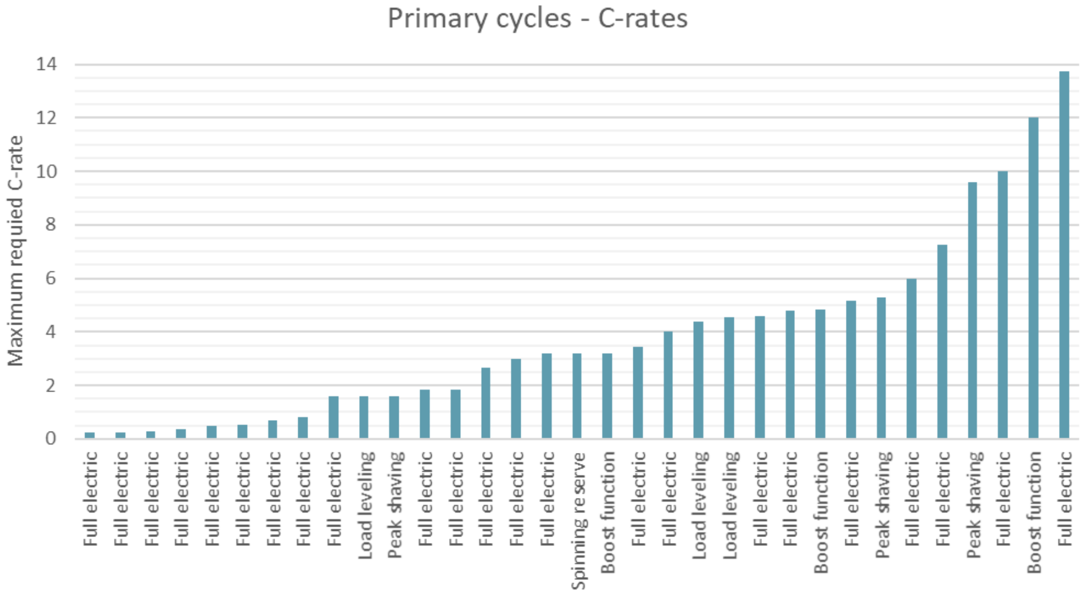

Figure 13 Maximum required C-rates for primary cycles

3.1.2 Number of cycles

The number of average performed cycles per day ranges from 0.08 (30 cycles per year) to 480 cycles per day. The application with 480 cycles per day is a peak shaving application and is clearly in a different range compared to the other applications. The overview in Figure 14 is provided on a logarithmic scale because of the large differences in number of performed cycles per day. Approximately half of the applications require less than 2 cycles per day for the primary cycles. The other half of the applications has a much higher spread. The two applications with the highest number of cycles per day are both peak shaving applications. However, the application with the lowest number of performed cycles per day is a peak shaving application as well. This is explained by the type of operations for which this peak shaving application is used. This particular vessel uses the battery for peak shaving during dynamic positioning operations, which are not performed on a regular basis in this case.

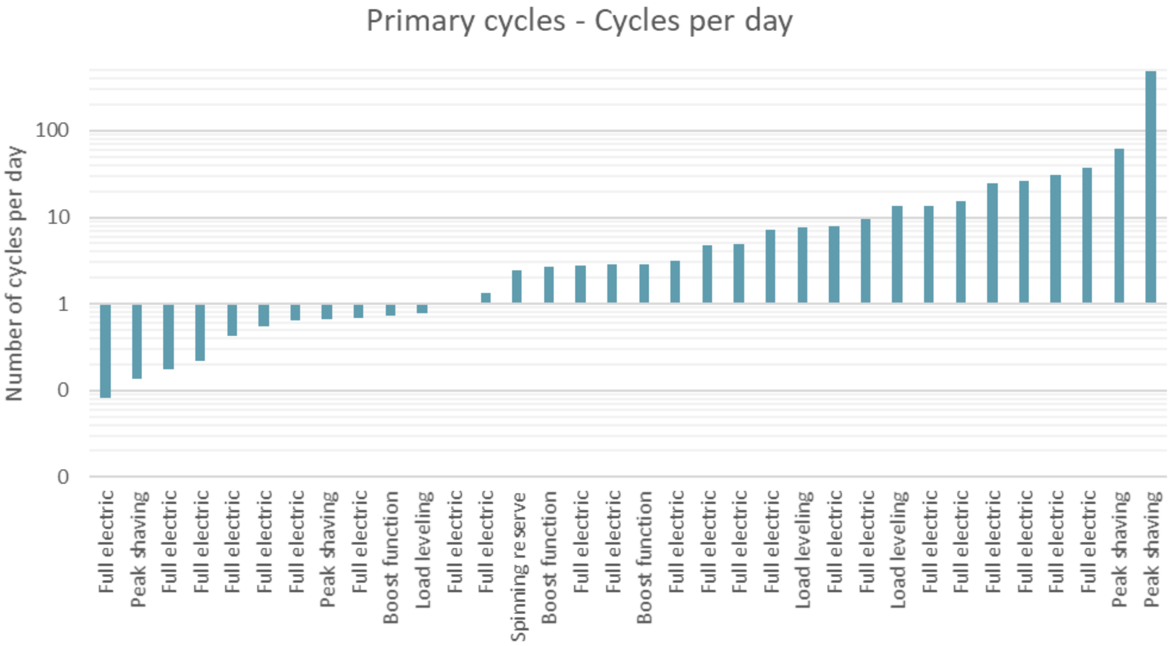

Figure 14 Number of performed primary cycles per day

3.2 Secondary Cycles

The secondary cycles represent the alternative operations that the vessel will perform with the batteries, with a smaller occurrence compared to the primary cycles, which automatically results in a lower cycle count compared to the primary cycles. Although the occurrence is less, these types of cycles can have a large influence on the design of a battery system, as the battery also must cope with these exceptional conditions.

3.2.1 C-rates

The maximum required C-rates for the secondary cycles ranges from 0.1C to 9C. The average C-rate of all secondary cycles combined is 2.2C, which is significantly lower compared to the C-rate requirements of the primary cycles, with an average of 6.6C.

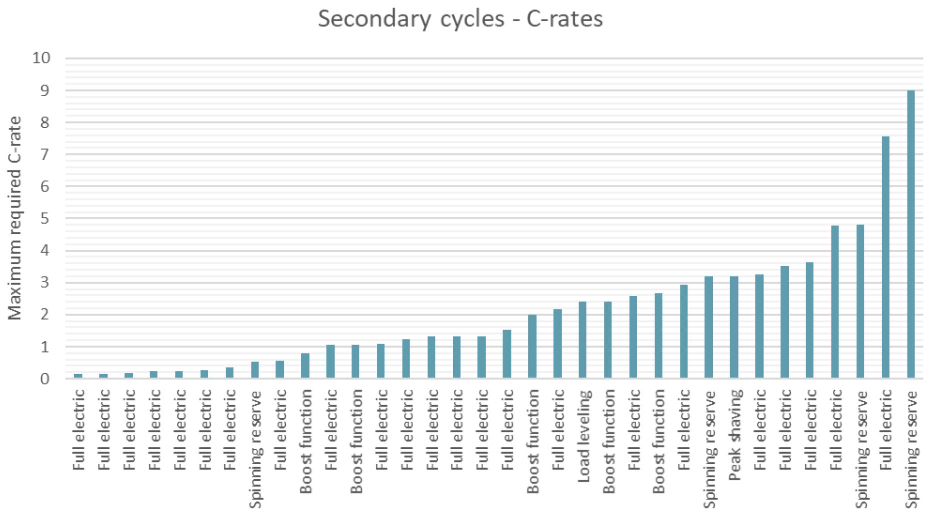

Figure 15 Maximum required C-rates for secondary cycles

3.2.2 Number of cycles

The number of performed secondary cycles ranges from 0.003 cycles per day (1 cycles per year), to 3.4 cycles per day. The largest part of the secondary cycles are performed less than once per two days.

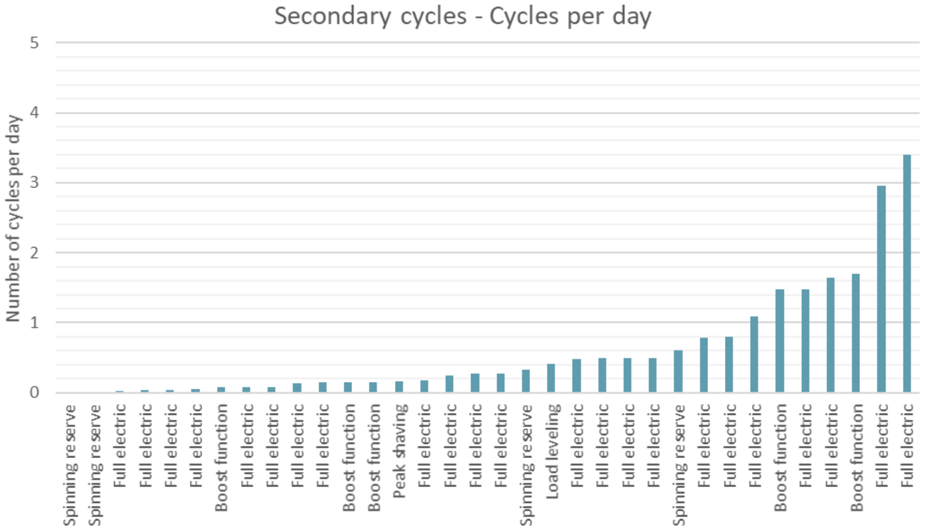

Figure 16 Number of performed secondary cycles per day

3.3 Requirements

The next step is to investigate the requirements for C-rates and number of cycles independently from being for primary and secondary cycles to identify any possible clusters of battery requirements for specific types of applications.

3.3.1 C-rates

The C-rates from the defined applications varied from 0.1C to 96C. The requirements from the primary cycles for C-rates are higher than the for the secondary cycles. This is mainly caused by the lower energy requirements for primary cycles, because the power requirements are often similar for both primary and secondary cycles. 80% of the primary cycles have a C-rate requirement below 6C, while 80% of the secondary cycles have a C-rate requirement below 3C.

Besides the C-rate requirements for the primary and secondary cycles, Figure 17 also shows the C-rate requirement for the baseline cycles. This represents the C-rate requirements for the application where the primary and secondary cycles are combined. As can be seen, the C-rates requirements for the baseline cycles are equal to the C-rates of the secondary cycles. This is caused by the fact that the energy as well as power requirements for the baseline cycles are determined mainly by the secondary cycles and therefore the required C-rates are the same.

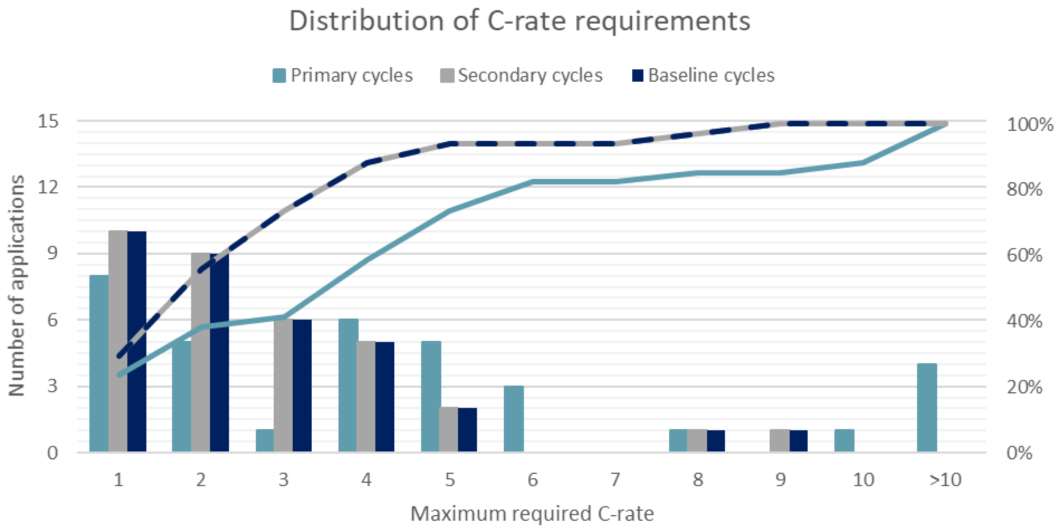

Figure 17 Distribution of maximum required C-rates per application

According to the analysis of current marine battery systems in SEABAT Deliverable 2.2 the KPI report [2], the majority of the NMC and LFP based marine battery systems have a maximum charge or discharge C-rate between 1C and 3C. There are high energy batteries which typically have a maximum C-rate below or up to 1C. There are also several high power battery systems that can go up to 6C, but above that the capabilities of lithium-ion batteries are limited. Therefore a differentiation is made between 4 different types of C-rate requirements for the applications:

- Less than 1C
- Between 1C and 3C
- Between 3C and 6C
- Above 6C

Figure 18 shows the combination of C-rate requirements for both the primary cycles and secondary cycles. The application with a 96C C-rate requirement for the primary cycles is removed in Figure 19 for a better overview of the majority of the applications.

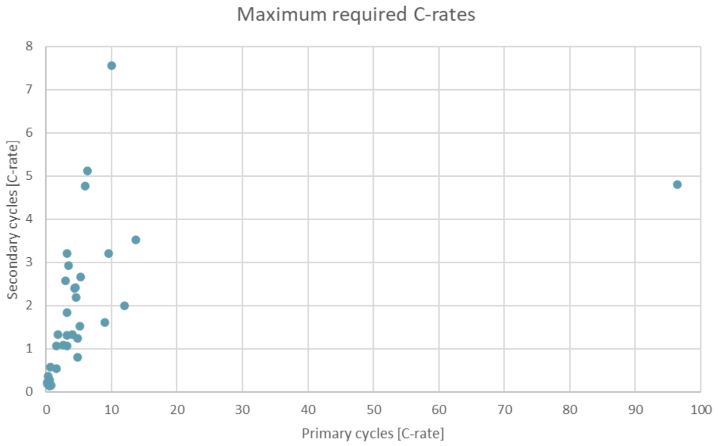

Figure 18 Maximum required C-rates of primary cycles compared to secondary cycles

As can be seen in Figure 19 there are several applications with C-rate requirements above 6C. To use a lithium-ion battery for these applications it would be required to oversize the battery significantly to manage the required C-rates, which makes these applications good candidates for a HESS if a battery technology is considered which can reach these high continuous C-rates. A larger installed battery capacity with the same power requirements will result in lower C-rates of the final system design. An alternative option would be to look into a different technology, such as capacitors. A significant number of the applications have maximum C-rates within the practical limits of lithium-ion batteries, but what can be interesting are the applications that require less than 1C. It might be possible that there also is a market for high energy batteries which can only handle very low C-rates, below 0.5C for example.

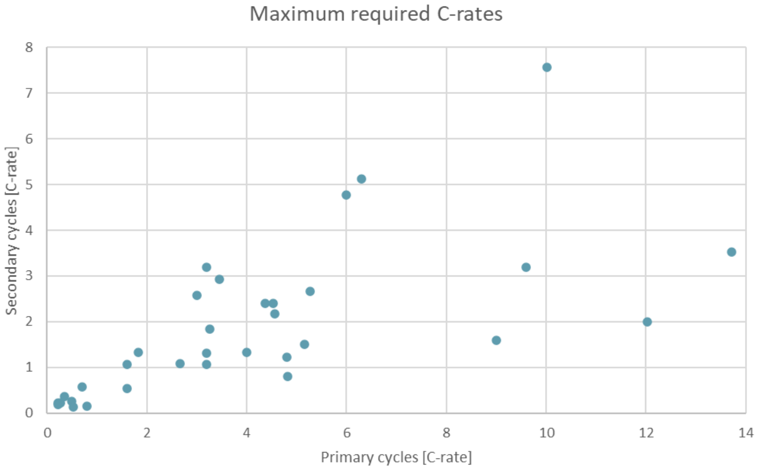

Figure 19 Maximum required C-rates of primary cycles compared to secondary cycles

3.3.2 Number of cycles

The number of cycles performed daily ranges from 0.003 cycles per day (1 cycle per year) to 480 cycles per day. Approximately 30% of the applications have a requirement to perform their primary cycles 10 or more times per day. For most lithium-ion technologies this can only be achieved by reducing the depth of discharge (DoD) and therefore oversizing the battery significantly, resulting in inefficient use of installed battery capacity. These applications are therefore also considered as good candidates for a HESS, on the condition that a matching type of battery technology can be found. The majority of the secondary cycles are performed less than once per day.

In contrary to the C-rate requirements for the baseline, which are similar to the secondary cycle C-rate requirements, the cycling requirements for the baseline are different compared with the requirements for the primary and secondary cycles. Although the primary cycles are relatively small compared to the baseline energy requirement in most cases, the large number of cycles does have an influence on the overall energy requirement for the baseline.

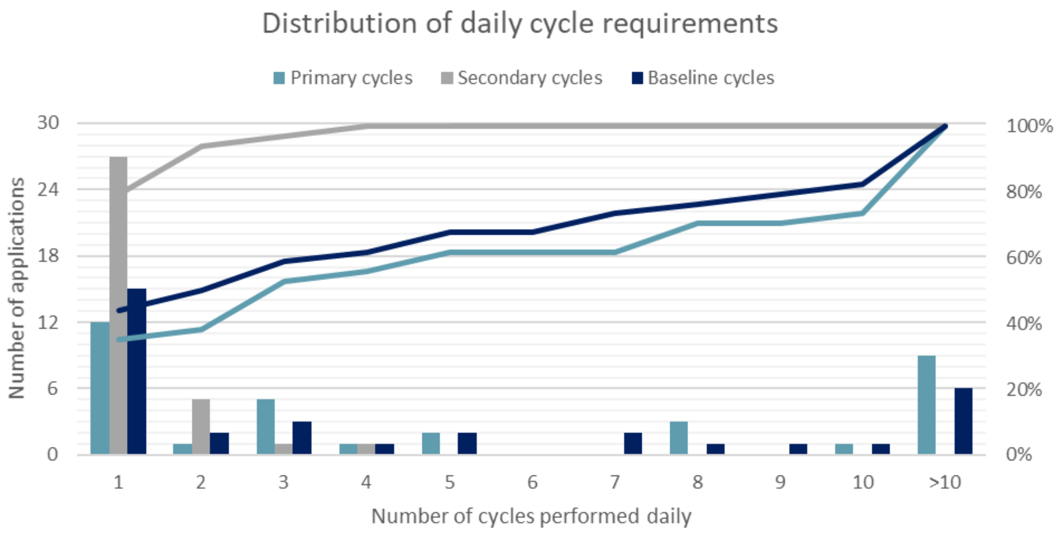

Figure 20 Distribution of number of daily cycles per application

Marine battery systems currently on the market can perform between 3000 and 25000 cycles at 80% DOD, 1C and 25°C, based on the information provided by the suppliers as determined in SEABAT Deliverable 2.2, the KPI report [2]. Where NMC and LFP battery types are in the range of 3000 to 10000 and LTO batteries go up to 25000. Most marine battery systems have a design life of 10 years. This results in 300 to 1000 cycles per year, or 0.8 to 2.7 cycles per day, based on 365 days per year, for LFP and NMC types of batteries. For LTO batteries this would be 2500 cycles per year, or 6.8 per day. Therefore the cycling requirements are divided in three different groups:

- Less than 1 equivalent cycle per day
- Between 1 and 3 equivalent cycles per day
- Between 3 and 7 equivalent cycles per day
- More than 7 equivalent cycles per day

Figure 21 shows the complete overview of the daily performed primary and secondary cycles per application. The application with 480 primary cycles per day is left out in Figure 22 to provide a better overview.

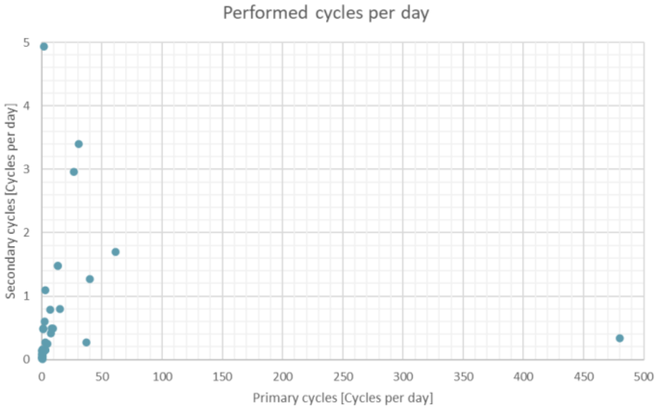

Figure 21 Number of performed primary cycles compared to secondary cycles

Figure 22 shows the overview of performed daily cycles without the application with 480 primary cycles per day. The amount of daily performed primary cycles is clearly larger compared to the secondary cycles.

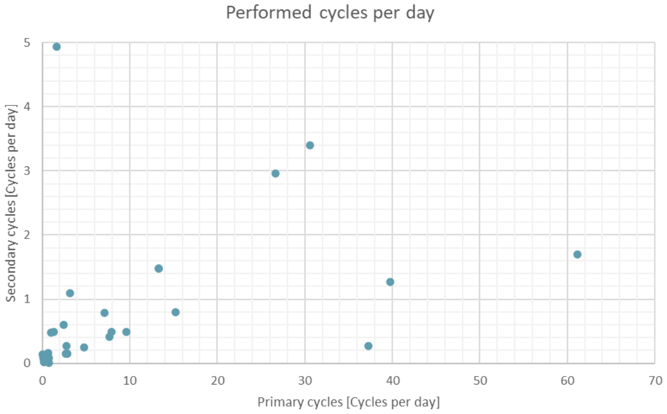

Figure 22 Number of performed primary cycles compared to secondary cycles

Zooming in on the applications below 10 daily primary cycles and below 1 daily secondary cycle provide a better overview of the majority of the applications in Figure 23. There are only limited applications with requirements for the amount of performed cycles which are located within the typical range of current marine lithium-ion battery systems. Most of the applications have either less required cycles or require more cycles than is optimal for current marine battery systems.

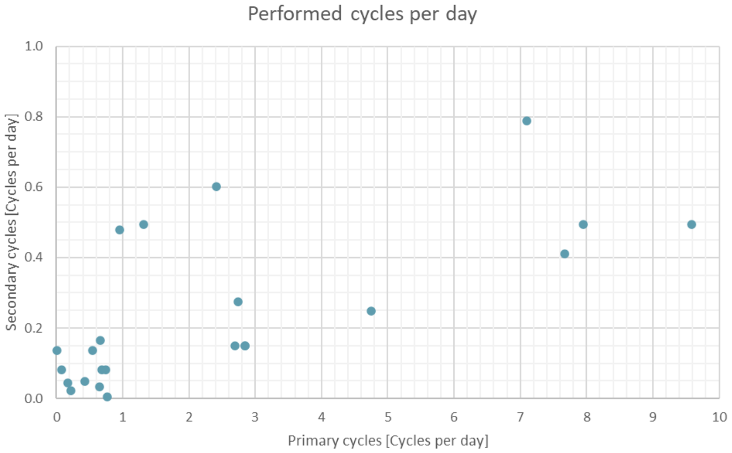

Figure 23 Number of performed primary cycles compared to secondary cycles

3.4 Application matrix

The application matrix is determined by the type of application based on C-rate and Cycling requirements for its primary and secondary cycles. The application matrix is then used to determine the feasibility of each application for the use of a hybrid battery system.

3.4.1 Battery requirements

The types of battery requirements are determined according the types described in Table 2, according to the findings in SEABAT Deliverable 2.2, the KPI report [2], as discussed in section 3.3.1 and 3.3.2. There are four different types of requirements defined both for the C-rates and for the number of cycles per day.

Although in some cases it is true that a battery system with specifications matching a specific type of C-rate requirement, for example type B, also have specifications matching type B for the cycling requirements, this is not the case for all batteries. A battery system can also have specifications matching for example a type C regarding C-rates and type A regarding number of cycles.

Type	C-rates	Cycles per day
A	< 1C	< 1 cycle
B	1C - 3C	1 – 3 cycles
C	3C - 6C	3 – 7 cycles
D	> 6C	> 7 cycles

Table 2 Types of requirements based on basic battery requirements

3.4.2 Battery requirements per vessel type

The vessels which are gathered as input for this research are evaluated for their requirements for both C-rate and cycling requirements, for both their primary and secondary cycles. This analysis is performed to identify if there are any clusters of types of applications which can be identified. These clusters can support in identifying typical requirements for marine battery systems, independently from the type of vessel, type of propulsion system or type of battery application.

Table 3 on the next page shows the different types of applications for the vessels used in this analysis. The vessels are sorted on their type of applications in alphabetical order, from AAAA to DDDD. The first 6 vessels are AAAA types of applications, meaning that for both the primary and secondary cycles the requirements for C-rates and number of cycles performed daily are low. These are typical high energy applications. Other types of applications that are occurring more frequently are CDBB (4), CDBA (3) and DDCA (3). These types of applications require large C-rates and a large number of cycles for the primary cycles and relatively lower C-rates and number of cycles for the secondary cycles.

There is no clear relations between the type of marine battery application and the resulting types of battery requirements, other than that applications with type AAAA requirements are all full electric applications, which is to be expected given the current characteristics of batteries. This shows that it is not likely that it is possible to classify the battery requirements for different vessels based on their type of battery application. This means that for example not all peak shaving applications will be optimally served by the same type of battery system. There are other factors determining what type of battery system should be used for what type of vessel.

Vessel	Application	Primary C-rates	Primary cycles	Secondary C-rates	Secondary cycles
Fishing vessel	Full electric	A	A	A	A
Fishing vessel	Full electric	A	A	A	A
Fast Crew Supplier	Full electric	A	A	A	A
Inland container vessel	Full electric	A	A	A	A
Small tug	Full electric	A	A	A	A
Yacht	Full electric	A	A	A	A
Fast Crew Supplier	Full electric	A	B	A	A
Fast Ferry	Full electric	A	D	A	A
Cable lay vessel	Load leveling and spinning reserve	B	A	A	A
Hybrid tug	Full electric	B	A	B	A
Patrol vessel	Full electric	B	A	B	A
Fast Crew Supplier	Peak shaving and spinning reserve	B	A	D	A
Fast Crew Supplier	Full electric	B	C	C	B
Ferry	Full electric	B	D	B	A
Shoalbuster	Boost function	C	A	B	A
Harbour tug	Boost function	C	B	A	A
Harbour tug	Full electric	C	B	B	A
Harbour tug	Full electric	C	B	B	A
Fishing vessel	Spinning reserve	C	B	C	A
Cruise vessel	Full electric	C	C	B	B
Urban ferry	Full electric	C	C	C	A
Ro-Ro ferry	Full electric	C	D	B	A
Waterbus	Full electric	C	D	B	A
Waterbus	Load leveling	C	D	B	A
Fishing vessel	Peak shaving and boost function	C	D	B	B
Ro-Ro ferry	Load leveling and boost function	C	D	B	B
Ro-Ro ferry	Full electric	C	D	B	B
Ro-Ro ferry	Full electric	C	D	B	B
TSHD	Peak shaving	D	A	C	A
Harbour tug	Boost function	D	B	B	A
Fish carrier	Peak shaving and spinning reserve	D	D	C	A
Urban ferry	Full electric	D	D	C	A
Ro-Ro ferry	Full electric	D	D	C	A
Ro-Ro ferry	Full electric	D	D	D	C

Table 3 Types of battery requirements per vessel type

The majority of the primary cycles have a C type application (41%) for its C-rate requirements. The majority of the secondary cycles have a B type application (44%) for its C-rate requirements. For most applications the required energy for the primary cycles is lower compared to the required energy for the secondary cycles, but the required (dis)charge power is often similar. Therefore it seems correct that the C-rate requirements for the primary cycles are higher than for the secondary cycles.

Type	Primary cycles C-rates		Secondary cycles C-rates	
	Number of vessels	Percentage	Number of vessels	Percentage
A	8	23%	10	29%
B	6	18%	15	44%
C	14	41%	7	21%
D	6	18%	2	6%

Table 4 Distribution of application types for C-rate requirements

The requirements for the number of primary cycles are very much divided, with 35% type A applications and 38% type D applications. For the secondary cycles it is more one-sided as can be expected by the definition of what makes up a secondary cycle, with 79% type A applications. Considering that type A is based on requirements which are less than what current marine battery systems on the market can handle and type D is based on requirements which are more than what current marine battery systems on the market can handle, it seems that the current battery systems that are being used are either over-qualified for their tasks, or need to be oversized to fulfil or the requirements of the application where they are being installed. This can be interpreted to the possibility that there is a market for technologies that are either offering a much higher energy density, but lower C-rate and cycling capabilities than current marine battery system, as well as a possibility for technologies with much higher C-rate and cycling capabilities. This also is assumed to indicate that there is a possibility for a HESS to be beneficial for the applications which have primary and secondary cycles with requirements of different types. The next step is to find these applications and determine the feasibility and of a hybrid battery system and how the application could benefit from using different types of battery systems.

Type	Primary cycles Daily cycles		Secondary cycles Daily cycles	
	Number of vessels	Percentage	Number of vessels	Percentage
A	12	35%	27	79%
B	6	18%	6	18%
C	3	9%	1	3%
D	13	38%	0	0%

Table 5 Distribution of application types for cycling requirements

3.4.3 Application matrix

The main goal of this document is to create an overview of the different types of marine battery applications and to determine if it is possible to identify different clusters of application types which have similar operational requirements regarding batteries. This overview is provided by the application matrix discussed in this section.

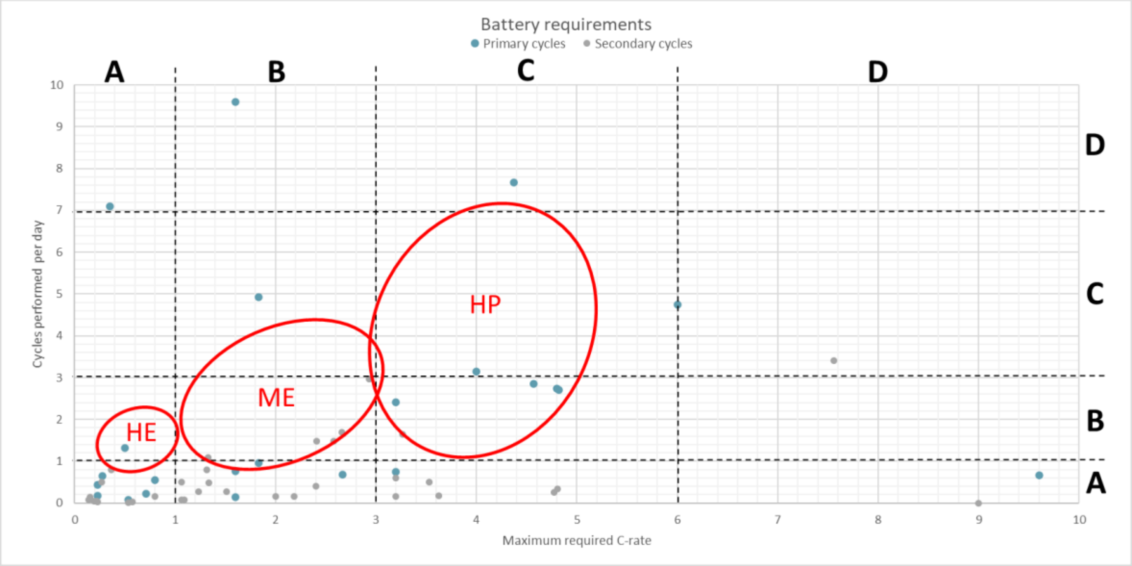

Figure 24 Overview of application types based on basic battery requirements and current marine battery types (HE=high energy, ME=medium energy, HP=high power)

The figure above does not show all applications, as there are a few outliers mainly in the DD type of applications (6% of the applications). However, this figure shows a better overview of the main application clusters and how the performance of the marine battery systems currently on the market matches the requirements. Based on the results from [2] the maximum continuous discharge C-rates and the number of estimated cycles per day (considering 365 days per year and a 10 year design life) is shown for the 3 main battery types: high energy (HE), medium energy (ME) and high power (HP). There are only a few of the application requirements which are located inside the capabilities of current marine battery systems.

There are two main groups of applications, AA (24%) and BA (21%). The most common type for a single requirements (C-rate or number of cycles) is type A for the number of cycles. A total of 57% of the applications require 1 or less cycles per day. This is caused mainly by the secondary cycles, where 79% of the applications have been identified as type A for the number of cycles. However, the results point out the opportunities for high energy battery systems with low cycling capability, a type of battery system which is not common on the marine battery market currently.

On the other end of the spectrum about 20% of the applications have some kind of combination with CC, CD, DC or DD type of battery requirements. So 1 out of 5 applications require relatively large C-rates and a large number of cycles. Battery systems using LTO cells for example are assumed to be a good match for these applications, but there are not many marine battery systems which make use of this technology yet.

Number of cycles

	Type	A	B	C	D	Total
C-rates	**A**	23.5%	1.5%	0.0%	1.5%	26.5%
	B	20.6%	7.4%	1.5%	1.5%	30.9%
	C	10.3%	7.4%	2.9%	10.3%	30.9%
	D	2.9%	1.5%	1.5%	5.9%	11.8%
	Total	57.4%	17.6%	5.9%	19.1%	

Table 6 Occurrence of battery type combinations

3.4.4 Feasibility for hybrid battery systems

As shown in section 3.4.3, there definitely are marine applications which require battery systems which are either specialized as high energy systems, with a low cycle live, as well as high power systems, with a long cycle life. The goal of this section is to identify the vessels and applications which have both these types of requirements combined, which would make them suitable as use cases for the design of a HESS.

The feasibility for a hybrid battery system is determined by assigning a score for each application. The scores are based on the multiplied difference between the C-rate requirements and the cycling requirements for the primary and secondary cycles.

$$\begin{pmatrix} |Primary\ C\text{-}rate - Secondary\ C\text{-}rate| \\ * \\ |Number\ of\ primary\ cycles - Number\ of\ secondary\ cycles| \end{pmatrix}$$

The difference in C-rate and cycling requirements for primary and secondary cycles are evaluated separately, as not all battery cells which can withstand high C-rates can also perform a high number of cycles and vice versa. A high score is assumed to be an indication for the application to be feasible as a use case for a HESS.

The scores for all applications are shown in Table 7, sorted from highest final score to the lowest. The 5 applications with the highest final scores are used as use cases for further investigating the HESS concept. The top 5 applications are:

- A fish carrier using the batteries for peak shaving and as spinning reserve, application type DDCA
- A fishing vessel using the batteries for peak shaving and as boost function, application type CDBB
- A Ro-Ro ferry using the batteries for full electric propulsion, application type CDBA
- A Ro-Ro ferry using the batteries for full electric propulsion, application type DDCA
- An urban ferry using the batteries for full electric sailing, application type DDCA

When taking a look at the complete list of applications it is noticed that the top half, the vessels which have been identified as most likely to benefit from a HESS, mainly are either ferries or tugs. These types of vessels usually have an operational profile in which multiple cycles are performed daily. The battery systems are ideally designed for this standard cycle, but the final sizing is usually determined by the operational circumstances which are not standard and require more energy.

Vessel type	Battery application	Application type	C-rate score	Cycle score	Final score
Fish carrier	Peak shaving, spinning reserve	DDCA	91.6	479.7	43927
Fishing vessel 1	Peak shaving, boost function	CDBB	2.6	59.5	155
Ro-Ro ferry 1	Full electric	CDBA	3.6	37.0	135
Ro-Ro ferry 2	Full electric	DDCA	3.6	24.6	76
Urban ferry 1	Full electric	DDCA	10.2	7.5	67
↑Top 5 highest scores↑					
Ro-Ro ferry 3	Full electric	DDDC	2.5	27.2	45.6
Waterbus 1	Full electric	CDBA	1.9	2.5	27.1
Harbour tug 1	Boost function	DBBA	10.0	14.4	27.1
Ro-Ro ferry 4	Load leveling, Boost function	CDBB	2.1	27.2	25.1
Waterbus 2	Load leveling	CDBA	2.0	23.7	14.3
Ro-Ro ferry 5	Full electric	CDBB	0.5	11.8	12.5
Harbour tug 2	Boost function	CBAA	4.0	2.5	10.3
Harbour tug 3	Full electric	CBBA	3.6	7.3	8.8
Harbour tug 4	Full electric	CBBA	2.4	0.5	6.4
Urban ferry 2	Full electric	CCCA	1.2	0.1	5.5
Cruise vessel	Full electric	CCBB	2.7	2.1	5.5
Ro-Ro ferry 6	Full electric	CDBB	0.4	9.1	5.0
Ferry	Full electric	BDBA	0.5	11.8	4.9
Fast Crew Supplier 1	Full electric	CBBC	1.4	2.7	4.7
TSHD	Peak shaving	DACA	6.4	0.6	3.2
Shoalbuster	Boost function	CABA	2.1	6.3	1.4
Fast Crew Supplier 2	Peak shaving, spinning reserve	DABA	7.4	3.3	1.0
Hybrid tug	Full electric	BABA	1.6	0.7	1.0
Cable lay vessel	Load leveling, spinning reserve	BAAA	1.1	4.5	0.8
Small tug	Full electric	AAAA	0.6	0.8	0.3
Patrol vessel	Full electric	BABA	0.5	0.8	0.2
Fast Crew Supplier 3	Full electric	ABAA	0.2	1.8	0.2
Fast Ferry	Full electric	ADAA	0.0	0.1	0.1
Fast Crew Supplier 4	Full electric	AAAA	0.0	0.4	0.0
Fishing vessel 2	Full electric	AAAA	0.1	0.5	0.0
Inland container vessel	Full electric	AAAA	0.0	0.6	0.0
Fishing vessel 3	Full electric	AAAA	0.0	0.4	0.0
Fishing vessel 4	Spinning reserve	CBCA	0.0	0.2	0.0
Yacht	Full electric	AAAA	0.4	0.0	0.0

Table 7 Scores for feasibility of HESS application

4 C-rate optimization

As discussed in section 2.5 the maximum continuous C-rate of the battery systems currently on the marine market is compared to the C-rate requirements of the investigated applications. The goal is to determine which applications could possibly benefit from a HESS by means of C-rate optimization.

4.1 C-rate performance

In [2] an analysis is made of 30 marine battery systems currently on the market. Figure 25 shows the maximum continuous discharge C-rates of these 30 battery systems. The system with the lowest maximum continuous discharge C-rate can do 0.4C, the highest maximum continuous discharge C-rate is 5C.

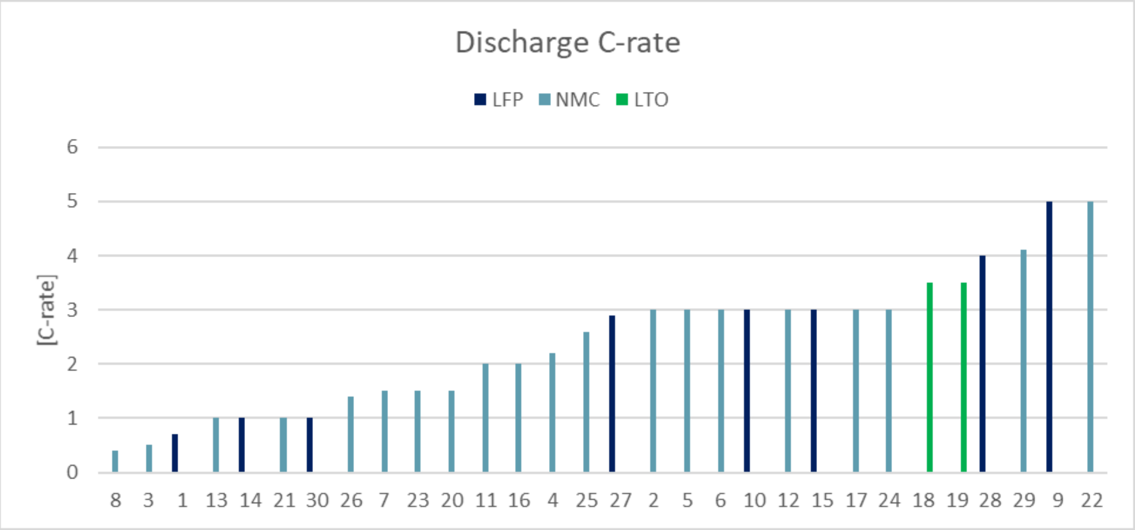

Figure 25 Maximum continuous discharge C-rates of current marine battery systems **[2]**

There are 6 different types of batteries identified in [2]. Starting with High energy, Medium energy and High power batteries based on the C-rate requirements as shown in Figure 26. These three battery types are then divided in heavy duty batteries and not heavy duty batteries, but this is not of importance for the C-rate requirements.

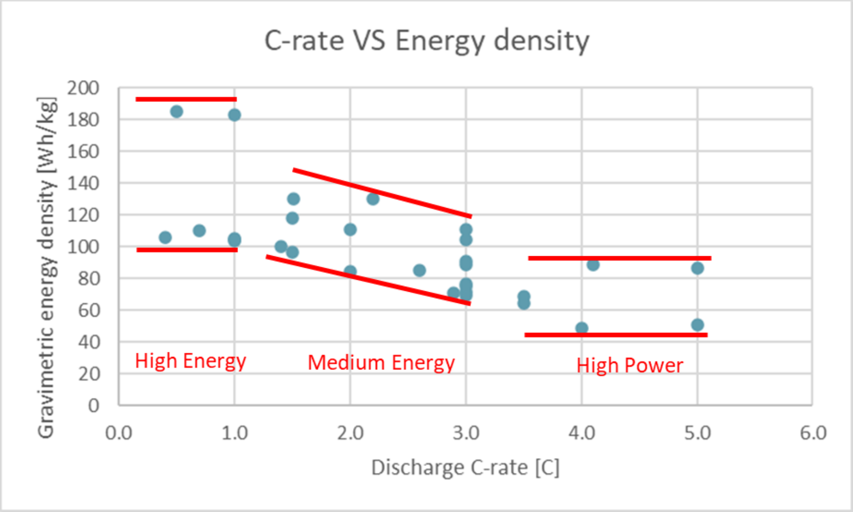

Figure 26 Overview of energy density and discharge C-rates for different types of batteries

It is recommended in [2] to design the HESS based on a high energy battery and a high power (heavy duty) battery. The high energy battery is assumed to have a typical maximum continuous discharge C-rate of 1C. The high power (heavy duty) battery is assumed to have a typical maximum continuous discharge C-rate of 3.5C.

4.2 C-rate requirements

The baseline C-rate requirements are compared to the described maximum continuous discharge C-rate of 1C for the high energy battery and 3.5C for the high power battery. Then it is determined which applications have a baseline C-rate requirement which lays exactly between the two C-rates of 1 and 3.5, where it is assumed for the HESS to have the largest impact by means of C-rate optimization. The 5 vessels with the largest difference between the required C-rate compared to the 1C maximum of the high energy battery and the 3.5C maximum of the high power battery are shown in Table 7

Vessel type	Battery application	Application type	Required C-rate
Harbour tug 4	Full electric	CBBA	2.2
Waterbus 2	Load leveling	CDBA	2.4
Ro-Ro ferry 4	Load leveling, Boost function	CDBB	2.4
Harbour tug 1	Boost function	DBBA	2.0
Ro-Ro ferry 6	Full electric	CDBB	2.6

Table 8 5 Applications most feasible for C-rate optimization

Because 3 out of the 5 applications in Table 7 are not fully battery powered, those are not further taken into account in the investigation for HESS feasibility. Additionally, there are already 2 Ro-Ro ferries taken into consideration based on the cycle analysis from chapter 3. Therefore it is determined that only the full electric harbour tug is further used in the analysis of HESS feasibility in section 5.6.

5 HESS applications

There are 5 applications selected to be investigated for the HESS based on the cycle analysis and based on the theory of C-rate optimization for HESS application the full electric harbour tug is selected as sixth application for further investigation as well in section 5.6.

For each application an operational profile is created which will be used in Work Package 3 as input to the simulations of the different HESS topologies. The operational profiles are created for the battery which has to perform the primary cycles, the battery which has to perform the secondary cycles and for a baseline (monotype) battery system, which has to perform both the primary and secondary cycles. The feasibility of a HESS should be investigated by two different approaches.

- It should be investigated if designing one part of the HESS to be optimized for primary cycles and the other part of the HESS to be optimized for secondary cycles will result in an overall better performing battery system compared to a monotype battery system.
- It should be investigated if C-rate optimization by application of a HESS results in a more optimal battery system compared to an oversized monotype battery system.

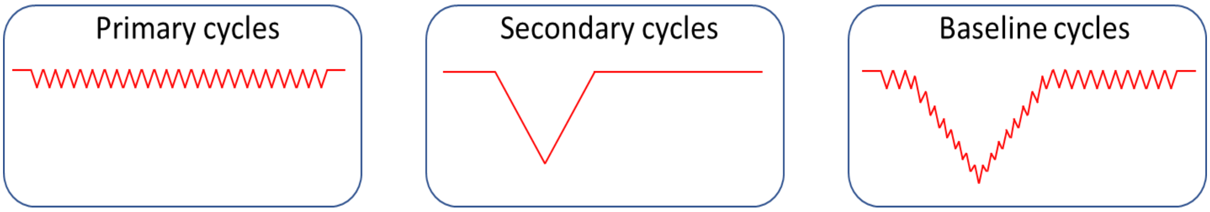

Figure 27 Required power for primary, secondary and baseline cycles vs time

The requirements for the baseline battery system also depend on the fact if the primary and secondary cycles are performed simultaneously. In the example in Figure 27 above the primary and secondary cycles are performed at the same time. However, there are also applications where the primary and secondary cycles are season bound and will not be performed simultaneously.

Two out of the six selected applications are not fully battery powered vessels. The batteries are used for peak shaving, spinning reserve or as boost function, in combination with a diesel engine or generator. As the goal for the SEABAT project is to develop a HESS for fully battery powered vessels, for these two applications it is also investigated what the requirements would be for the batteries in case they are fully battery powered and what effect this will have on the use of a HESS.

5.1 Fish carrier

Fish carrier	Primary battery	Secondary battery	Baseline battery
Application type	DD	CA	CD
Battery application	Peak shaving	Spinning reserve	-
Usable energy	8.3 kWh	450 kWh	450 kWh
Installed energy	10.4 kWh	562.5 kWh	562.5 kWh
Annual cycles (80% DoD)	175322	122	3285
Max C-rate discharge	96.0 C	4.8 C	6.6 C
Max C-rate charge	96.0 C	1.8 C	3.6 C
Max discharge power	1000 kW	2700 kW	3700 kW
Max charge power	1000 kW	1000 kW	2000 kW

Table 9 Operational requirements for fish carrier

The primary cycles are significantly smaller in size compared to the secondary cycles. Although the primary and secondary cycles are performed simultaneously the baseline battery has the same energy requirement compared to the secondary battery due to the small primary cycles. The secondary cycles do have an influence on the maximum C-rates, which are higher for the baseline battery compared to the secondary battery. The baseline battery is cycled 175322 times per year with a DoD of 1.5% for the primary cycles and 122 time at a DoD of 80% for the secondary cycles. Resulting in a total annual energy throughput of 3285 cycles at 80% DoD.

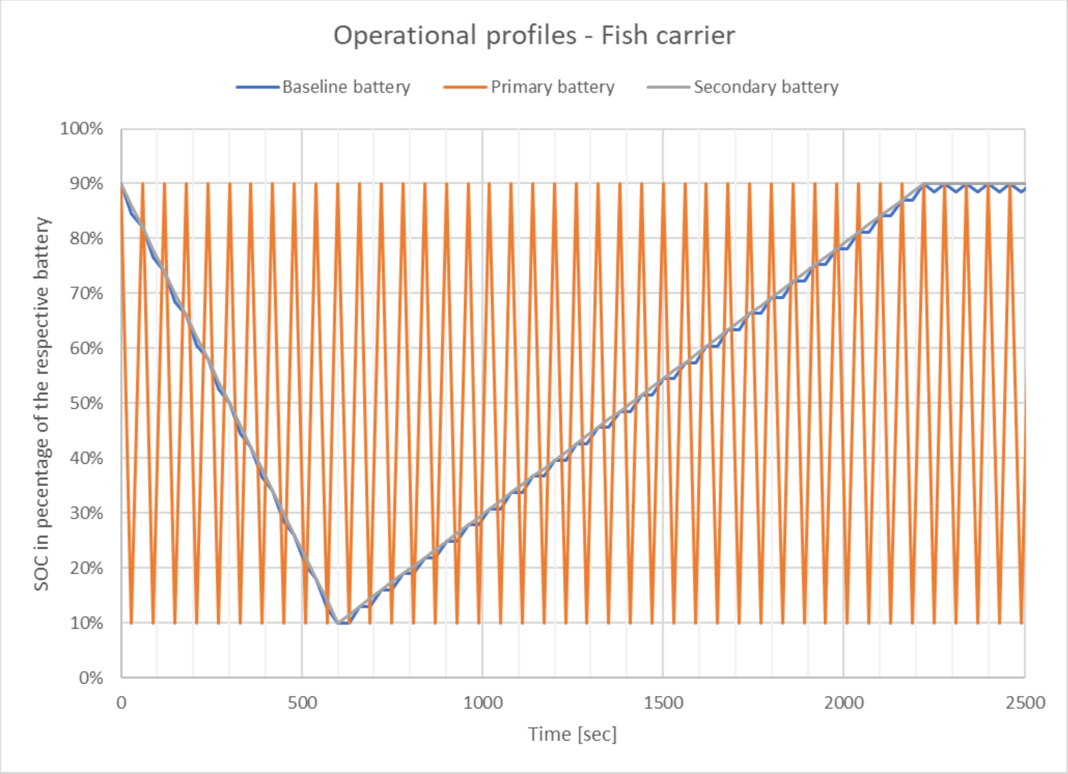

Figure 28 Operational profile – Fish carrier – SOC in percentage of the respective battery

Full electric fish carrier

The fish carrier application has a hybrid propulsion system where the batteries are used for peak shaving and as spinning reserve. A fully battery powered fish carrier will require a significantly larger battery system to fulfill all energy requirements. The required capacity for a full electric version is estimated to be more than 5 MWh. With a battery of this size installed the maximum C-rate will decrease to below 1C and the vessel will not be cycled more than once per day. Therefore a high energy battery solution will be a logical option in this case. From the point of view of the cycle analysis with primary and secondary cycles the HESS concept does not show any specific value. However, for C-rate optimization it can still be considered a valuable option. Therefore it is important to investigate the benefits of C-rate optimization using the HESS concept to discover its potential for applications which might not have a significant or clear difference in primary and secondary cycles. At the same time this application shows that there are potentials for the HESS for hybrid vessels as well, which could be a significant share of the market for marine batteries and therefore should not be forgotten.

5.2 Fishing vessel 1

The fishing vessel uses the battery system for peak shaving and as a boost function for shooting and hauling the trawl. The peak shaving application results in a large number of cycles and relatively high C-rates. The boost function requires more energy and has lower C-rate and cycle requirements. Both peak shaving and the boost function can be performed simultaneously, which results in a higher energy requirement for the baseline battery. The baseline is cycled 22320 times per year at a DoD of 18% for the primary cycles and 620 times per year at 70% DoD, for the secondary cycles. Resulting in a total energy throughput of 5091 cycles at 80% DoD annually.

Fishing vessel	Primary battery	Secondary battery	Baseline battery
Application type	CD	BB	BD
Battery application	Peak shaving	Boost function	-
Usable energy	47.5 kWh	189.6 kWh	215.7 kWh
Installed energy	59.4 kWh	237.0 kWh	269.7 kWh
Annual cycles (80% DoD)	22320	620	5091
Max C-rate discharge	4.8	2.7	3.4
Max C-rate charge	4.8	1.3	2.2
Max discharge power	285 kW	632 kW	917 kW
Max charge power	285 kW	316 kW	601 kW

Table 10 Operational requirements for fishing vessel

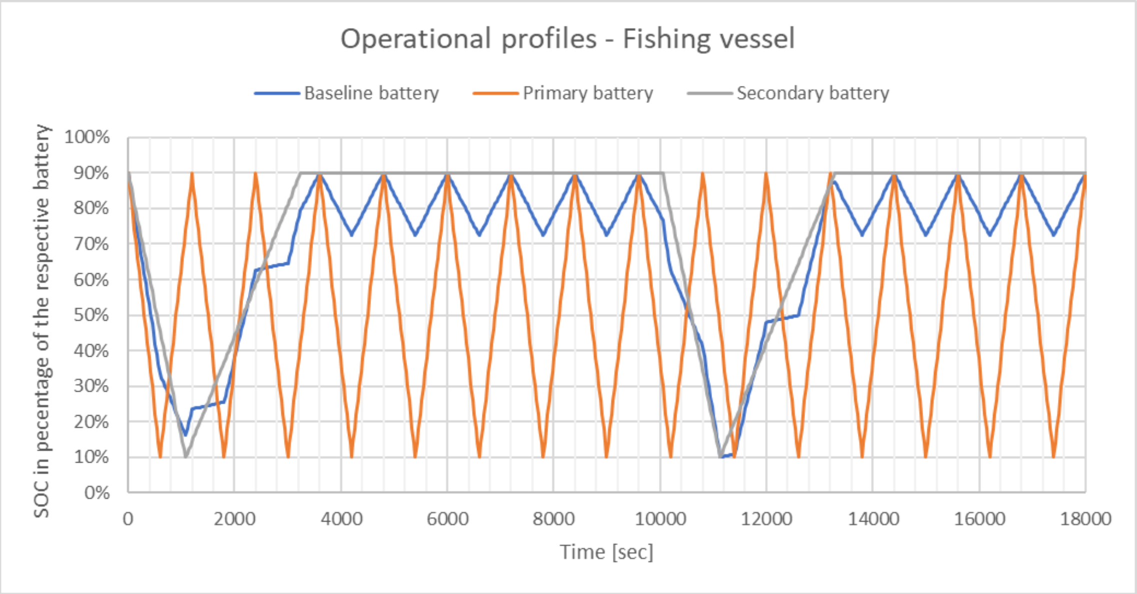

Figure 29 Operational profile – Fishing vessel – SOC in percentage of the respective battery

Full electric fishing vessel

Fishing vessels are often required to remain at sea for multiple days. This results in large energy requirements and makes them currently unsuitable to be fully battery powered. Similar to the fish carrier applications the combination of peak shaving and boost function in a hybrid vessel is important to consider for HESS technology. When other new zero emission technologies will emerge, it is expected that battery systems will also play a role in these types of systems.

5.3 Ro-Ro ferry 1

This Ro-Ro ferry has a season dependent operational profile. A summer profile, 335 days per year, when there is no ice, the ferry makes 37 crossings per day. During winter, 30 days per year, when there is ice, the ferry makes only 3 crossings per day on a different route which require significantly more energy. The annual energy throughout for the baseline battery in cycles of 80% DoD is 1371. This are 90 cycles of 80% DoD and 12375 cycles of 8% DoD.

Ro-Ro ferry 1	Primary battery	Secondary battery	Baseline battery
Application type	CD	BA	BC
Battery application	Full electric	Full electric	Full electric
Usable energy	124 kWh	1200 kWh	1200 kWh
Installed energy	155.3 kWh	1500 kWh	1500 kWh
Annual cycles (80% DoD)	12375	90	1371
Max C-rate discharge	5.2	1.5	1.5
Max C-rate charge	2.6	0.3	0.3
Max discharge power	800	2270	2270
Max charge power	400	400	400

Table 11 Operational requirements for Ro-Ro ferry 1

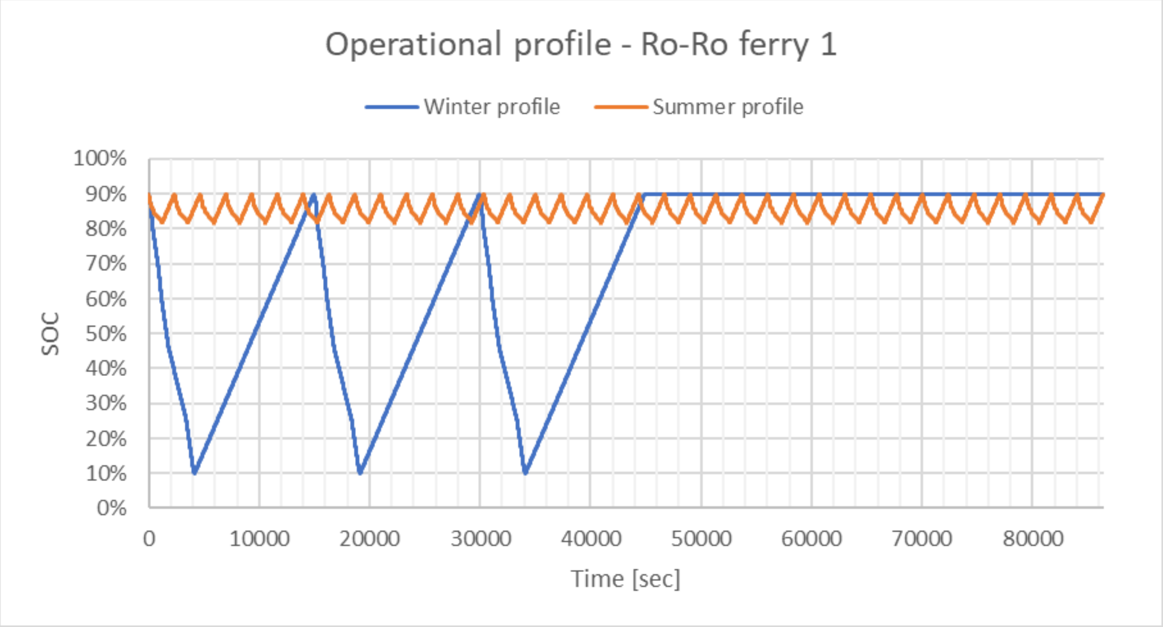

Figure 30 Operational profile – Ro-Ro ferry 1 – SOC in percentage of the baseline battery

5.4 Ro-Ro ferry 2

This Ro-Ro ferry performs 34 round trips per day, with a charging station on each side. It is assumed that approximately 5% of the time the weather conditions will result in a larger power and energy demand during the trip, which is represented by the last two cycles in the operational profile. The battery has to be sized for the case that one of the charging stations is not operational, without having an impact on the operational schedule of the ferry. It is assumed that approximately 5 days per year there is a problem with one of the charging stations. Therefore there is an operational profile provided for 2 active chargers and for 1 active charger, representing the primary and secondary cycles. The resulting number of annual cycles in energy throughput is 4601 cycles at 80% DoD, divided in:

- 11520 cycles at 30% DoD, normal conditions and 2 active chargers
- 720 cycles at 40% DoD, heavy conditions and 2 active chargers
- 80 cycles at 60% DoD, normal conditions and 1 active charger
- 5 cycles at 80% DoD, heavy conditions and 1 active charger

Ro-Ro ferry 2	Primary battery	Secondary battery	Baseline battery
Application type	DD	CA	CD
Battery application	Full electric	Full electric	Full electric
Usable energy	263 kWh	525 kWh	525 kWh
Installed energy	329 kWh	657 kWh	657 kWh
Annual cycles (80% DoD)	9049	63	4601
Max C-rate discharge	5.8	2.9	2.9
Max C-rate charge	7.2	3.6	3.6
Max discharge power	1900	1900	1900
Max charge power	2380	2380	2380

Table 12 Operational requirements for Ro-Ro ferry 2

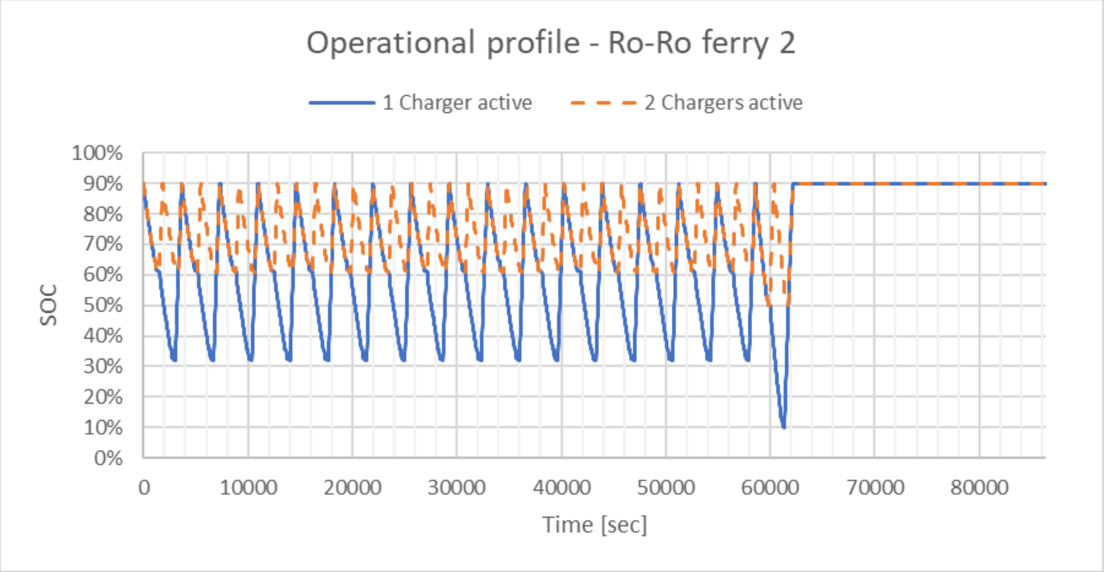

Figure 31 Operational profile – Ro-Ro ferry 2 – SOC in percentage of the baseline battery

5.5 Urban ferry

The urban ferry is a small vessel operating on a fixed route in an urban area. The route has multiple stops where passengers get on or off the ferry. At one of the stops there is a charging station with a maximum charge power of 600 kW. The ferry makes 8 trips per day which in normal conditions require about 35 kWh, which will be charged in a few minutes at 400 kW. In 5% of the time there is a trip which takes longer and requires more power, resulting in an energy requirement of 136 kWh. To charge the batteries sufficiently again in the available time after this larger trip the maximum charge power of 600 kW is required. The primary cycles, normal condition trips, have a DoD of 20% compared to the secondary cycles. So the baseline performs 2738 annual cycles at 20% DoD and 183 annual cycles at 80% DoD.

Urban ferry	Primary battery	Secondary battery	Baseline battery
Application type	CD	BB	BD
Battery application	Full electric	Full electric	Full electric
Usable energy	35 kWh	136 kWh	136 kWh
Installed energy	43.8 kWh	170 kWh	170 kWh
Annual cycles (80% DoD)	2738	183	887
Max C-rate discharge	2.3	0.9	0.9
Max C-rate charge	9.1	3.5	3.5
Max discharge power	100 kW	150 kW	150 kW
Max charge power	400 kW	600 kW	600 kW

Table 13 Operational requirements for Urban ferry

The operational profile below shows 2 days.

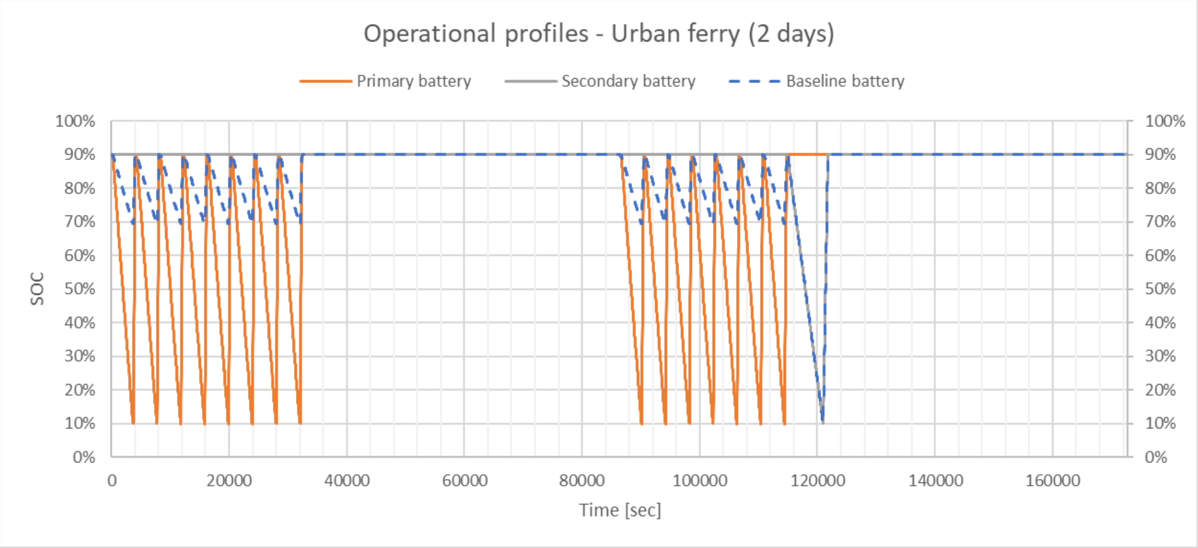

Figure 32 Operational profile – Urban ferry – SOC in percentage of the respective battery

5.6 Harbour tug

The harbour tug is selected based on the C-rate optimization theory and performs on average 3 jobs per day, which require approximately 525 kWh at a relatively high C-rate. After every job the vessel has time to charge the batteries with a 1000 kW charger. Once every week the three standard jobs are followed by a larger job, which requires approximately 1100 kWh. This application is selected based on the C-rate optimization theory, where the HESS is used to create a battery system with a maximum continuous C-rate of 2.2C, out of a high energy and high power battery.

Harbour tug	Primary battery	Secondary battery	Baseline battery
Application type	CB	BA	BB
Battery application	Full electric	Full electric	Full electric
Usable energy	525 kWh	1100 kWh	1100 kWh
Installed energy	656 kWh	1375 kWh	1375 kWh
Annual cycles (80% DoD)	939	126	574
Max C-rate discharge	4.6	2.2	2.2
Max C-rate charge	1.5	0.7	0.7
Max discharge power	3000 kW	3000 kW	3000 kW
Max charge power	1000 kW	1000 kW	1000 kW

Table 14 Operational requirements for a Harbour tug

Figure 33 shows the operational profiles for the harbour tug. The standard day has 3 relatively small cycles. One day per week on a heavy day the 3 small cycles are followed by one large cycle.

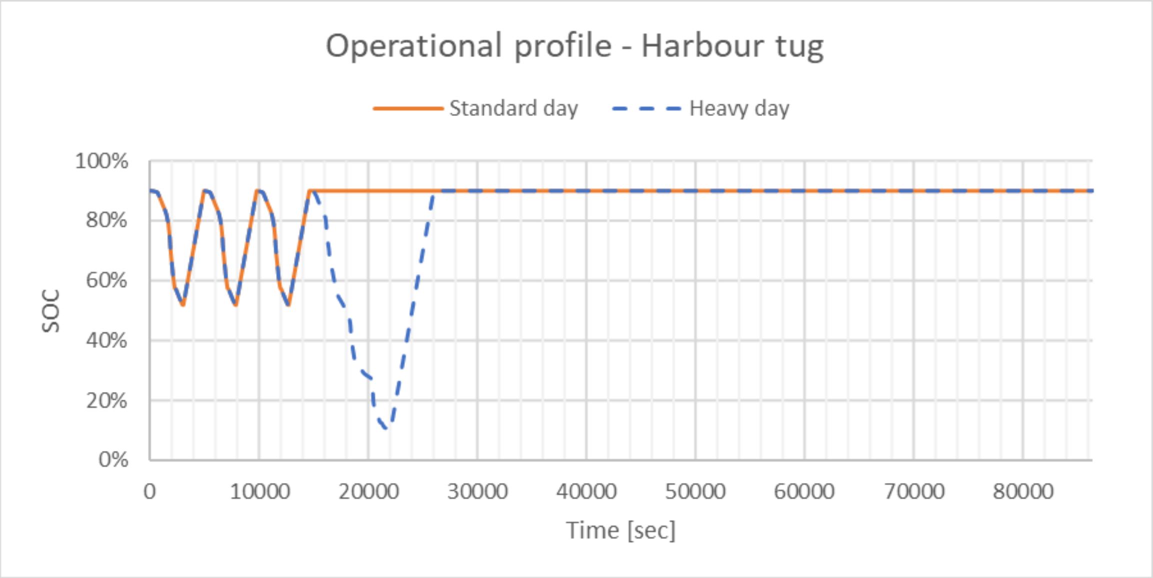

Figure 33 Operational profile - Harbour tug – SOC in percentage of the baseline battery

6 Discussion, Conclusions and Recommendations

6.1 Conclusions

The operational profile of vessels very rarely consists of only one type of cycle for the batteries. Therefore, for all the 34 vessels that have been investigated in this study a primary cycle and a secondary cycle was determined. The primary cycle is defined as the most common type of operation and therefore results in a higher number of cycle and usually a smaller energy requirement. The secondary cycle is defined as the alternative operation, which is performed less often by the vessel, but usually has a strong impact on the energy requirements of the battery system and therefore on the size and design of the battery system. Both the primary and secondary cycles have been analyzed for 34 different types of vessels and were grouped into application types based on their C-rate and cycling requirements according to the definition in Table 15, which are identified as the basic requirements for battery system initial design.

Type	C-rates	Cycles per day
A	< 1C	< 1 cycle
B	1C - 3C	1 – 3 cycles
C	3C - 6C	3 – 7 cycles
D	> 6C	> 7 cycles

Table 15 Types of requirements based on basic battery requirements

By separating the requirements for primary and secondary cycles multiple clusters of type of battery requirements have been identified independently of vessel type or type of battery application. There is a large difference in operational requirements for marine battery systems, which makes it impossible for a single type of battery technology to be optimal for all applications. This rules in favor of investigating the HESS concept. Where most marine battery systems currently on the market are designed for the average requirements of vessels, the combination of a high energy battery systems with a short cycle life and a high power battery system with a long cycle life can potentially improve the efficiency of battery usage in the marine market.

The analysis has shown that two vessels which use the battery system for different types of battery applications, for example as a peak shaving and spinning reserve application, are identified as the most feasible application for a HESS. However, this is not the case for all vessels which use their batteries in similar combinations of applications. Nevertheless, the aim for the SEABAT project is to design a HESS for a fully battery powered vessel and most applications which combine different types of battery applications have a hybrid propulsion system. The fully battery powered vessels that showed most compatibility with a HESS are ferries with a relative high number of cycles as their nominal operation, but with additional energy requirements for the batteries under certain circumstances.

The main conclusion from the application matrix is that ferries and tugs are the types of vessels which are most likely to benefit from a HESS. In some particular (hybrid) cases fishing vessels are an interesting candidate as well. The main reason for the ferries and tugs to be interesting for a HESS is the fact that these types of vessels usually have a primary cycle which is relatively small compared to their overall energy requirement and which is performed at a relevant high number of times per day. Additionally C-rate optimization can be a serious benefit for HESS application for vessels that have a C-rate requirement that does not match the specifications of most battery systems and therefore will require oversizing of the batteries in case of a monotype battery system.

It is important to mention that for the vessels without a clear difference between primary and secondary cycles there can still be a possible benefit for the HESS. This is based on the C-rate optimization theory, where the C-rate performance of the HESS can be optimized based on the requirements of the vessel. This in theory reduces the need for oversizing either a high energy battery or a high power battery.

6.2 Recommendations

The first recommendation for the continuation of the research work in the following work packages in SEABAT is to start with the 3 electric ferries as input for the design process of the different HESS topologies. The ferry applications have the most predictable operational profiles and are a good starting point to develop the HESS concept. The three different types of ferries can be used to validate the flexibility of the HESS design.

Secondly it is interesting to also have a look at the operational profiles of the tug application. This is similar to the ferries regarding the requirement for a relatively large number of primary cycles, but its operational profiles is more unpredictable. The main goal for a HESS in the tug application would be C-rate optimization. It will have to be investigated if it is beneficial to combine a high energy and high power battery to a battery system which has exactly 2.2C as maximum discharge C-rate, so it will not be required to oversize either a higher energy or a high power battery for this application.

The fish carrier and fishing vessel are identified as most feasible applications for a HESS, but they both had a hybrid propulsion system, instead of full battery power. Although the aim for the SEABAT project is to develop a HESS for a fully battery powered vessel, it can be interesting to take hybrid applications into account as well to enlarge the market potential. For a large number of vessels, on the short term, it will not be realistic to have a fully battery powered propulsion system, also not with significant improvements of battery performance in the foreseeable future. Therefore, batteries will play an important role in hybrid vessels as well. This can be a significant share of the market for marine batteries and will be worth to be considered for HESS applications as well.

It will be interesting for the work to be performed in WP 3 to describe the different types of operational scenarios for the HESS and the logic behind. As shown in this report there are multiple approaches to a HESS and how to design and apply it.

Finally, for the work performed for deliverable 2.2, the KPI report, it will be interesting to see how the battery systems currently on the market perform according to the definition of type A, B, C and D for C-rate and cycling requirements as discussed in this document.

7 Deviations from Grant Agreement Annex 1

There are no deviations with respect to Annex 1.

8 References

[1] SEABAT, "D1.2 "Market evolution and potential within 5, 10, 15 years"," 2021.
[2] SEABAT, "D2.2 "KPI Report"," 2021.

9 Acknowledgements and disclaimer

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 963560. The information and views set out in this publication does not necessarily reflect the official opinion of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf, may be held responsible for the use which may be made of the information contained therein.

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	Ro-Ro	Roll on – Roll off
9	TSHD	Trailing Suction Hopper Dredger

Appendix B – List of tables

Appendix C – List of figures