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University of Applied Sciences

Comparative LCA of storage concepts for full electric car ferries in Norway

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Submitted to:

Bernhard Fäßler, MSc

Handed in by:

Sven Jona, BEng

1510727026

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Abstract

In times of global climate change, it is increasingly important to investigate emissions and resource consumption of all machines and, if possible, to improve them. This includes within the transport sector car ferries.

In order to reduce the environmental impacts of car ferries, the electrification has penetrated into this sector, which has led to the world's first fully electric car ferry. One of the most important components to operate this ferry is the energy storage. Not only the battery storage of the ferry itself is needed, but also an onshore battery storage system is needed to support the electrical grid.

The present study examines how storage technologies and concepts can impact the environment considering the world's first all-electric car ferry, MF Ampere, which operates in Norway.

To examine this, the current onshore battery storage system is compared to a concrete sphere storage system. For this purpose, data from the first test run of this new storage technology, which was successfully carried out by the Fraunhofer Institute in 2016, is considered. Subsequently, a life cycle assessment of the two storage systems is carried out to compare the environmental impacts.

The concrete sphere storage system performs better for 15 of 17 impact categories compared to the existing onshore battery storage system. Depending on the impact category the impact reduction is about 2% to 8%.

Nevertheless, it is difficult to estimate how long the useful life and how good the efficiency of the concrete ball storage will be, since no system of this size has been tested yet. Also, the costs of the concrete sphere storage system have not been considered.

Kurzreferat

In Zeiten des globalen Klimawandels wird es immer wichtiger, die Emissionen und den Ressourcenverbrauch aller Maschinen zu untersuchen und, wenn möglich, zu verbessern. Dazu gehören auch Autofähren innerhalb des Transportsektors.

Um die Umweltbelastung durch Autofähren zu reduzieren, ist die Elektrifizierung auch in diesen Sektor vorgedrungen. Dies hat zur weltweit ersten vollelektrischen Autofähre geführt. Eine der wichtigsten Komponenten, um diese Fähren zu betreiben, ist der Energiespeicher. Nicht nur der Batteriespeicher der Fähre selbst wird benötigt, sondern auch ein Batteriespeichersystem, das an Land installiert ist und zur Unterstützung des Stromnetzes gebraucht wird.

Die vorliegende Arbeit untersucht, wie sich Speichertechnologien und -konzepte auf die Umwelt auswirken können, wenn man die in Norwegen operierende erste vollelektrische Autofähre der Welt, MF Ampere, betrachtet.

Um dies zu untersuchen, wird das aktuelle Land-Batteriespeichersystem mit einem Betonkugelspeichersystem verglichen. Zu diesem Zweck werden Daten aus dem ersten Testlauf des Betonkugelspeichersystems berücksichtigt, der 2016 vom Fraunhofer-Institut erfolgreich durchgeführt wurde. Anschließend wird eine Ökobilanz der beiden Speichersysteme durchgeführt, um die Umweltauswirkungen zu vergleichen.

Das Ergebnis dieser Ökobilanz ist, dass das Betonkugelspeichersystem für 15 von 17 Wirkungskategorien besser als das vorhandene Land-Batteriespeichersystem ist. Abhängig von der Wirkungskategorie beträgt die Reduzierung der Auswirkungen etwa 2% bis 8%. Dies ist größtenteils auf den Ressourcenverbrauch in der Bauphase der beiden Systeme zurückzuführen, da die Ressourcen für die Batterien deutlich Umweltschädlicher sind.

Es ist jedoch schwierig die Nutzungsdauer und die Effizienz des Betonkugelspeichers abzuschätzen, da noch kein System dieser Größe getestet wurde. Auch die Kosten für das Betonkugelspeichersystem wurden nicht berücksichtigt.

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BMS	battery management system
bs	Battery storage
css	concrete sphere storage
d_{sp}	diameter, sphere
E_{sp}	Energy, sphere
fu	functional unit
g	acceleration of gravity
h	water depth
kW	kilowatt
kWh	kilowatt hour
LCA	life cycle assessment
LCI	life cycle inventory
n	buffer rate
$P_{charging}$	charging power
p_u	hydrostatic pressure
SOC	State of Charge
V_{sp}	Volume, sphere
η	efficiency
ρ_w	water density

1 Introduction

Never has mankind influenced the environment as strong as in the last century. Since the beginning of the industrial revolution, the lives of human beings in western, capitalistic and highly industrialized countries became much easier, due to many ground-breaking inventions and technologies.

The advantages of new technologies and developments came along with other problems and impacts such as the very present and highly discussed change in climate. This is not only evident in climate change and the increase in temperature causing an augmented appearance in floodings, hurricanes etc., it also provokes the toxication of marine waters, agricultural land and air. Especially the view on the ever-increasing human population arises the question of how we deal with these topics in order to secure life on earth in the future.

This issue is not new. A lot of things are going into a direction of a more conscious and more sustainable future, as e.g. the Paris Climate Agreement imposes. Accepted by many countries, the focus turns to a sensitive and active climate policy by enforcing renewable energy production, optimisation, increase in efficiency and decrease of resource depletion. New trends in technology such as electro mobility mark rising the awareness of manmade climate change.

Norway, a country with one of the highest share of hydro-electric power (96,4 % in 2016), which is considered particularly environmentally friendly, is a pioneer with the electro mobility policies and subsidies [1]. Having an electricity mix with a high grade of renewables is one of the key prerequisites for a broad transition being environmentally friendly. The share of full electric and Plug-In-Hybrid vehicles in June 2017 was 52%, while exceeding the rate of conventional fuel cars for the first time [2]. Norway stated to deny the readmission of new conventional cars by 2025, which seems to be a realistic goal by looking at the current trends.

The transport sector not only includes the road vehicles, but also watercrafts like car ferries. Due to the geographic conditions of Norway, including mountains and numerous deep fjords, the necessity of bridging road connections via ferries are indispensable [3]. For this reason, there are currently 180 ferries, operating in Norway, of which 84 are suitable for fully electric operation [4]. The world's first fully electric car ferry is the MF Ampere, which started operating in 2015[5].

To run an electric ferry such as the pilot project with MF Ampere, certain circumstances or conditions have to exist. The relatively small energy density of battery technology compared to conventional diesel represents one of the major obstacles. This obstacle can be lowered by a short and scheduled sailing. In the case of MF Ampere, its batteries are charged with every docking. The grid is not able to deliver the charging power, while a land-based battery is supporting the charging process, acting as some sort of buffer.

By looking at the stated goal of carbon emission reduction of ferries, the question pops up how this concept is really performing in terms of its environmental footprint. The necessity of supporting the grid with buffering systems might lower the reduction of emissions. This thesis examines the environmental performance of such systems.

2 System description

The first successful testing of an electric propulsion for a boat dates back in 1839. Wilhelm Jacobi developed the first motorized boat, but this technology was quickly and successfully replaced by fuel burning engines [5]. The advantages of the much higher energy density of fossil fuels displaced the electric idea of propulsion, as the range of such burning systems is much higher. In addition, the refuelling, respectively charging process is much faster and simpler than the electric counterpart.

The current environmental situation drives the need for more eco-friendly solutions of transportation and energy production. The MF Ampere, which you can see in Figure 1, originated from this idea and is the first fully electric operated ferry in Norway. It started to operate in 2015 and bridges the European highway E39 between Opedal and Lavik on the Sognefjord. One crossing of this 6 km long route takes around 20 minutes. Ampere's capacity includes 120 cars and 350 passengers [6].

The development of the ferry included the whole system. Not only the power train is fully electric, also the hull and weight design were made to provide an optimal and highly efficient vessel. The catamaran shaped hull (ZeroCat120) was made completely from lightweight Aluminium [5].

Figure 1: MF Ampere[7]

The ferry is powered by electric motors. The energy required for this purpose is provided by a ship's battery system. But this ship battery system can only be considered as a cache. Because the electric energy with which this ship battery system is loaded, comes originally from the public Norwegian electrical grid.

This public Norwegian electrical grid transports the electrical energy from the power plants, which are mostly hydropower plants in Norway, to the consumers, which includes the MF Ampere.

In order to get the electrical energy from the public Norwegian electrical grid into the ship battery system, a charging system is needed. The charging system will be considered more in the further course of this work.

The charging system has several main tasks. From the special circumstances of the ferry operation, the first task arises. This is storing electrical energy which comes from the electrical grid. As mentioned above, a ferry crossing takes about 20 minutes, after which the ferry docks.

The docking time of the ferry of 10 minutes for disembarking and embarking is used to charge the onboard batteries [6]. The actual charging time is approximately 9 minutes, since time is needed to connect the ferry to the charging system.

During the charging time of 9 minutes an electrical power of about 1307kW has to be delivered to the ferry. However, this power cannot be provided by the public Norwegian electric grid at the connection points in Oppedal and Lavik where the charging systems are located. At both connection points, where the charging systems are connected, only a power of 250kW can be taken from the network.

Therefore, during the time in which the ferry is not charged, the respective land battery system is charged and stores electrical energy. When the ferry docks again and the ship's battery system is charged, the electrical power comes partly from the electrical grid and partly from the land battery system.

In you can see the charging infrastructure to make the ferry operation possible. On both sides of the fjord is a charging system, which includes the power electronics, the connection to the electric grid and an onshore battery system, which is the same on both sides.

3 Goal and scope

The goal is to determine how good the current type of energy supply of MF Ampere is in terms of environmental impacts and whether there is a better option that will allow the ferry to operate. For this purpose, another storage concept is created, which makes it possible to operate the ferry with the given circumstances.

As initially described several electric ferries are currently under construction or in planning, which can differ by hull design or propulsion concepts [8]. To provide useful data for such future projects, only the components for the charging system are considered. In other words, the ferry itself is not considered at all.

3.1 Considered charging systems

In order to be able to make a comparison, the currently used storage system is mapped in the first step and analyzed for its environmental effects.

As described in Chapter 2, this current storage system essentially consists of the onshore battery system, the necessary electronics with cables and a building in which this technology is mounted. It should also be mentioned that this storage system is identical on both sides of the fjord at the docking station Lavik and Oppedal.

The battery technology used for the onshore battery system is lithium polymer. More specifically, this consists of lithium cobalt dioxide batteries.

Since lithium battery technology is very resource-intensive and requires many rare earths, there is the question of whether there is an alternative storage technology which enables the MF Ampere to operate and which is better for the environment at the same time.

In order to be able to answer this question a technology is selected which can meet the technical requirements of this project on one hand and uses materials that are as simple as possible, and which are better for the environment on the other hand.

The technology under consideration is the concrete sphere storage technology. This was first tested by the Fraunhofer Institute in 2016 on a scale of 1:10. It is interesting because it uses a hollow concrete sphere, which is sunk in the water. It uses the hydrostatic pressure as storage potential and therefore has to be dimensioned the smaller, the deeper it is in the water. More details in the following chapters.

This is exactly what makes this technology so interesting for this work. All the necessary conditions for the successful use of this technology are available in connection with the ferry service.

These include the presence of water, which is always present in connection with a ferry. Furthermore, in connection with the location of Norway, there is the relatively high water depth that the fjords in Norway largely have. In the case of the examined ferry route Oppedal - Lavik, where the fjord is about 6 km wide, the water depth in the immediate vicinity of the ferry route is about one kilometer. This is relatively high and results in a smaller concrete sphere as it was if it were not installed at such a great depth. This in turn saves construction material and resources.

The third point is the special operation of car ferries. They often go on the same route during the day. This in turn has the advantage for the storage system that no long distances with cables must be bridged.

In a further step, an optional charging system will be developed and tested for its environmental effects using the same method.

The two charging systems that are compared to each other are thus the existing battery storage system and the concrete sphere storage system.

As mentioned above, these differ primarily by the storage technology, but this has the consequence that the necessary ancillary equipment is different. These exact differences are shown in more detail in Chapter 5.

Finally, the environmental impact of these two overall storage systems are examined, using the simapro software and the results are compared and discussed to determine if there is an alternative for the current type of energy supply that causes less environmental damage. As there are also two other ferries operating on this ferry route, it is considered whether the fully electrical operation of these ferries can be made possible and whether it makes sense to operate these ferries according to the current grid situation.

3.2 functional unit and system boundary

The systems under consideration are the storage systems. This is either the battery storage system or the concrete sphere storage system. Figure 2 represents the system boundary for the battery storage system. This includes the batteries, with all the required power electronics, the battery building and the cable connection. This system is mounted on both sides of the fjord.

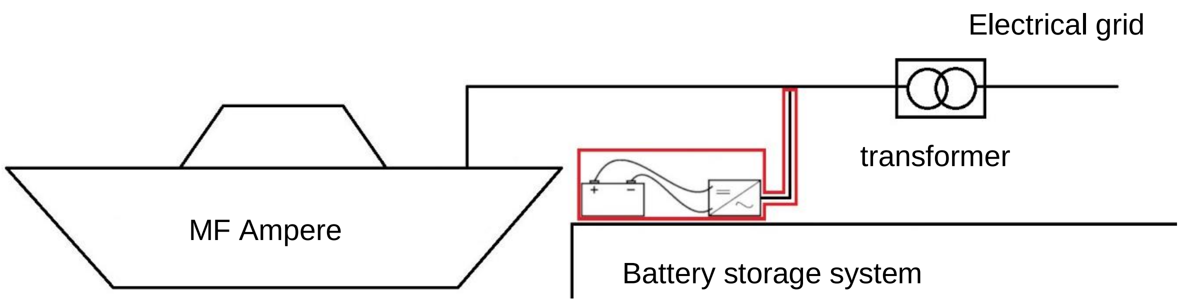

Figure 2: System boundary of the battery storage system

Figure 3 shows the system boundary for the concrete sphere storage system. This includes the concrete sphere with all mechanical and electrical components, as well as the cable connections that connect the sphere to the two charging stations. Please note that the cable connection is connected to the transformer on the side where the electrical grid is connected. Further details in chapter 5.

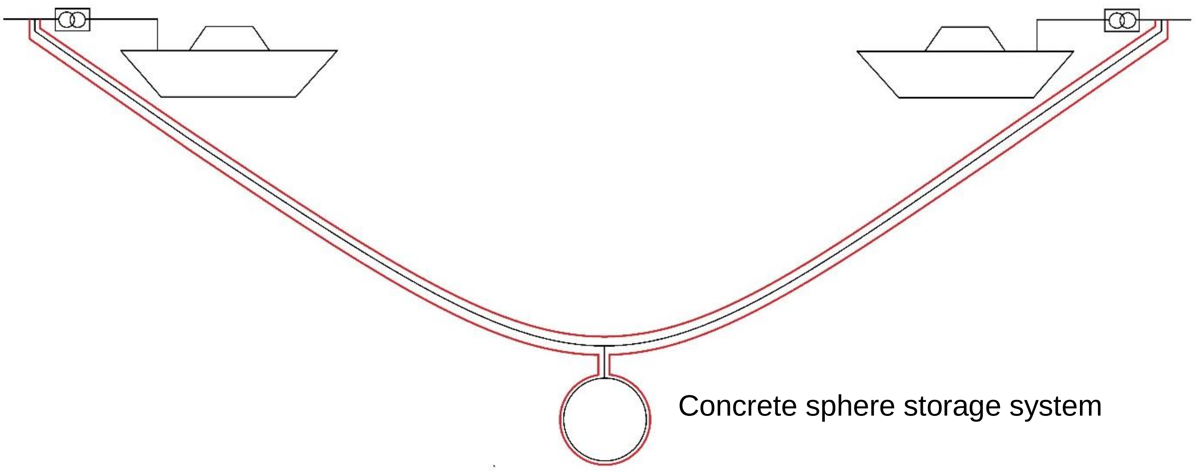

Figure 3: System boundary of the concrete sphere storage system

The definition of the functional unit (fu) is another important part of LCA.

Two storage systems are compared. The main benefit of these systems is providing a certain amount of energy to operate the ferry. The ferry in turn has the main benefit to bridge a distance. The basis for the fu is therefore a combination of both benefits. Therefor the fu is the delivered energy per kilometer in kWh/km. All calculations are converted to this unit.

Functional unit → delivered energy per kilometer in [kWh/km]

4 Background

This chapter describes the basic characteristics of the considered storage technologies and the life cycle methodology.

4.1 Storage Technologies

For this project two different storage technologies are considered, these are Li-ion batteries and concrete sphere storages.

4.1.1 Lithium-Ion

In recent years, Li-ion batteries have become more and more the main technology in electrochemical storage systems. Everyone knows them from consumer electronics, power tools, private home storage systems and from the electromobility [9, p. 248] ff..

Compared to other Battery technologies, Li-Ion got some advantages, such as the high charging and discharging currents, the relatively high life expectancy, the good performance weight and the high cell voltage. But there are also some disadvantages. Depending on the cell mixture, there can be a risk of fire and explosion, whereby safety devices for these cells are unavoidable. Permanently, voltages, currents and temperatures of the cells must be monitored to be able to switch off the cells if it is necessary. Another disadvantage is the consumption of rare-earths and other materials such as lithium, manganese, cobalt, nickel, copper, phosphorus and aluminum. But Lithium is the main component of this Batteries [9, p. 248] ff.

The largest lithium producing nations are Australia with an annual production of about 14300 tons and Chile with 12000 tons. In addition, there are significant lithium deposits in Bolivia, China, Argentina and the US, but these are not yet mined as much as they could. [10]

Table 1: Lithium production & reserves, biggest nations[10]

Annual production [tons]	2014	2015	2016	Mine reserves	Total reserves
Bolivia	n.v.	n.v.	n.v.	9,000,000	9,000,000
Chile	11,500	10,500	12,000	7,500,000	over 7,500,000
P.R. China	2,300	2,000	2,000	3,200,000	7,000,000
Argentinia	3,200	3,600	5,700	2,000,000	9,000,000
Australia	13,300	14,100	14,300	1,600,000	over 2,000,000

Portugal	300	200	200	60,000	n.v.
Brasil	160	200	200	48,000	200,000
U.S.	n.v.	n.v.		38,000	6,900,000
Simbabwe	900	900	900	23,000	100,000
Canada	n.v.	n.v.	n.v.	n.v.	over 2,000,000
D.R. Kongo	n.v.	n.v.	n.v.	n.v.	1,000,000
Russia	n.v.	n.v.	n.v.	n.v.	1,000,000
Serbia	n.v.	n.v.	n.v.	n.v.	1,000,000
Mexiko	n.v.	n.v.	n.v.	n.v.	200,000
Austria	n.v.	n.v.	n.v.	n.v.	100,000
World				14,469,000	46,900,000

The next step in the production chain is the battery cell manufacturing, which is dominated by China. Therefore, the lithium from Chile and Australia, is shipped to China, where the cells are manufactured. From there the battery cells are sold all over the world. The biggest customers are the automotive industry or power tool manufacturers where the cells are further processed according to requirements of the customer. [11]

4.1.2 Concrete Sphere

There are two ways to store energy via mechanical systems. These potential or kinetic storage systems are based on Newtonian mechanics and thus on the physics of the 18th and 19th century [9, p. 455]. Examples are pumped storage, compressed air or flywheel storage systems.

The concrete sphere storage technology is based on the same principal, such as pumped storage power plants. The storage is based on a pressure potential, which can be used in the form of water. The pressure potential arises due to the hydrostatic pressure. If only gravity acts, the hydrostatic pressure is the sum of the atmospheric pressure at the surface and the pressure resulting from the weight of the fluid column above the point under consideration[13, p. 6]. If it is assumed that water is incompressible, the hydrostatic pressure increases linearly with the water depth.

For a pumped storage system, the potential between an upper and a lower water reservoir can be used by operating a water turbine. Therefore, the reservoirs must be connected by a waterpipe. Due to the pressure potential, the water flows through the pipeline into the lower basin. Within this pipeline, the pump turbine is mounted, which is driven in the case of emptying the upper reservoir and generates electricity by using an electric machine.

To charge the storage system, the water from the lower basin can be pumped back into the upper reservoir. In this case the turbine operates as a pump and is driven by the electric machine, which now consumes electricity. By pumping the water to the higher level, the pressure potential is rebuilt, and the upper reservoir is filled again.

For the concrete sphere storage, the system components are the same. There are two basins where the water can flow back and forth. These two basins are connected to a pump turbine. However, the shape of the two basins are completely different.

The lower basin is represented by a hollow sphere which you can see in Figure 4, which is placed in a lake or the sea. The water that surrounds this sphere represents the upper basin. The hollow sphere has an opening through which water can enter the sphere.

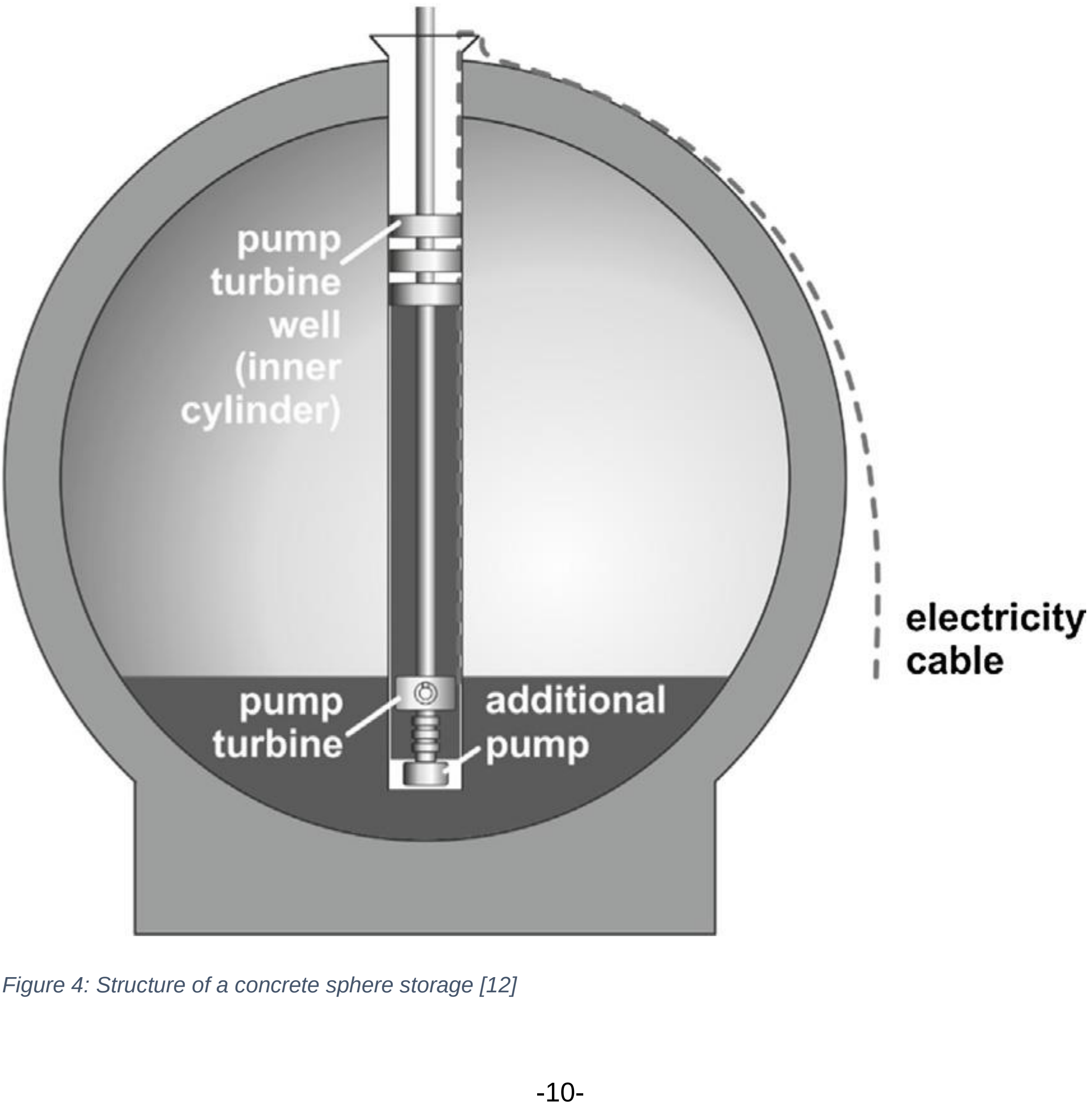

Figure 4: Structure of a concrete sphere storage [12]

The pressure potential is built up by the water column, which is above this sphere. Accordingly, the deeper the sphere is mounted, the higher the pressure potential. The third important system component is the pump turbine. It must be installed in the sphere opening. So, when water is fed into the sphere, it flows through this turbine, which uses the pressure difference and generates an electric current by an electric machine. Conversely, electrical energy can be consumed, and the water can be pumped out again.

Thus, the storage is energetically empty when it is filled with water. To refill it energetically the water must be pumped out of the sphere. The sphere without any water in it represents a fully charged energy storage.

To use the electrical energy generated by the electric machine, the storage system must be connected to the sink or source by a cable connection. This can be the electrical grid.

According to [13] the following basic formulas are used to dimension the sphere. The hydrostatic pressure: p_h in a certain water depth h depends on the gravitational acceleration g and the density of the fluid ρ_{water}[12].

$$p_h = \rho_w \cdot g \cdot h \qquad (4.1)[12]$$

Including the volume formula for the sphere

$$V_{sp} = \frac{1}{6} \cdot \pi \cdot d_{sp,in}^3 \qquad (4.2)[12]$$

The following formula for the stored energy results:

$$E_{sp} = \rho_w \cdot g \cdot h \cdot V_{sp} \cdot \eta_{turb} \qquad (4.3)$$

So, there are two parameters to vary the storage size. On the one hand, a higher water depth increases the storage capacity and on the other hand, it increases by a higher sphere diameter, even in the third power. Hence to build a concrete sphere storage with a high capacity, the system should be placed as deep as possible and be as large as possible [12]. The overall efficiency of the pump turbine is represented by η_{turb}.

The advantages over conventional pumped storage systems are potentially lower losses, since there are no pressure pipes, which are causing friction, and a higher location variability. Since no expensive dam must be built, and the spheres are simply attached to the sea ground, it is much easier to find suitable locations all over the world [12].

In 2016, one of these sphere-storage systems was successfully tested for the first time. This first test run, which was carried out by the Fraunhofer Institute (Project: SteEnSea), was performed on a model with a diameter of 3m. From this test run, some system parameters are known, such as the system efficiencies, which are considered for this project [12].

4.2 Methodology Life Cycle Assessment

LCA is a method to assess the environmental impact of a product or process. As the name implies, the product should be considered throughout its life cycle [13]. "From cradle to grave" means that everything from the extraction of raw materials through product manufacturing and use, to waste disposal should be considered.

To get a simpler overview of a product life, it can be divided into the three main sections manufacturing, use and end of life. Every of these sections got some main in- and outputs.

But it is often hard to get the data of every detail of a product life. There are too many small details, which would affect an enormously effort to collect. Besides, most of these details wouldn’t cause a significant impact on the results of the analysis.

Hence, it is important to set system boundaries considering the data basis on the one hand and on the other hand to not distort the result too much, to maintain the comparability.

How to proceed and what to do with life cycle assessments is described in EN ISO 14040 and EN ISO 14044 standards. From raw material extraction, energy production, material production, application to waste disposal at the end of the life cycle, everything should be included [13].

There are several software applications for LCA. One of them is SimaPro, which is used in this work. The basis of the software is a database, which contains worldwide data for the most common raw materials and energy sources. SimaPro uses the ecoinvent database, an international database from the Swiss ecoinvent Center for the central collection, calculation, administration and offering of LCA data. It is used by over 4500 users in more than 40 countries. It contains material and process as well as emission information. The current version 3.3, which was updated in August 2016, is used in this work [14].

The quality of the data is different. Most materials contain data for certain regions of the world, e.g. copper production in Norway. But some data is not that accurate, what means there is only an average value for the world production of this material.

4.2.1.1 Life Cycle inventory

Life cycle inventory analysis is the compilation aspect of LCA [13]. The aim is to gather information about the material and energy flows, as well as the associated emissions to the environment.

First, it is necessary to know the system components. Hence, it is important to divide the overall system into smaller system components. Different lifespans of the components should also be considered by this partitioning. It is also important to know how these components are put together to form the overall system. The easiest way is by visualization. The components can be visualized by blocks, which are logically linked. The advantage of separate components is that, for example, the size of these components can be easily varied.

Another advantage of this approach is that the different lifespans of the system components can be considered. For this purpose, all inputs or outputs of a system are normalized to a common unit. This can be, for example, a year. For this purpose, the amount of in or outputs is divided by the respective usage time, so that ultimately the entire system is considered over this period.

Furthermore, each of these components should be subdivided into the three phases production, use and end of life. Each of these product phases can have different in and outputs. For example, manufacturing is very much influenced by material flows, whereas energy flows often play a major role in the use phase.

For the next step, material flows, energy flows and emissions must be summarized for each component. The type and the value of the in or output is important, for example, 5kg chromium steel production in Norway.

If the data collection is completed for every system component, this data can be transferred to the software. In practice, this often happens rather simultaneously, and in many cases, it is also not possible to get the data in the desired accuracy or time. In this case, other sources can be used. Often there is data from a similar system, which can be transferred.

4.2.1.2 Life cycle impact assessment

The quantified inputs from the LCI are attributed to different impact categories. Examples of impact categories are human carcinogenic toxicity, climate change or marine ecotoxicity.

These impact categories may differ depending on the used method. One method of impact assessment is the ReCiPe method, which is mainly used in Europe. The latest version is called ReCiPe 2016. It is based on the latest scientific background [14].

Within the ReCiPe2016 methodology, there are further different viewpoints and periods they take to account which are shown in Figure 5Figure 5: Impact categories ReCiPe 2016. The analysis can be focused on the midpoint or the endpoint level. In this project, the midpoint level is considered, as it contains common impact categories and thus provides good comparability to other projects.

In addition, there are three periods to choose, which are called, hierarchist, egalitarian and Individualist. The individualist considers a relatively short period and the egalitarian the longest period. Hierarchist considers a medium period and is chosen for this project.

Each of these impact categories has a specific unit in which it is measured. Climate change, for example, is measured in $kgCO_2$ equivalent. Thus, all emissions that can be assigned to this impact category, such as SO_2 or NO_X are converted to CO_2 equivalent to make them comparable. These impact categories are summarized in the midpoint level.

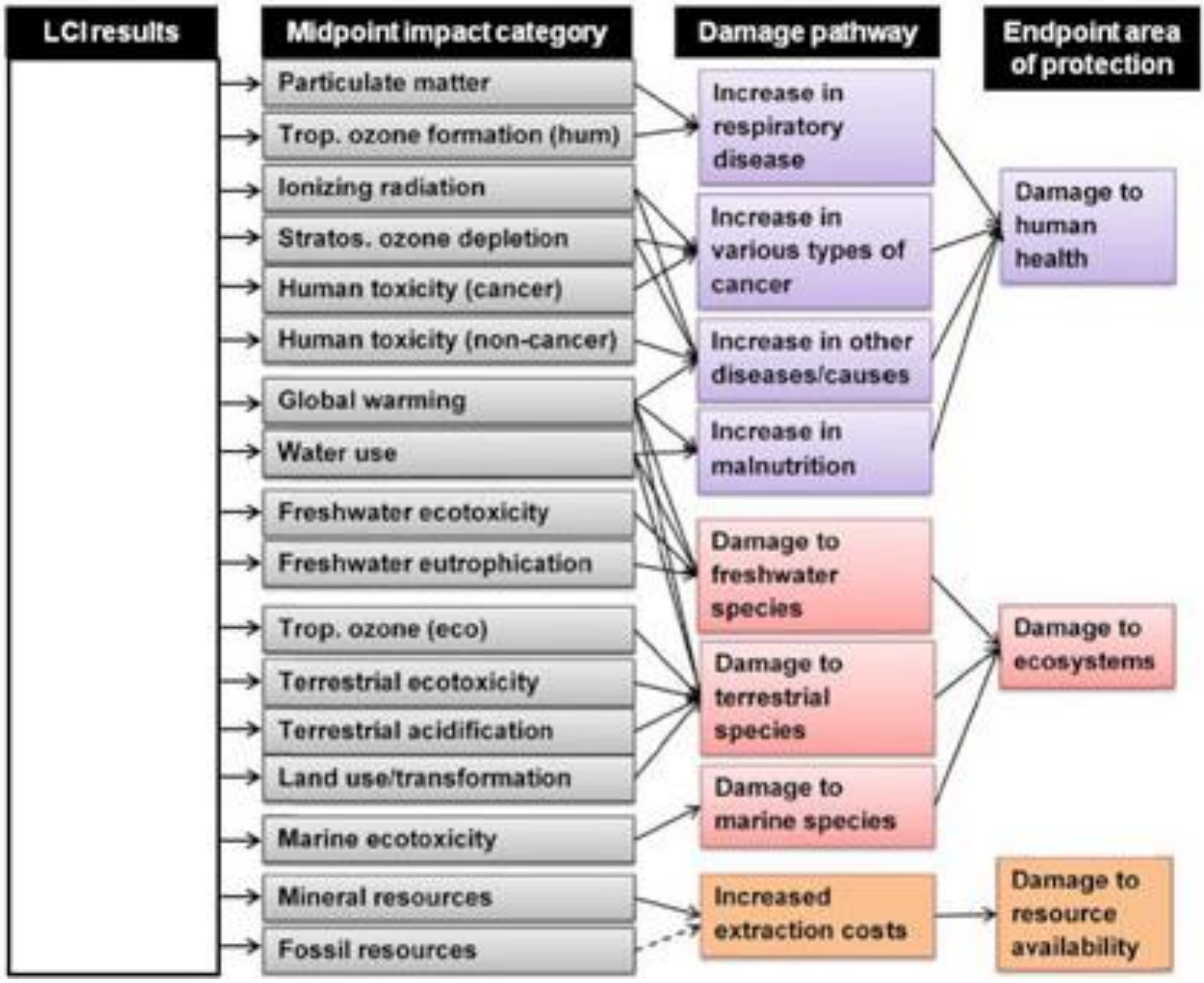

Figure 5: Impact categories ReCiPe 2016[14]

These impact categories can be further summarized. All impact categories that affect, for example, human health can be summed up. This is also called the endpoint level.

In addition, the results can be used to calculate further characteristic values which make the comparison to other projects possible. A good comparison with other modes of transport, such as cars, trucks, buses or trains, can be achieved by CO_2 emissions per ton-kilometer.

5 Creating the LCA

In the following chapter the life cycle assessment is systematically complied. This procedure is divided into several steps.

Since this work is not just about mapping and considering the existing system, but also comparing it to another system, the first step is to calculate the dimensions of the concrete sphere storage system. To figure out the dimensions it is necessary to get a better understanding of the system correlations.

Therefore, a first simulation of the energy flows of the existing storage system is worked out. The discovered values of this system will be transferred to the optional storage system in order to get a comparable system.

The next step will be the life cycle inventory. According to the description in the previous chapter, every system component will be elaborated and the material and energy in and outputs will be figured out. Finally, a material list for every system component will be presented. These lists are the basis to carry out the life cycle impact assessment.

5.1 Simulation of the system components

The shown simulations are carried out with excel.

5.1.1 Simulation, existing system

To get an idea of how the system components behave during a day, a simulation is created based on the real ferry timetables [15]. The temporal processes are mapped within one day and the course of the current flows and state of charges (SOC) of the different system components are examined in order to be able to figure out how an alternative system can look like.

The total storage system consists of the three main components ship storage, land storage 1 and land storage 2. In the simulation, these are connected to each other via the power flows.

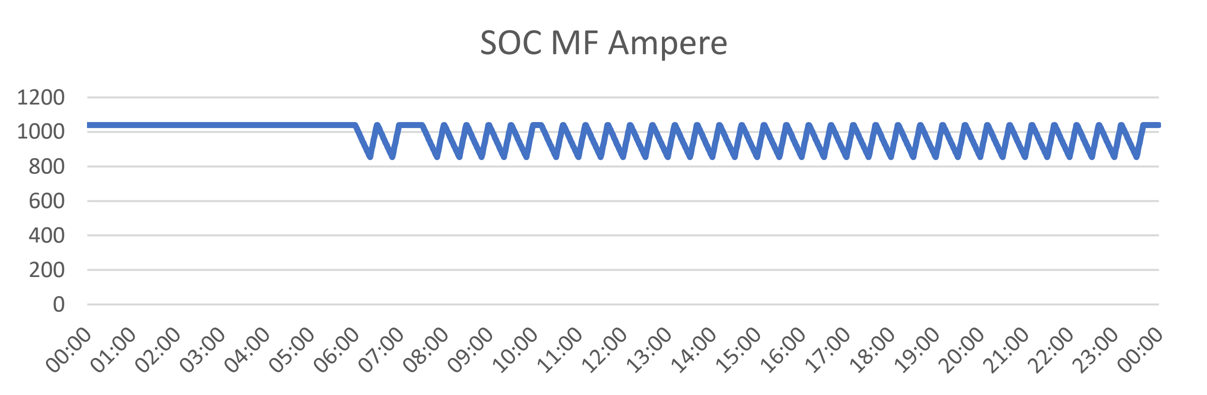

Figure 6: SOC MF Ampere [15]

In Figure 6 you can see the SOC of the ship storage system for one day. The ferry service starts at around 06:00 in the morning and is maintained until 23:40 with two smaller breaks. The battery capacity of 1040kWh is kept as full as possible throughout the day. The average energy consumption for a crossing is 186kWh, which can vary between 150kWh and 200kWh depending on external conditions such as weather, water flow, wind and load. The energy that has to be recharged is higher since there are charging and discharging losses. To recharge this missing amount of energy after crossing, two sources are used. On the one hand, the electrical grid and on the other hand, one of the two land batteries. With an average charging time of 9 minutes per stay, this results in a necessary charging power of 1307kW. [6]

$$P_{charging} = \frac{186kWh}{\frac{9}{60}h * 0{,}94868} = 1307\ kW$$

This charging power is divided into the electrical grid and a land battery. Preferably, the power should come from the electrical grid to preserve the battery lifetime. The maximum power supply from the grid is 250kW. Therefore, 1057kW of the required 1307kW come from the battery system.

In average operation, all the energy needed for one crossing can be recharged during one charging process. However, as there may also be irregularities in the ferry service, the batteries are designed with a relatively high buffer. With the battery size of 1040kWh the ferry can accomplish the distance of 6km about 5.59 times without the need of recharging.

$$n_{Ship} = \frac{1040kWh}{186kWh} = 5.59$$

In Figure 8 and Figure 8 you can see the SOC of both onshore battery systems through one day. The land storages are dimensioned smaller than the ship's battery. Each of them got a capacity of 410kWh. The land storage systems will be charged and discharged according to the timetable of the electric ferry whenever the ferry is in the respective port. In these 9 minutes, the SOC of a battery is reduced according to the charging power and the charging time with approximately 158.49 kWh. [6]

$$E_{charging,Land} = 1057.067\ kW \cdot \frac{9}{60} h$$
$$= 158.49\ kWh$$

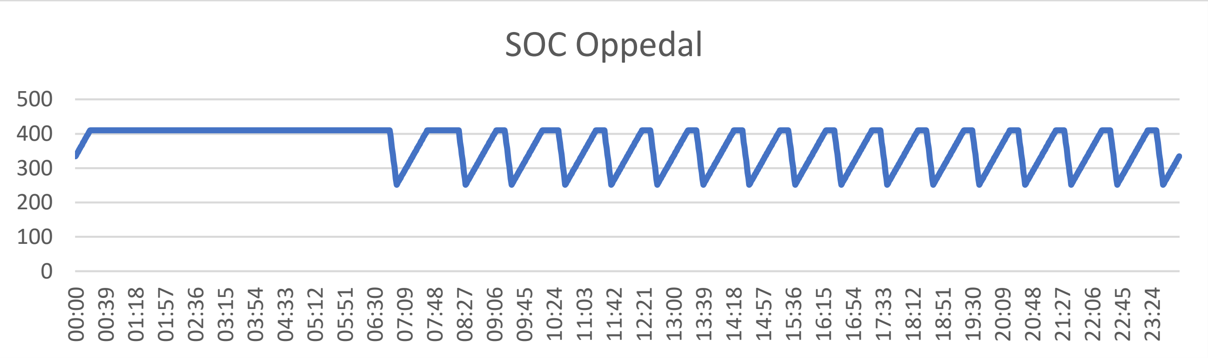

Figure 7: SOC battery Oppedal[15]

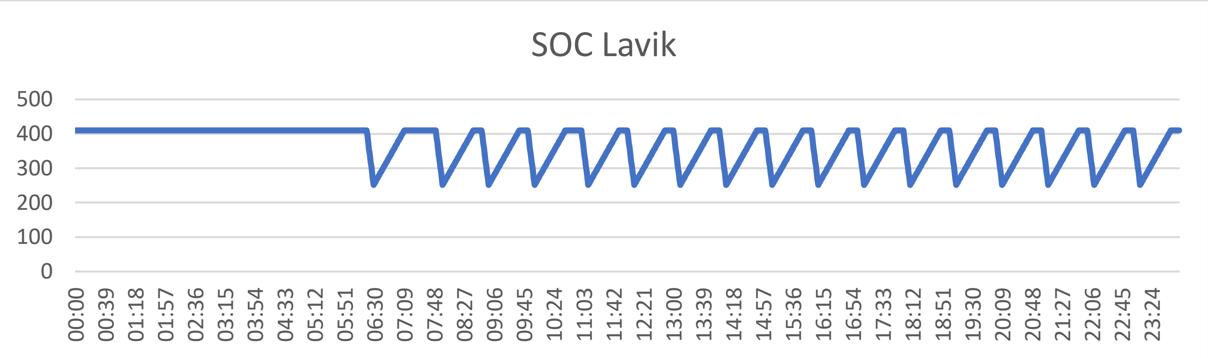

Figure 8: SOC battery Lavik[15]

As soon as the ferry leaves the harbor in the direction of the other side of the fjord, the charging process of this land battery begins. It is also charged from the electrical grid with the available power of 250 kW, until it is fully charged again. After a short period, when the onshore battery systems are not charged by the grid and not discharged by the ferry, you can see a flat part in the diagram. Since this process is identical on both sides except for the offset of the ferry's journey time, the two diagrams are almost identical.

In addition, the buffer can be seen, with which the land batteries were designed. Considering the storage systems on both sides of the fjord, the total onshore storage system is 820 kWh. Compared to the buffer of the ship's storage, it is almost identical with approx. 5,68.

$$n_{Land} = \frac{820\ kWh}{158.49\ kWh} = 5.17$$

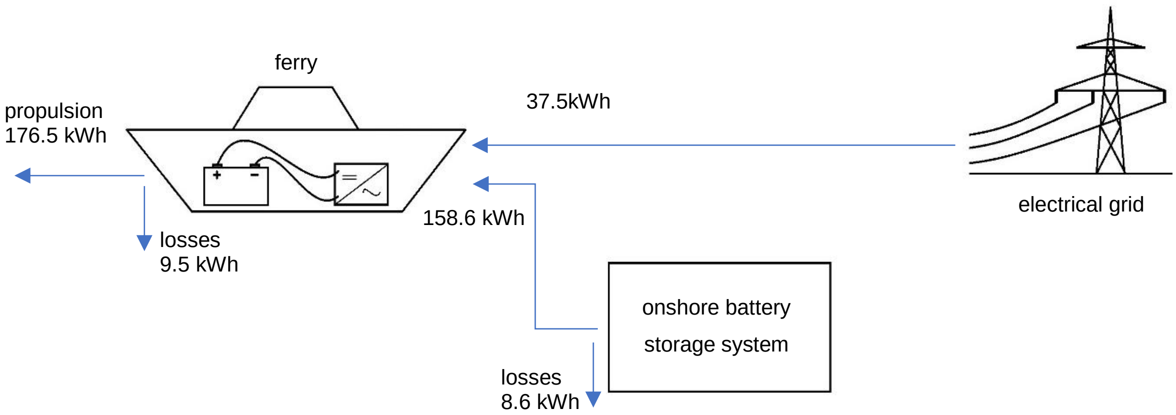

Figure 9: Energy flows during the charging process of the ferry

Figure 9 shows the energy flows during the charging process of the ferry. The ferry uses 186kWh for every crossing. Not all of this energy goes to the propulsion system since there are discharging losses of the batteries. The overall charging and discharging losses of the ferries battery system are assumed with 90%. Half of this are charging and the other half discharging losses. The energy which is used for one crossing is recharged every time. Since there are charging losses for the ferries battery system the charging energy for one charging process that has to be delivered is 196.1kWh. 37.5kWh come from the electrical grid and 158.6kWh come from the onshore battery storage system. The efficiency of the onshore battery storage system is assumed to be the same as for the ferry storage system. Therefor the losses are 8.6kWh for one ferry charging process. The energy that is consumed from the onshore battery storage system during one process is 167.2kWh.

The energy losses for charging the onshore battery system are considered as well. Therefor the amount of energy that has to be consumed from the electrical grid to charge the onshore battery system is 176.2kWh for one ferry charging process.

5.1.2 Simulation concrete sphere system

Since the optional storage system is represented by a completely different technology with different parameters, it is necessary to figure out, how it must be constructed to get a comparable system.

For the following comparison, it is first necessary to dimension the concrete sphere. The concrete sphere storage replaces the two onshore storages, hence to compare these two different technologies, they must have the same benefit.

The first guess which is coming up to achieve the same benefit, might be to choose the same dimension of the sphere system as the dimension of the two land storages, which is 820kWh. But there is not only a difference between the way of storing, they also differ by changing system links.

Basically, it is assumed that there is only a single storage, placed in the middle of the fjord. Thus, the storage system in the middle of the fjord has to be connected to the charging stations in the two ports by a cable. For this reason, in addition to the benefit of connecting the storage to both charging stations, this cable connection has yet another benefit. It also connects the two charging stations to each other. This enables electrical power to be routed from one port to the other port when necessary. Thus, this connection doubles the possible charging power, which can be obtained from the grid to 500kW.

If this new system component is considered, the necessary power supply from the sphere storage is reduced by another 250kW. This means that the sphere only has to provide a charging power of 807 kW over 9 minutes during a charging process. This results in an energy consumption of 121.05 kWh per charging process for the sphere storage. To achieve comparability with the replaced land storage system, the buffer must be the same. This results in a storage size of the concrete sphere of about 111kWh, which equates to a reduction of about 25.3 %. The discharging efficiency of the concrete sphere storage system is about 82%.

$$
\begin{aligned}
E_{sphere} &= 121.05\ kWh \cdot 5.17/0{,}82 \\
&= 763.21\ kWh
\end{aligned}
$$

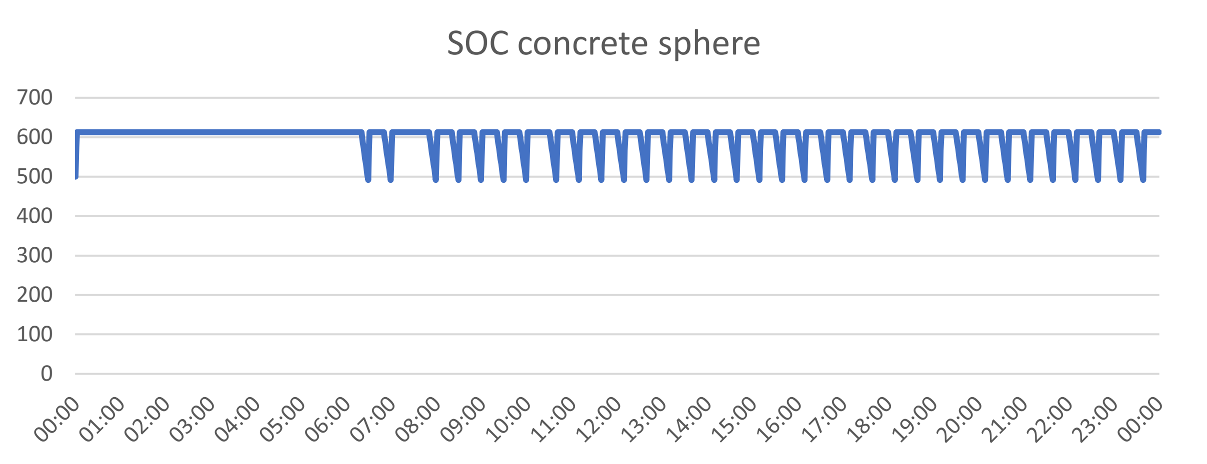

Figure 10: SOC concrete sphere storage system during one day [15]

5.1.3 Extension of the ferry service

Since on the ferry route Oppedal – Lavik in addition to the electrically operated MF ampere two more, conventionally operated ferries operate in parallel, the question of whether it is possible to operate the other two ferries also electrically, arises in terms of reducing greenhouse gas emissions. To answer this question, let's first look at the amount of energy the electrical grid can provide in one day. On both sides a power of 250kW is available. This is a total power of 500kW. Therefore, within 24 hours an amount of energy of 12000 kWh can be provided.

The next step is the calculation of the additional ferry energy consumption. It is assumed that the three ferries are constructed identical. So, they also have the same energy consumption per crossing of about 186kWh. By comparing the timetables, it is striking that the three ferries have different operation times and thus also the number of crossings per day is different.

Table 2: Crossings per day and energy consumption

	Crossings / day	**Energy / day**
MF Oppedal	46	8556kWh
MF Ampere	34	6324 kWh
MF Stavanger	24	4464 kWh
Sum	104	19344 kWh

To keep the energy consumption below 12000kWh per day there is only one possible combination which you can see in green in Table 3.

Table 3: Possible operation

	MF Stavanger	MF Oppedal	MF Stav. + MF Opp.
MF Ampere	10788kWh	14880kWh	19344kWh

Only the electrical operation of the two ferries MF Ampere and MF Stavanger would be possible. Hence, this option will be examined below.

5.1.3.1 Two ship operation, battery system

This variant is also first simulated and visualized by using the data of the real timetables to recognize whether the operation is possible over time. Primarily the soc of the ships batterie should be kept fully charged like in the previous versions. This results in required energy consumptions at certain times for both onshore batteries.

By comparing the diagrams of the onshore batteries with the previous versions, there are significant differences. As you can see in Figure 11: SOC onshore battery system Oppedal, 2 ship operationFigure 11 and Figure 12 the start of the ferry service of the MF Ampere can be recognized at approx. 06:00. As long as only one electric ferry is in operation, the operation can be guaranteed without any problems. It is still possible to completely recharge the two batteries after every trip. However, the system gets out of balance as soon as the second ferry starts operating at around 10:00. From this time, it is no longer possible to fully recharge the onshore batteries between two ferry charging processes. For this reason, the SOC decreases gradually from this time. Only when the energy is enough again to fully charge the batteries, the charge level recovers. This happens when one ferry stops operating.

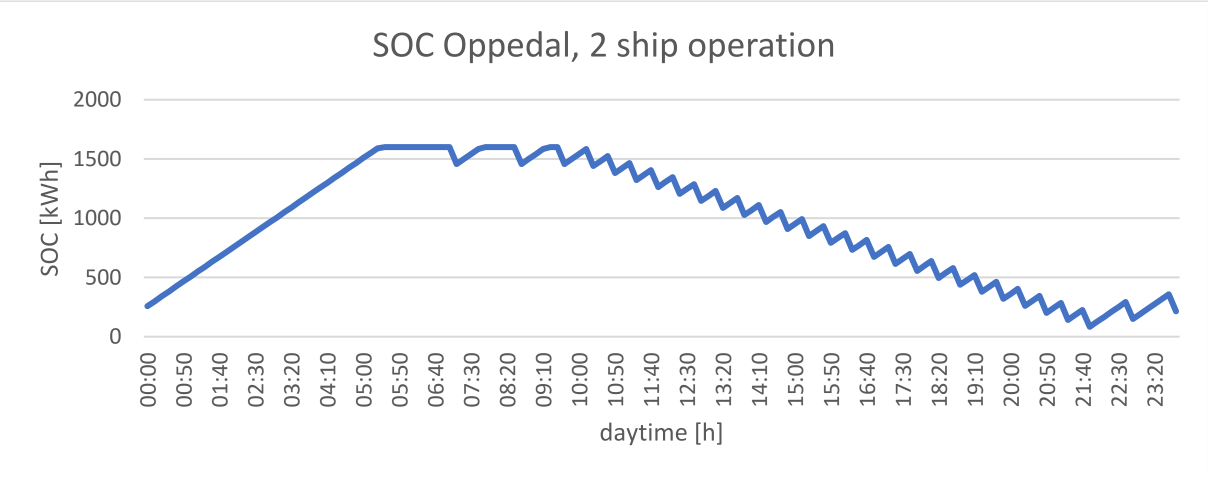

Figure 11: SOC onshore battery system Oppedal, 2 ship operation[15]

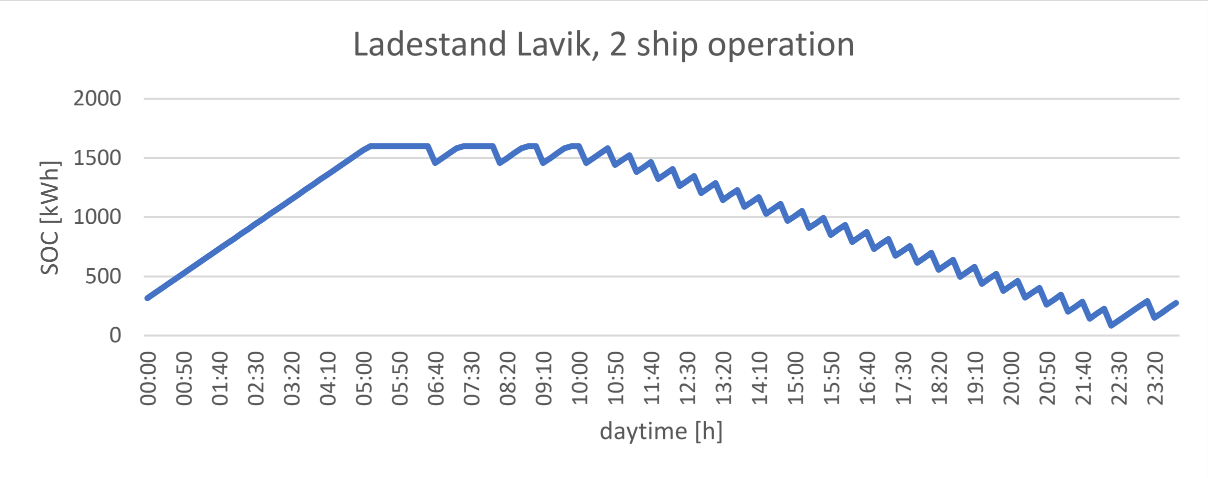

Figure 12: SOC onshore battery system Lavik, 2 ship operation[15]

Since this state of the successive reduction of the soc continues until 22:00 a massive increase in the storage size is necessary to make the operation possible at all. The minimal value for the storage size is 1517kWh on both sides. To consider the same buffer as before of 5.6 a storage size of 8495,2kWh would be necessary. For this reason, an operation in this system constellation is hardly reasonable. To make the operation of two ferries possible, it could be helpful to increase the available power of the electrical grid.

5.1.4 Two ship operation, concrete sphere system

Since the replacement of the storage system in combination with the additional cable connection caused a significant reduction of storage size in the previous version and since an increase in the available electrical grid power on each side is possible by this additional cable connection, this variant should also be considered. The procedure is the same as in the example under point 5.1.2. However, the number of required ferry charging processes is increasing and the time for recharging the storage system is decreasing, while both ferries are operating simultaneously.

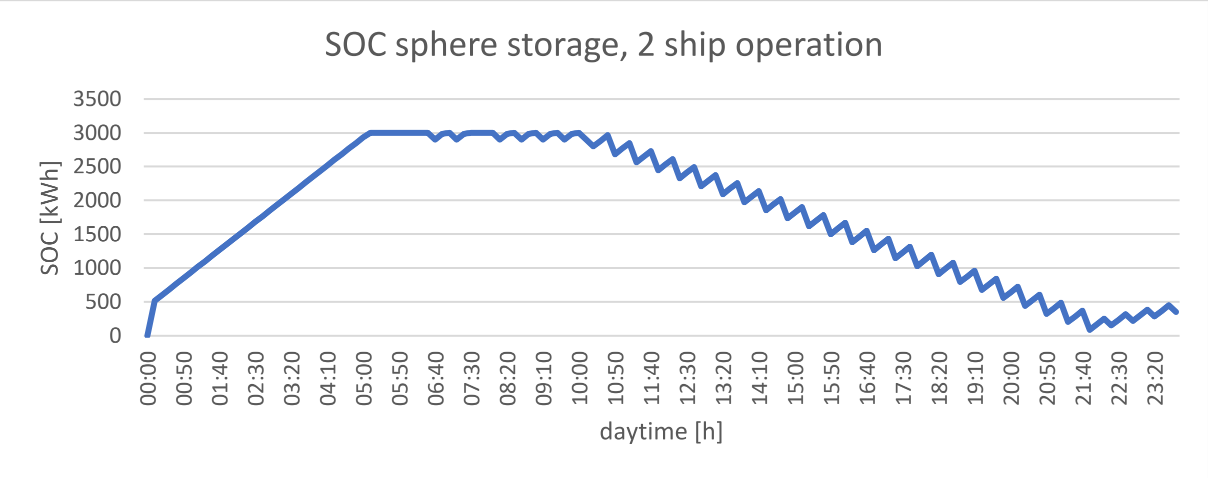

Figure 13: SOC concrete sphere storage system, 2 ship operation[15]

As shown in Figure 13, it is not possible to fully recharge the concrete sphere storage system after every charging process. Again, the SOC starts to decrease successive when the second ferry starts operating. It can be attributed to the fact that though enough energy is available during 24h, but the consumption is not distributed consistently throughout the day but focuses on the time from 10:00 to 22:00. So, in average, significantly more power is required during this period, which must be buffered by the storage system. Therefore, an enormous amount of additional storage capacity is needed.

Compared to the solution with two electrically operated ferries and battery storage, there is again an advantage in terms of the required storage size, but this percentage is much lower. The minimum storage size in this case is 2832kWh and thus 7% lower than the battery version.

To make the two-ferry operation possible without any improvement of the available grid supply, is possible, but with an unreasonable increase of necessary storage capacity. So, this case will no longer be considered in this work. Nevertheless, the simulation showed the limits of the existing system.

5.2 Life cycle inventory

The following chapter describes the individual components of the used systems. The aim is to compile all the in- and outputs of every system component, based on the product life periods. These are manufacturing, use and end of life. To enter these information’s to the SimaPro software in a further step easily, they will be presented as a list for every component. In addition, the lifespan of every component is considered. To do so, every input or output is divided by its lifespan, to get a consistent proportion of one year.

5.2.1 Phase 1 - Manufacturing

In the manufacturing phase, the required material and energy in and outputs as well as transportation are summarized, which are necessary for the creation of the systems or processes.

5.2.1.1 Onshore battery storage system

The onshore storage system basically uses the same battery type, but not the same number as on the ship. The storage size is 410kWh per docking station, which is a total size of 820kWh[6].

The onshore battery storage system is set up in battery buildings which you can see in Figure 14. These are relatively simple sheet steel buildings, which are equipped with a thermal insulation layer. These are glass fiber wool panels to comply with fire safety regulations. There are two of these buildings in every port. They are each equipped with a refrigeration machine to cool the batteries. In contrast to the systems onboard, however, water cooling is used[6].

Figure 14: Battery Building onshore station

The battery storage technology is lithium-polymer and the batteries come from Corvus Energy[16]. The lithium polymer technology is a development of the widely used lithium-cobalt-dioxide batteries. This technology was created to maintain the advantages of lithium cobalt batteries, such as the relatively high power and energy density, and on the other hand to reduce the disadvantages such as the low intrinsic safety which causes the risk of fire and explosion[17, p. 27]. The main difference to a conventional lithium cobalt dioxide battery is mainly between the electrolyte compound, which is not liquid, but can be solid to gelatinous[17].

As mentioned above, the onshore battery storage system consists of a battery capacity of 820kWh. These 820kWh are divided into two subsystems of 410kWh each.

The total onshore battery storage system includes 21 strings. Each string in turn consists of 6 sub-packs, each consisting of 8 modules and these modules consisting of 104 individual battery cells[6].

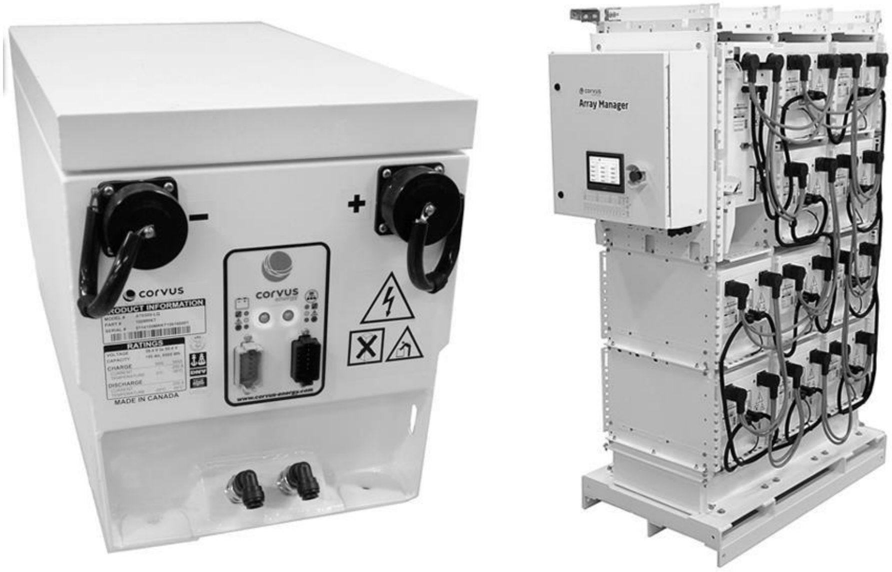

Figure 15: Corvus energy battery system[16]

This results in a battery system, as shown in Figure 15. It should be noted that every product level just described requires a certain amount of additional materials and energy costs to produce the next higher product level. The battery modules are protected, for example, with an iron case from water and mechanical damage.

Furthermore, a so-called battery management system (BMS) is required for the operation of the storage system. This is an electronic system that monitors the safety-relevant parameters such as cell voltage, current, temperature, SOC and, if necessary, can switch off the batteries. It performs a cell balancing, which is necessary to compensate the voltage differences, caused on the minimally different internal resistances of the individual cells and to keep the individual cells at the same voltage level[17, p. 177].

The cooling effort for both battery rooms is approx. 11.5 kW and is realized by cooling the room air.

As you can see in Figure 16 the electrical network of the ship is basically constructed as an AC network. Since the storage units can only provide DC, they are connected to the AC network both on the ship and on the shore via inverters. The advantage is that the shipboard network can be operated as AC, without having to make any significant changes. In addition, another advantage of the connection via inverter is that they can provide the AC voltage regardless of the SOC of the batteries.

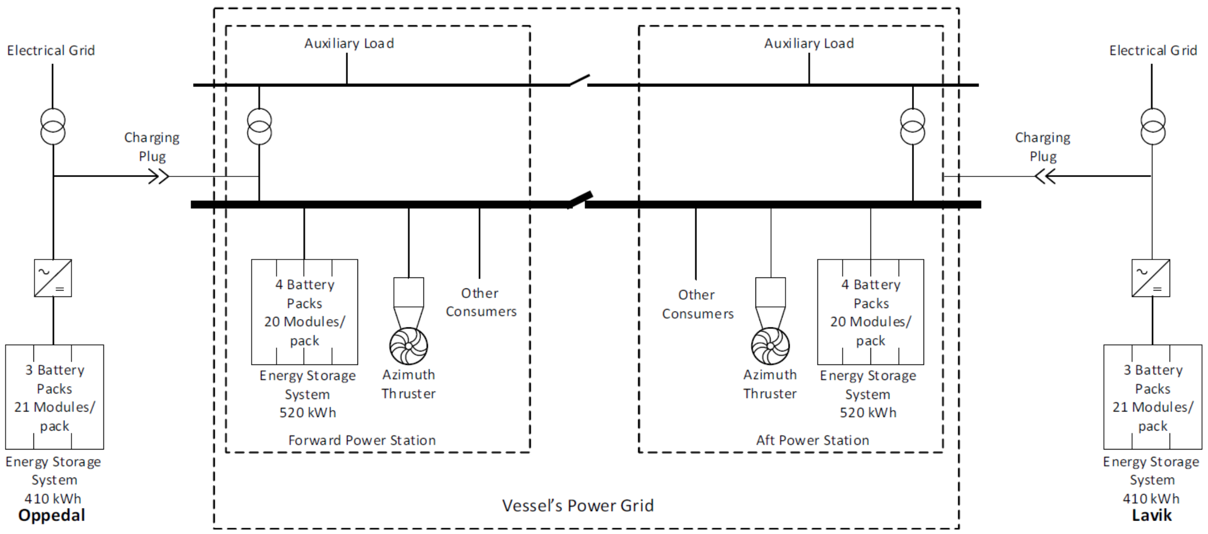

Figure 16: Electrical system scheme of MF Ampere [16]

In summary, the following is a list of the used in and outputs for the ship storage system.

In Table 4 to Table 9 the manufacturing of the battery components is listed. It is first hand data from the manufacturer and therefore high-quality data. Since the data was based on the storage size of the MF Ampere battery storage system the amount of product which is used for the battery system e.g. amount of battery cells was adapted to the storage size of the onshore battery system. So the values of the

Table 4 shows the manufacturing of one battery cell. The total onshore battery storage system consists of 104832 battery cells.

Table 4: Inventory manufacturing battery cell

battery cell	***quantity***	***unit***	***eco invent***

Separator	0,0014	kg/cell	market for battery separator (GLO)
Cathode Al foil	0,0031	kg/cell	aluminium, wrought alloy (GLO)
Aluminium sheet rolling	0,0031	kg/cell	market for sheet rolling, aluminium (GLO)
Cathode active material	0,0113	kg/cell	market for cathode, LiMn2O4, for lithium-ion battery (GLO)
Anode Cu foil	0,0075	kg/cell	market for copper, GLO
Anode active material	0,0062	kg/cell	market for graphite, battery grade (GLO)
Electrolyte (LiF6)	0,0044	kg/cell	market for lithium hexafluorophosphate (GLO)
Can	0,0092	kg/cell	market for steel, chromium steel 18/8, GLO
Can	0,0092	kg/cell	market for metal working, average for chromium steel prod manufacturing (GLO)
Electricity	200	kWh/ kWh-cell	market for electricity, medium voltage (RoW)
Transport-sea	0,74844	tkm/cell	market for transport, freight, sea, transoceanic tanker, GLO
Transport-truck	0,04158	tkm/cell	market for transport, freight, lorry >32 metric ton, EURO5, GLO
Welding battery system	0,00388889	kWh/ kWh-cell	Market for electricity medium voltage

The next product level is a battery module, which you can see in Table 5. The total onshore battery storage system consists of 1008 modules.

Table 5: Inventory manufacturing battery module

Modules	Quantity	Unit	Eco invent
Aluminium	0,0232	kg/module	market for aluminium, cast alloy (GLO)
Aluminium metal working	0,0232	kg/module	aluminium, wrought alloy (GLO)
Copper	0,5283	kg/module	market for copper, GLO

Copper metal working	0,5283	kg/module	market for metal working, average for copper product manufacturing
ABS plastic	0,439	kg/module	acrylonitrile-butadiene-styrene copolymer production, RER
Steel (electrogalva nized steel)	0,0279	kg/module	market for metal working, average for chromium steel prod manufacturing (GLO)
Steel metal working	0,0279	kg/module	market for steel, low-alloyed, GLO
EPDM 70 shore (BMS card holder)	0,0075	kg/module	market for synthetic rubber, GLO
PCB (BMS printed circuit board)	0,0089	kg/module	market for integrated circuit, memory type
Transport-sea	16,76376	kg/module	market for transport, freight, sea, transoceanic tanker, GLO
Transport-truck	0,93132	kg/module	market for transport, freight, lorry >32 metric ton, EURO5, GLO

The next product level is a battery sub pack, which you can see in Table 6Table 5. The total onshore battery storage system consists of 126 sub packs.

Table 6: Inventory manufacturing battery sub-pack

Sub-pack	Quanitty	Unit	Eco Invent
Aluminium	5	kg/sub-pack	aluminium, wrought alloy (GLO)
Aluminium metal working	5	kg/sub-pack	market for metal working, average for aluminium product manufacturing, GLO
Copper	0,9	kg/sub-pack	market for copper, GLO
Copper metal working	0,9	kg/sub-pack	market for metal working, average for copper product manufacturing
Steel metal working	6	kg/sub-pack	market for metal working, average for steel product manufacturing
Steel (electroga	6	kg/sub-pack	market for metal working, average for chromium steel prod manufacturing (GLO)

lvanized)			
Steel (powder coated carbon)	1,11315	m2/sub-pack	market for powder coated steel, GLO
ABS Plastic	1,2	kg/sub-pack	acrylonitrile-butadiene-styrene copolymer production, RER
Transport-sea	212,22	tkm/sub-pack	market for transport, freight, sea, transoceanic tanker, GLO
Transport-truck	11,79	tkm/sub-pack	market for transport, freight, lorry >32 metric ton, EURO5, GLO

The next product level is a battery string, which you can see in Table 7. The total onshore battery storage system consists of 22 strings.

Table 7: Inventory manufacturing battery string

String	Quantity	Unit	Eco Invent
Low-alloyed steel	65	kg/string	market for steel, low-alloyed, GLO
Steel metal working	65	kg/string	market for metal working, average for steel product manufacturing
Transport-sea	1053	tkm/string	market for transport, freight, sea, transoceanic tanker, GLO
Transport-truck	59	tkm/string	market for transport, freight, lorry >32 metric ton, EURO5, GLO

There are 2 battery buildings on both side of the fjord. So, there are 4 battery buildings for the onshore battery storage system. The values in Table 8 are for the 4 buildings in total. These are assumptions. The product details for the walls come from the factsheets for sandwich panels in the appendix.

Table 8: Inventory manufacturing battery building

battery building			
	Quantity	Unit	Eco Invent
Foundation	1344	kg	Reinforcing steel {GLO}| market for | Alloc Def, U

Walls	1922	kg	Steel, low-alloyed {GLO}| market for | Alloc Def, U
Walls and roof	1462	kg	Rock wool {GLO}| market for | Alloc Def, U
Foundation	16.8	m³	Concrete, sole plate and foundation {GLO}| market for | Alloc Def, U
Walls	1922	kg	Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def, U
Transport	54,17	tkm	Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, U

Table 9: Inventory manufacturing cables

Cables	Quantity	Unit	Eco Invent
Aluminium	204.4	kg	aluminium, wrought alloy (GLO)
Aluminium metal working	204.4	kg	market for metal working, average for aluminium product manufacturing, GLO
Transport-sea	3312	tkm/cables	market for transport, freight, sea, transoceanic tanker, GLO
Transport-truck	184	tkm/cables	market for transport, freight, lorry >32 metric ton, EURO5, GLO

The converters which are used are 410kW for every docking station. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the values for one 410kW inverter This is also firsthand data.

Low-alloyed **steel**	277,98	kg **material/product**	market for **steel, low-alloyed, GLO**
Steel metal working	277,98	kg material/product	market for metal working, average for steel product manufacturing
Iron	86,92	kg material/product	market for cast iron (GLO)
Copper	99,22	kg material/product	market for copper, GLO

Copper metal working	99,22	kg material/product	market for copper, GLO
Aluminium cast alloy	49,61	kg material/product	market for aluminium, cast alloy (GLO)
Aluminium metal working	49,61	kg material/product	aluminium, wrought alloy (GLO)
Polyethylene	10,25	kg material/product	market for polyethylene, low density, granulate (GLO)
Electrical energy	463,3	kWh/product	market for electricity, medium voltage (FI) [kWh]
Heat energy	254,2	kWh/product	heat and power co-generation, hard coal (FI)
Transport-sea	8488,476	tkm/product	market for transport, freight, sea, transoceanic tanker, GLO
Transport-truck	471,582	tkm/product	market for transport, freight, lorry >32 metric ton, EURO5, GLO

5.2.1.2 Concrete sphere storage system

As described in 4.1.2, this technology is still relatively new. It is considered as an alternative to the battery storage onshore.

The results of the battery size calculations created in chapter 5.1.2 are considered for the following elaboration.

The concrete sphere storage system is basically designed differently than the battery storage system. Since the spheres are in the water and there is no need to install a storage system on both sides of the fjord, only a single bullet is placed in the middle of the fjord. This has the advantage that the sphere and especially turbine components are larger and must be manufactured only once, whereby an energetic advantage is expected. In addition, the deepest part of the fjord is nearby in the middle. However, a cable connection must be installed to both ports.

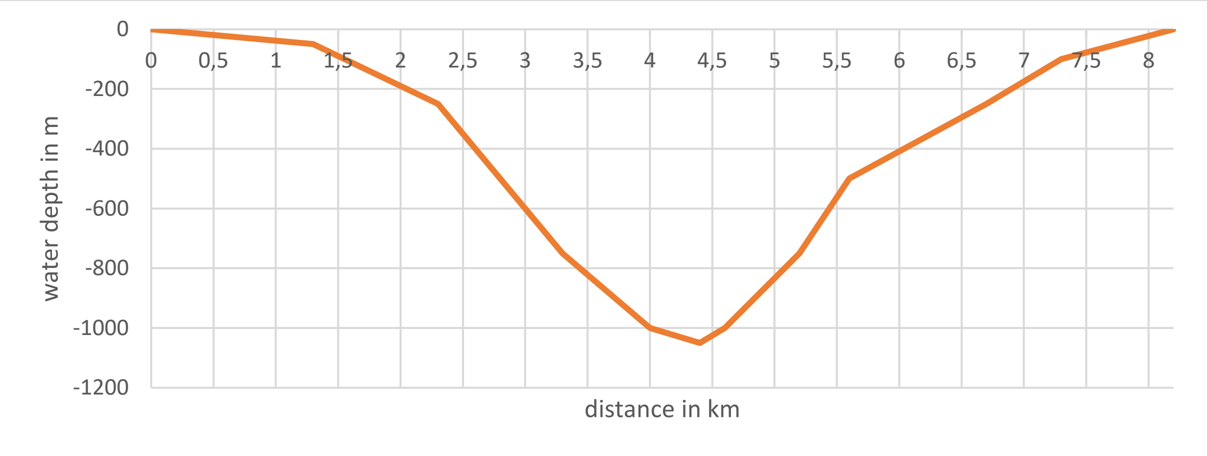

Figure 17: Water depth between the docking stations and the concrete sphere location

For the installation site for the sphere storage system, several low points of the fjord are possible in the immediate vicinity of the ferry route. At these points, a water depth of about 1000m is available. According to Fraunhofer ISE, a water depth of 600m to 800m will be necessary for the spheres, to be operated economically in Germany[18]. The distance of the closest possible location is about 4.4km from the port Oppedal and about 3.8km from the port Lavik. The water depth is about 1050m.

Figure 17 shows the water depth profile between the two docking stations and the concrete sphere location. Oppedal is located at the distance of 0km and Lavik on the distance of 8.2km in the graph. This results in a cable length of 4.585km to Oppedal and 4.067km to Lavik. Which is a total cable length of 8.652km[19]. In addition, a buffer should be included for the cables to connect them to the docking station. For the later consideration in the life cycle assessment, a cable length of 8.7 km is used.

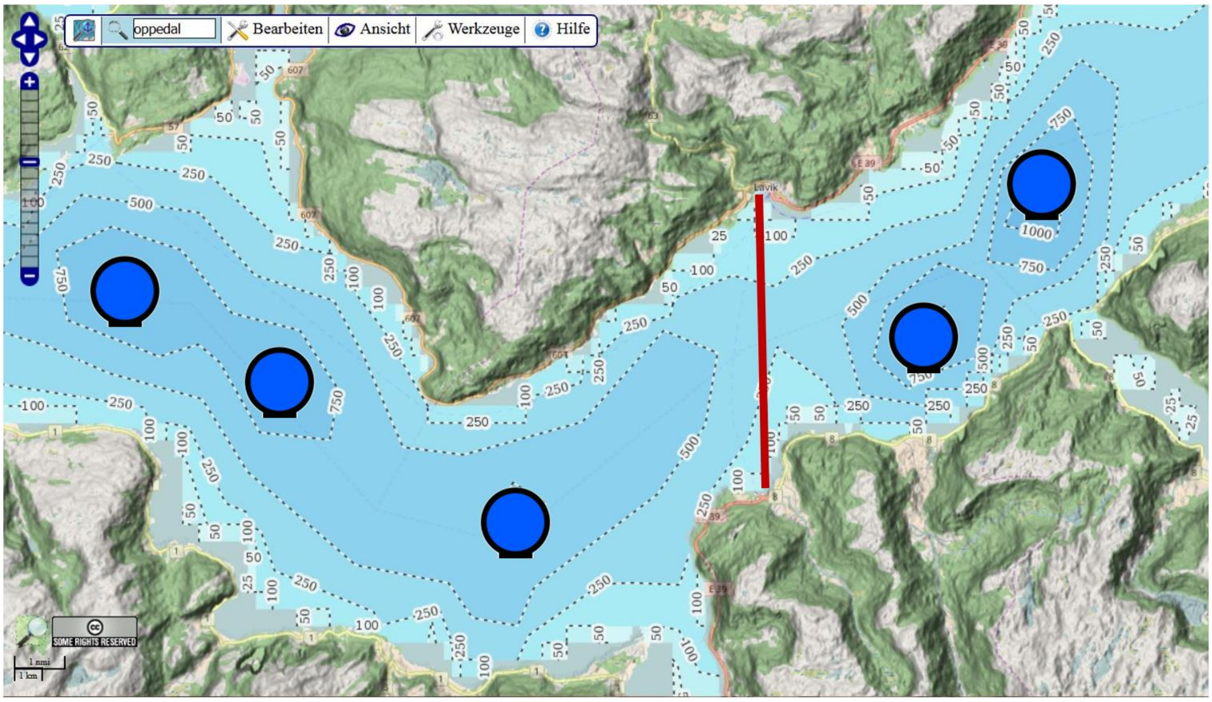

Figure 18: Possible locations, concrete sphere storage[19]

To dimension the concrete sphere, the required storage size of 763.2 kWh is considered. With the formula for the spheres energy, which is transposed to $V_{sp,\,in}$, the necessary storage volume can be calculated theoretically. But in addition, the efficiency of the sphere storage must be considered, which is 0.82 for turbine operation and 0.89 for pump operation[12]. This results in a total efficiency of 0.73. For the dimensioning of the sphere, however, only the turbine efficiency is required. Since the sphere is designed with a certain energy content, in this case 763.2kWh, and only the losses of the discharge have influence on the storage size, a size of

$$V_{in} = \frac{E_{sphere}}{\rho \cdot g \cdot h * \eta_{turb}}$$

$$V_{in} = \frac{763{,}205 * 1000 * 3600Ws}{1000\frac{kg}{m^3} \cdot 9{,}81\frac{m}{s^2} \cdot 1000m}$$

$$V_{in} = 280.07522\, m^3$$

By transposing the sphere volume formula to the diameter d, a required inside diameter of [13]:

$$d_{in} = \sqrt[3]{\frac{V_{sp,in} \cdot 6}{\pi}} \qquad (5.1)$$

$$d_{in} = \sqrt[3]{\frac{280.07522\ m^3 \cdot 6}{\pi}}$$

$$d_{in} = 8.11756\ m$$

What has not yet been considered is the wall thickness of the concrete sphere. We consider, that the buoyancy of the concrete sphere is compensated by the weight of the sphere, to ensure the sphere does not lift off the ground if there is no more water in it[12]. Which is the same method as Fraunhofer is using. This results in the following formula for the balance of the buoyancy forces. The mechanical components are not considered, to ensure the sphere got enough total mass to not float up[12].

$$V_{out} * \varrho_w = (V_{out} - V_{in}) * \varrho_c \qquad (5.2)$$

$$V_{out} = \frac{-V_{in} * \frac{\varrho_c}{\varrho_w}}{(1 - \frac{\varrho_c}{\varrho_w})}$$

$$V_{out} = 466.3\ m^3$$

The wall thickness can be determined by half the difference between the two diameters.

$$D_{KS} = \frac{d_{out} - d_{in}}{2}$$

$$D_{KS} = \frac{\sqrt[3]{\frac{6 * V_{out}}{\pi}} - d_{in}}{2}$$

$$D_{KS} = 0.752\ m$$

The resulting concrete volume is

$$V_c = V_{out} - V_{in}$$

$$V_c = 186.22\ m^3$$

And in combination with the reinforced concrete density of 2504.1kg/m³ a concrete mass of 466325.5 kg is required.

To build the concrete sphere, the concrete has to be reinforced by steel plaiting, what is common in the construction industry. The values for the degree of reinforcement can also be taken from the construction industry. For this construction a reinforcement degree of 150 kg steel per m^3 concrete is used[20, p. 216]. The result is, considering the density of steel and concrete per cubic meter of reinforced concrete, a mass of 150kg steel and 2354kg concrete per cubic meter. With a reinforced concrete volume of $186.22m^3$, this results in a steel mass of 27933 kg steel and 438361.88 kg concrete.

Figure 19: Construction concrete sphere[21]

Figure 19 shows how the concrete sphere of the pilot project StEnSea, of the Fraunhofer institute, is shaped. For this purpose, a special formwork device must be created, which is basically made of wooden boards and a steel construction. Furthermore, the picture shows the flange, in the middle of the sphere. Finally, the main steel tube which you can see in Figure 20 is bolted to this flange. This steel tube is used to bring the required mechanical components to their place of operation in the sphere. All the mechanical components can previously be mounted into this main steel tube, which is called the machine unit. The pump, turbine, electric machine, shaft, pressure pipe and the required electronics are in this steel tube. Due to this simple construction, in the case of maintenance, the main steel pipe can be loosened on the flange and pulled out completely.

Figure 20: Main steel tube[23]

The required power of the electrical machine depends on the charging and discharging power. These are clearly defined by the system. In average operation the sphere storage has to provide about 1307kW. Figure 21 shows the discharging case of the sphere storage, which looks the same for both charging stations. For charging on the other side of the fjord, the power flows just have to be mirrored.

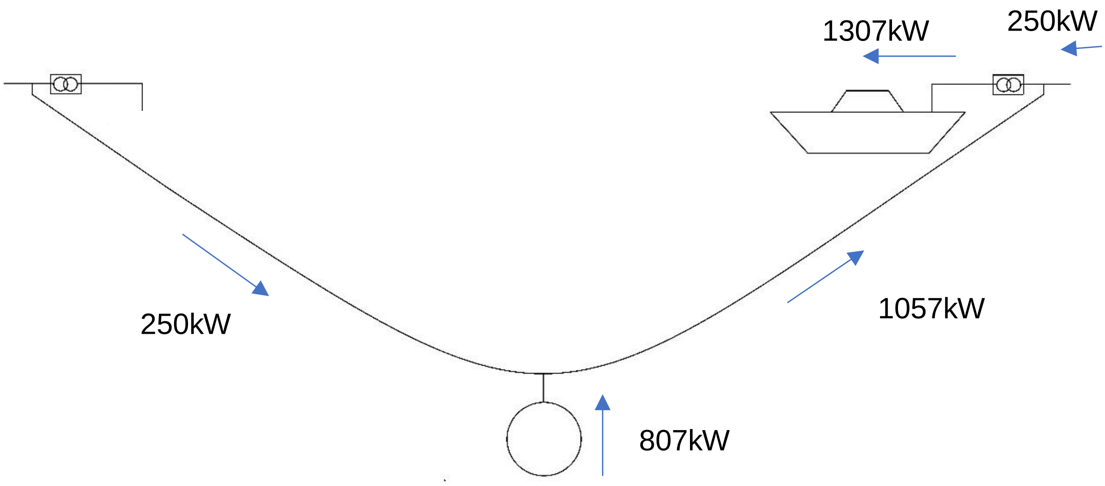

Figure 21: Power flows, ferry charging process with concrete sphere storage system

The second case is the charging case of the sphere storage which is shown in Figure 22. This is happening if the ferry is on the way, or the battery of the ferry is fully charged, so no electrical energy is required. Since only 250kW are available from the electrical grid on both sides, which is 500kW in total, the size of the electrical machine is sufficient for this case as well.

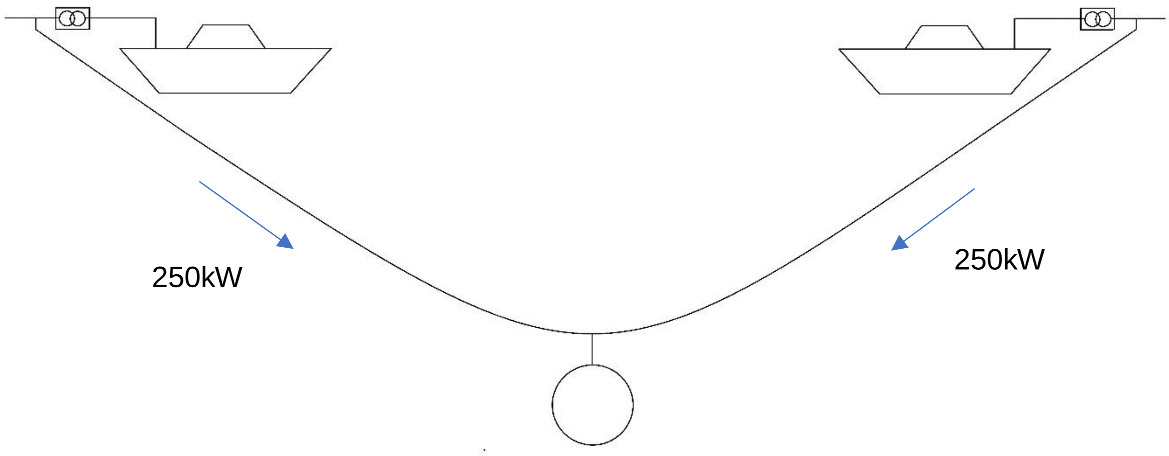

Figure 22: Power flows, sphere charging

To transfer the power of 807kW an aluminum submarine cable is used. This raises the question of whether this power can be transmitted with a voltage of 600V, which is required for the ship's electrical system. With a permissible voltage drop of 3% and the conductivity of aluminum, this results in a cable cross-section of 757.5 mm², which would cause a considerable material consumption and is unacceptable.

$$A = \frac{2 * I * l * cos\varphi}{\gamma * \Delta U}$$

$$A = \frac{2 * 34{,}09A * 87000m * 0{,}8}{36\frac{m}{\Omega * mm^2} * (400V * 0{,}03)}$$ [22, p. 164] ff

$$A = 757{,}56mm^2$$

Therefore, the voltage is brought to medium voltage level. This is 22kV. It is assumed that the electrical machine in the concrete sphere storage provides this voltage. In addition, it is assumed that the transformers at the docking stations can additionally transmit the required power. Therefore, the cable is connected to the power grid side of the transformer.

The necessary cable cross-section decreases to 13.8mm². However, the smallest submarine cable available on the market, rated at 22kV, is 50mm². But to choose only the required amount of materials, for the life cycle assessment only one, instead of three, of this cable is considered. The 50mm² cable divided by the necessary 13,8mm² equals 3.6. So, the amount of raw materials is 20% higher as necessary.

According to the datasheet in the appendix this submarine cable from Helukabel which you can see in Figure 23 contains an aluminum core, which operates as a conductive layer. In addition, it consists of several insulation layers, which consist of polyethylene and a copper layer, which operates as an electrical screen. Per kilometer this cable consists of 182kg copper, 145kg aluminum and 890kg polyethylene.

Figure 23: Cable structure [23]

Table 10: Inventory manufacturing concrete sphere cables

Cables	Quantity	Unit	Eco Invent
Aluminum	145	kg/km	Aluminium alloy, AlMg3 {GLO}| market for | Alloc Def, U
Copper	182	kg/km	Copper {GLO}| market for | Alloc Def, U
PE	563	kg/km	Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U
Transport	96.8	tkm/km	Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, U
Mounting	4.6	h/km	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Def, U
Aluminum	145	kg/km	Metal working, average for aluminium product manufacturing {GLO}| market for | Alloc Def, U
Copper	182	kg/km	Metal working, average for copper product manufacturing {GLO}| market for | Alloc Def, U

Table 11 shows the manufacturing of the concrete sphere. The values are assumptions as shown before. The formwork are assumptions, based on the surface of the sphere.

Table 11: Inventory manufacturing concrete sphere

Concrete Sphere			
	Quantity	Unit	Eco Invent
Concrete	175,67	m^3	Concrete, high exacting requirements {GLO}| market for | Alloc Def, U
Reinforcement	26350,8	kg	Reinforcing steel {GLO}| market for | Alloc Def, U
Formwork	9,58	m^3	Sawnwood, board, softwood, air dried, planed {GLO}| market for | Alloc Def, U
Formwork	7612,6	kg	Steel, low-alloyed {GLO}| market for | Alloc Def, U
Formwork	7612,6	kg	Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def, U
Formwork	72	m	Welding, arc, steel {GLO}| market for | Alloc Def, U
Transport	39076,4598	tkm	Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, U
Elektricity	320	kWh	Electricity, low voltage {NO}| market for | Alloc Def, U

Table 12 shows the manufacturing of the main steel tube. It includes only the tube itself. The Mechanical and electrical parts are listed in Table 13.

Table 12: Inventory manufacturing main steel tube

Main steel tube			
	Quantity	Unit	Eco invent
Chr. Steel	3012,4	km/product	Chromium steel pipe {GLO}| market for | Alloc Def, U
Welding	5	m/produkt	Welding, arc, steel {GLO}| market for | Alloc Def, U
Transport	328	tkm/produkt	Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, U

Elektricity	40	kWh/produkt	Electricity, low voltage {NO}| market for | Alloc Def, U

Table 13 shows the manufacturing of the pump turbine. It includes the water turbine as well as all necessary electronical parts. The values are assumptions which are derived from values of pumped storage power plants since there is no available data from Fraunhofer.

Table 13; Inventory manufacturing pump turbine [24]

PumpTurb	**Quantity**	**Unit**	**Eco invent**
Chr. Steel	2103,75	kg/produkt	Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U
L.A.Steel	5486,85	kg/produkt	Steel, low-alloyed {GLO}| market for | Alloc Def, U
Copper	821,03	kg/produkt	Copper {GLO}| market for | Alloc Def, U
Chr. Steel	2103,75	kg/produkt	Metal working, average for chromium steel product manufacturing {GLO}| market for | Alloc Def, U
L.A.Steel	5486,85	kg/produkt	Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def, U
Copper	821,03	kg/produkt	Metal working, average for copper product manufacturing {GLO}| market for | Alloc Def, U
Transport	2650	tkm/produkt	Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Alloc Def, U

5.2.2 Phase 2 – operation

Everything is considered for the operation of the system, which makes the use of the system possible. This is above all the energy that the ferry needs for the crossing. Since the energy source is the same for all three systems, the electric grid, the Norwegian electricity mix is used. However, this does not mean that this parameter can be excluded because the losses of individual installations may differ significantly, especially if they are used over a longer period of observation. Thus, although the source is the same for all, the necessary amounts of energy for the two systems are different. In addition, this part of the maintenance must be taken into account. This in turn differs for each individual component and is therefore very different. However, the scope of this effort is significantly lower than the energy supply.

The energy that is needed comes partly from the grid and partly from the storage systems. However, only the energy buffered in the storage systems is considered. The energy charged directly from the grid to the ferry battery storage system is not considered.

5.2.2.1 Operation onshore battery storage system

As described in 5.1 the efficiency is the main difference between the to storage technologies. The energy which is consumed by the onshore battery storage system from the electrical grid is 176.2kWh per crossing. With the distance of 6km the consumed energy for 1km is 29.4kWh.

5.2.2.2 Operation concrete sphere storage system

The energy which is consumed by the concrete sphere storage system from the electrical grid is 165,9kWh per crossing. With the distance of 6km the consumed energy for 1km is 27.7kWh. The difference in consumed energy to the onshore battery storage system is based on the different efficiencies of the two technologies.

The use of lubricating oil is based on a study about pumped storage power plants [24]. In this study a loss in lubricating oil of $2.27 \cdot 10^{-5}$ g/kWh to the water and a loss of $9.76 \cdot 10^{-6}$ g/kWh to the ground is quantified. Since the concrete sphere is mounted on the sea ground the losses in lubricating oil are added up. So, the losses in lubricating oil are $3.246 \cdot 10^{-5}$g/kWh.

5.2.3 Phase 3 – disposal

The disposal phase is not considered in this work because the data base is lacking in sufficient quality.

6 Evaluation

In this chapter the data generated by the SimaPro software in chapter 5 is evaluated. For this purpose, the respective environmental effects of the different systems are compared to each other. In addition, a sensitivity analysis is made to identify the parameters and assumptions that have a major impact on the results. This serves to evaluate the validity of the results, as some parameters are assumptions.

6.1 Impact assessment

As mentioned in chapter 4.2, there are 17 different impact categories that are considered at the mid-point level.

Table 14: Considered impact categories

Impact Category	**Unit**
Global warming	kg CO2 eq
Stratospheric ozone depletion	kg CFC11 eq
Ionizing radiation	kBq Co-60 eq
Ozone formation, human health	kg NOx eq
Fine particulate matter formation	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Terrestrial acidification	kg SO2 eq
Freshwater eutrophication	kg P eq
Terrestrial ecotoxicity	kg 1,4-DCB e
Freshwater ecotoxicity	kg 1,4-DCB e
Marine ecotoxicity	kg 1,4-DBC e
Human carcinogenic toxicity	kg 1,4-DBC e
Human non-carcinogenic toxicity	kg 1,4-DBC e
Land use	m2a crop eq
Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq
Water consumption	m3

6.1.1 Manufacturing

The manufacturing phase of the various system components is considered first. As described in chapter 5. Each component is initially considered in relation to one km of ferry operation in SimaPro.

6.1.1.1 Manufacturing of the onshore battery storage system

The batteries are responsible for the highest impact in 16 of 17 impact categories what you can see in Figure 24. The batteries have a share between 24% and 92% of the respective impact category. Only in the stratospheric ozone depletion the cooling unit has the highest share with about 25%. In global warming the share of battery manufacturing is about 58%. The cooling unit has the second highest share of impact in every impact category. The third, fourth and fifth highest impacts are caused by the converters the battery building and cables. They have a share of about 0% to 5%.

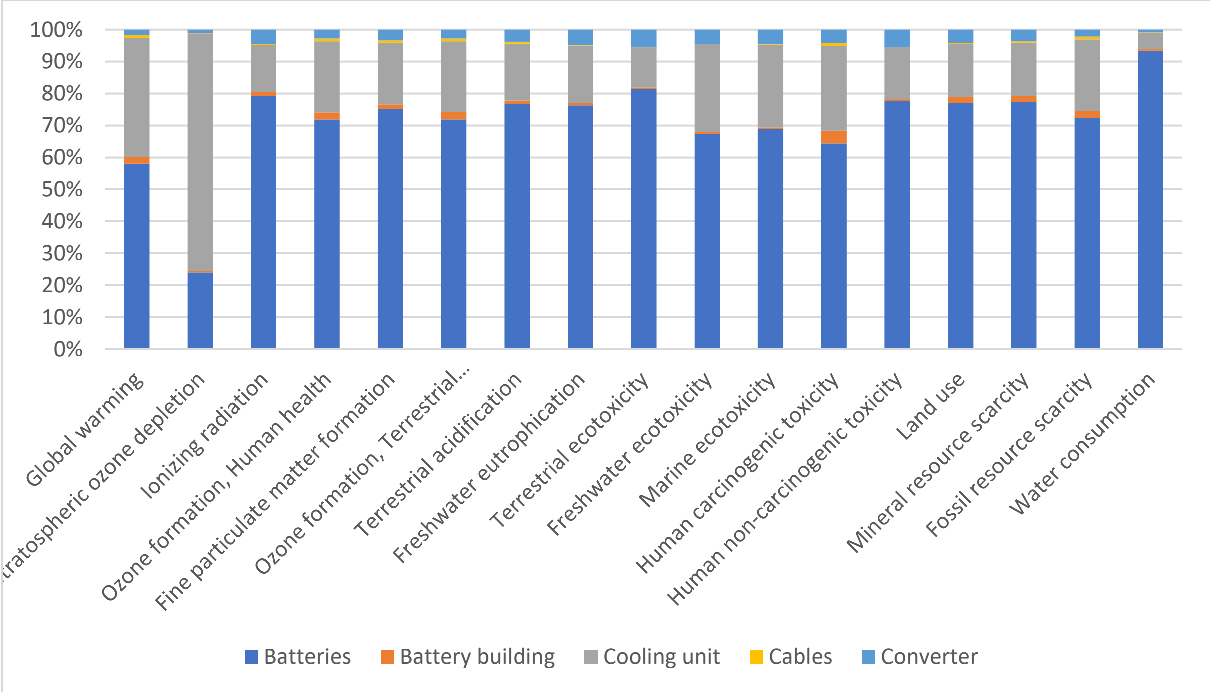

Figure 24: Impact of manufacturing of the onshore battery storage system

For the css, the manufacturing chart looks very different. It is shown in Figure 25. Most of the impact is shared by the concrete sphere and the machine unit with pump, turbine and electrical machine. The concrete hull has a greater impact on global warming, fossil resource scarcity and water consumption. Overall, the machine unit has the largest share of the impact. Freshwater ecotoxicity and marine ecotoxicity are mostly due to the machine unit. The cables and the main steel tube have a smaller share. The biggest transformer's impact in human carcinogenic toxicity.

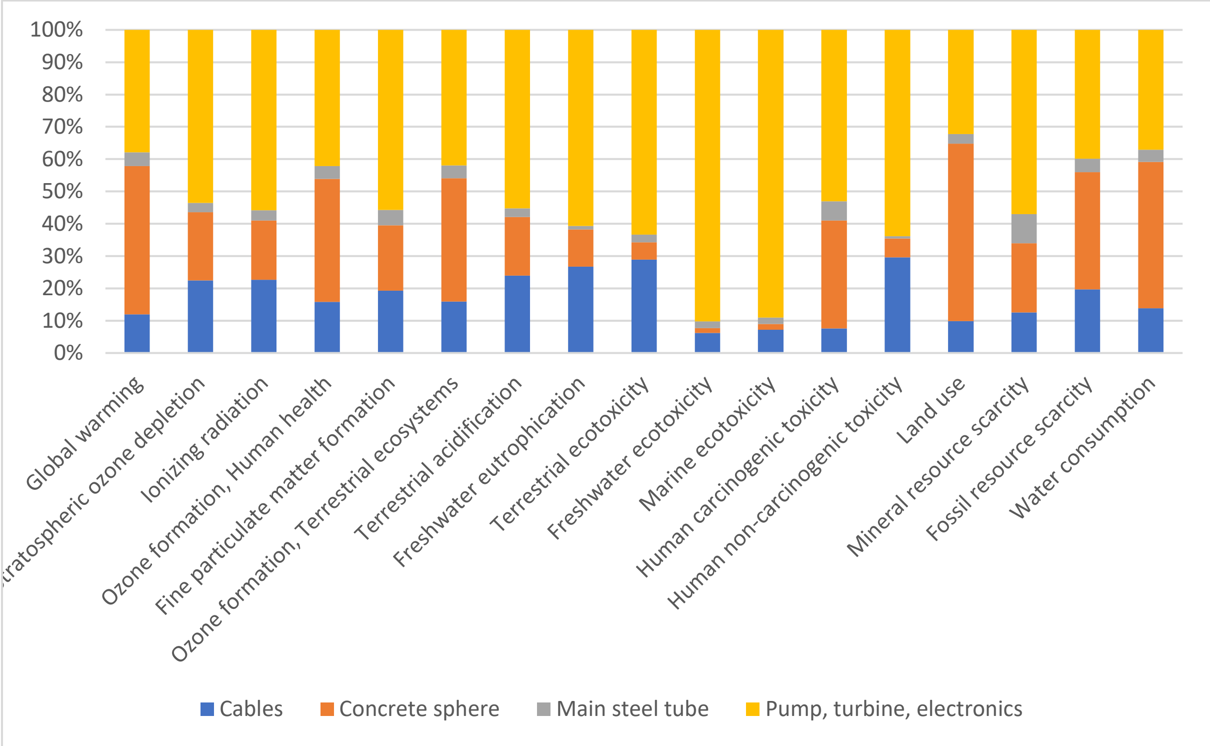

Figure 25: Impact of manufacturing of the concrete sphere storage system

The manufacturing comparison between the concrete sphere storage system and the onshore battery storage system which is shown in Figure 26 shows that the onshore battery storage system has a higher share of impact in 15 of 17 impact categories. In these 15 impact categories the share of the onshore battery storage system varies between 51% to 88%. The only two categories where the concrete sphere storage system has a higher share than the onshore battery storage system are freshwater ecotoxicity and marine ecotoxicity with a share of about 69% and 67%.

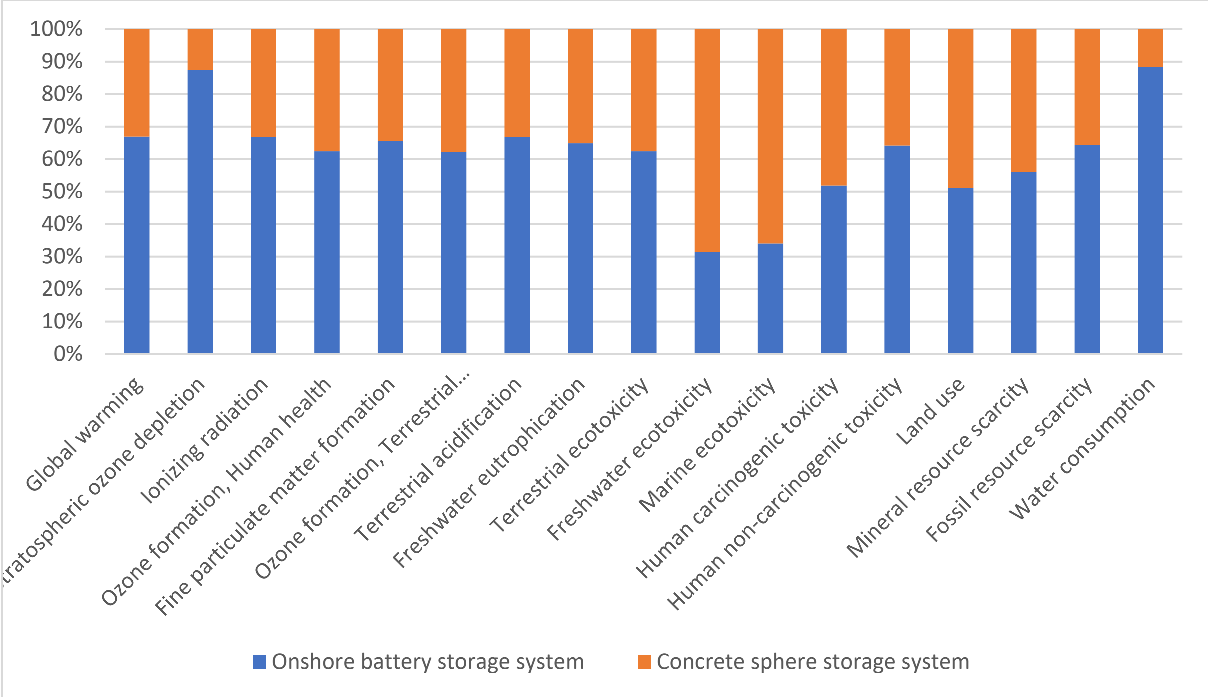

Figure 26: Impact comparison between onshore battery storage system manufacturing and concrete sphere storage system manufacturing

6.1.2 Use

Both systems use the same source of electrical energy. The differences in use are the amount of consumed energy from the electrical grid and the losses of lubricating oil to the water which are only existing for the concrete sphere storage system.

As you can see in Figure 27 the share of the two systems are almost the same in every impact category. The share of the onshore battery storage system is a bit higher than the share of the concrete sphere storage system in every impact category. It varies between 52% and 50%. Therefore, it is obvious that the loss in lubricating oil which is only existing for the concrete sphere storage system only has a very small impact. The highest impact on the difference between the to shares only can only be based on the higher energy consumption of the onshore battery system.

The percentage of impact categories within one storage system does not differ compared to the other storage system. Only the height is different. This difference is due to the different efficiencies of the two storage systems. Thus, the impacts of the concrete sphere storage system are higher during the use period, caused on his lower efficiency.

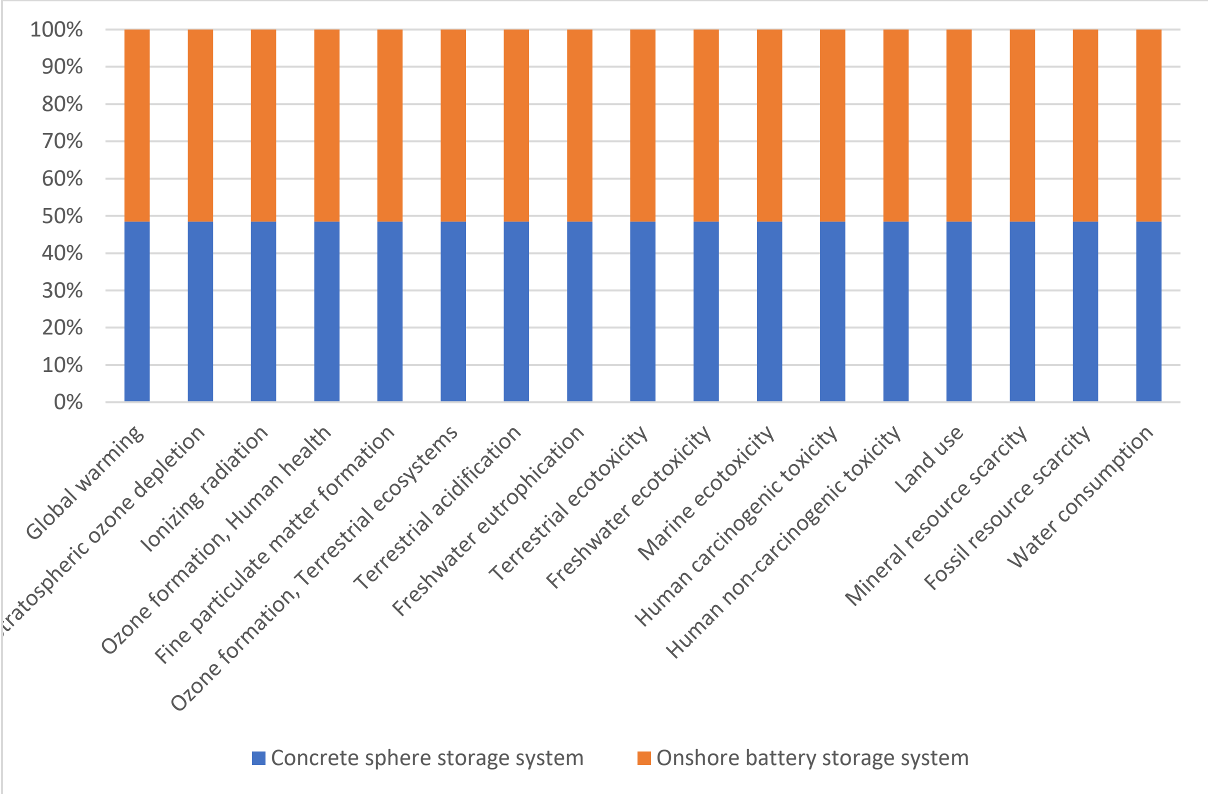

Figure 27: Use comparison between concrete sphere storage system and onshore battery storage system

6.1.3 Total impacts

Since the concrete sphere storage has performed better than the onshore battery storage system the most phases and system levels, it can be concluded that the total impact of the concrete sphere storage system is less than the impact of the onshore battery storage system.

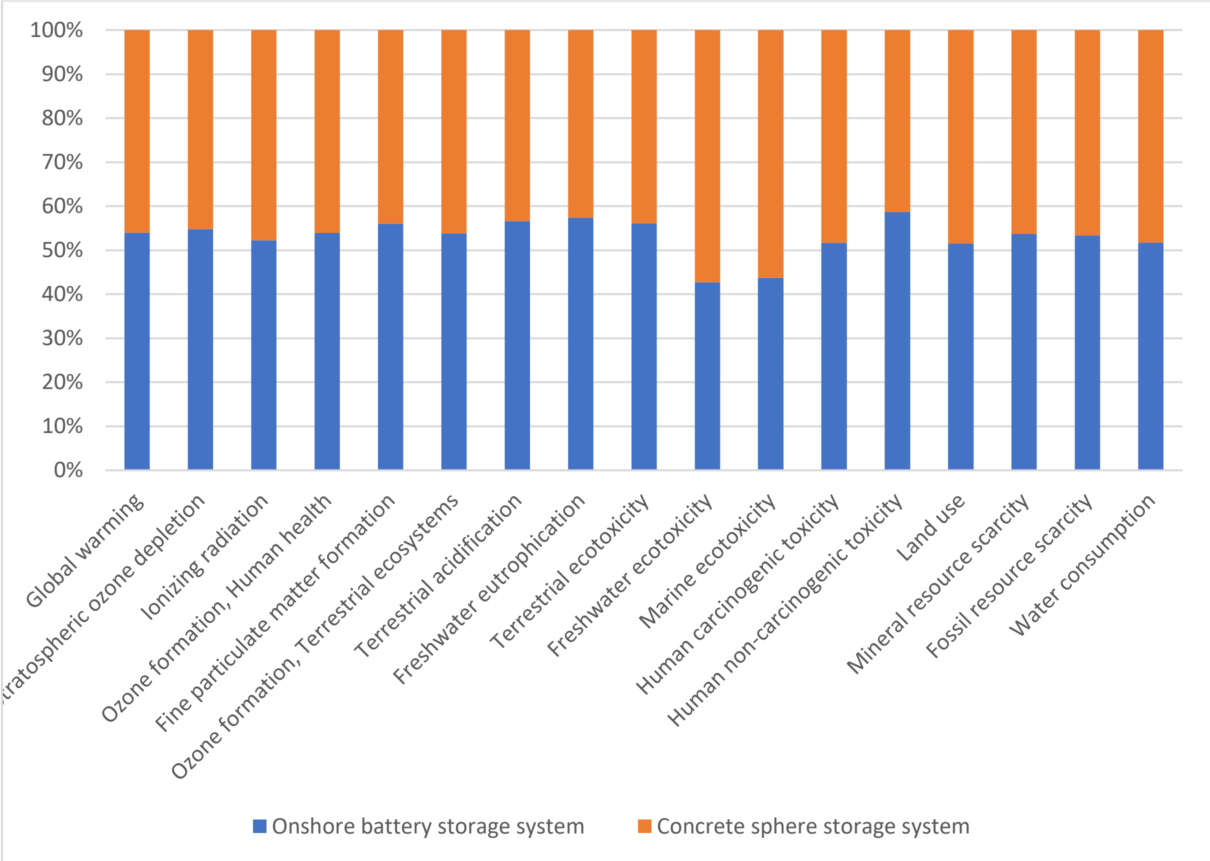

Figure 28: Comparison between the onshore battery storage system and the concrete sphere storage system, manufacturing and use

Figure 28 shows the comparison between the onshore battery storage system and the concrete sphere storage system. The manufacturing and the use phase are included. In this figure you can see that the onshore battery storage system has a higher share of impact in 15 of 17 impact categories. In these 15 categories the share of the onshore battery storage system varies between 52% and 59%. Freshwater ecotoxicity and marine ecotoxicity are the only two impact categories where the concrete sphere storage system has a higher share of impact than the onshore battery storage system.

6.2 Sensitivity analysis

A sensitivity analysis is used to find out how the results change by varying the input parameters. This is important because the data bases of the different components are not equally good. For the onshore battery storage system the data base is of high quality.

In contrast, a lot of assumptions must be made for the design of the concrete sphere storage, as not a single system of this size has been tested. The only firsthand data source for the sphere storage is a publication of the Fraunhofer institute, where the Stensea project is described and evaluated. However, this is only partially possible because it is a test model of much smaller dimensions. Therefore, there is still no experience in terms of continuous operation of such a system. The lifespan of the components can only be estimated very roughly and for this purpose, a variety of data is used, which describe the same systems in a different context.

The data for the pump turbine is data from pumped storage power plants. However, these are usually 100 times larger. Small hydropower plants therefore serve as the best data base. But, it is very difficult to estimate the useful life of the turbine which is operated by salt water. Salt water is highly more aggressive to mechanical parts than freshwater. Therefore, within the sensitivity analysis, the impact of the useful pump turbine life is considered.

The data from the Fraunhofer test also showed a total system efficiency of the concrete sphere of 73%. By increasing the size of the system, a better value is expected[12]. Therefore, it is considered how an increase in efficiency to 80% can affect the results. Furthermore, the reduction of the energy consumption is not the only effect of a better system efficiency. It also causes a smaller system size.

6.2.1 Different lifespan of the concrete hull

First, it is examined how the lifespan of the concrete hull affects the manufacturing phase. 40 years represent the basic scenario. Figure 29 shows the 40 years scenario as 100 percent. You can see that global warming, ozone formation, human health, land use, water consumption fossil resource scarcity and human carcinogenic toxicity are the 6 most effected impact categories. They show an increase for the 30 years scenario of about 10% to 18%. The increase for the 20 years scenario is higher. In these 6 categories the increase is about 38% to 58%. The increase in impact for the other impact categories is about 1% to 8% for the 30 years scenario and about 2% to 21% for the 20 years scenario.

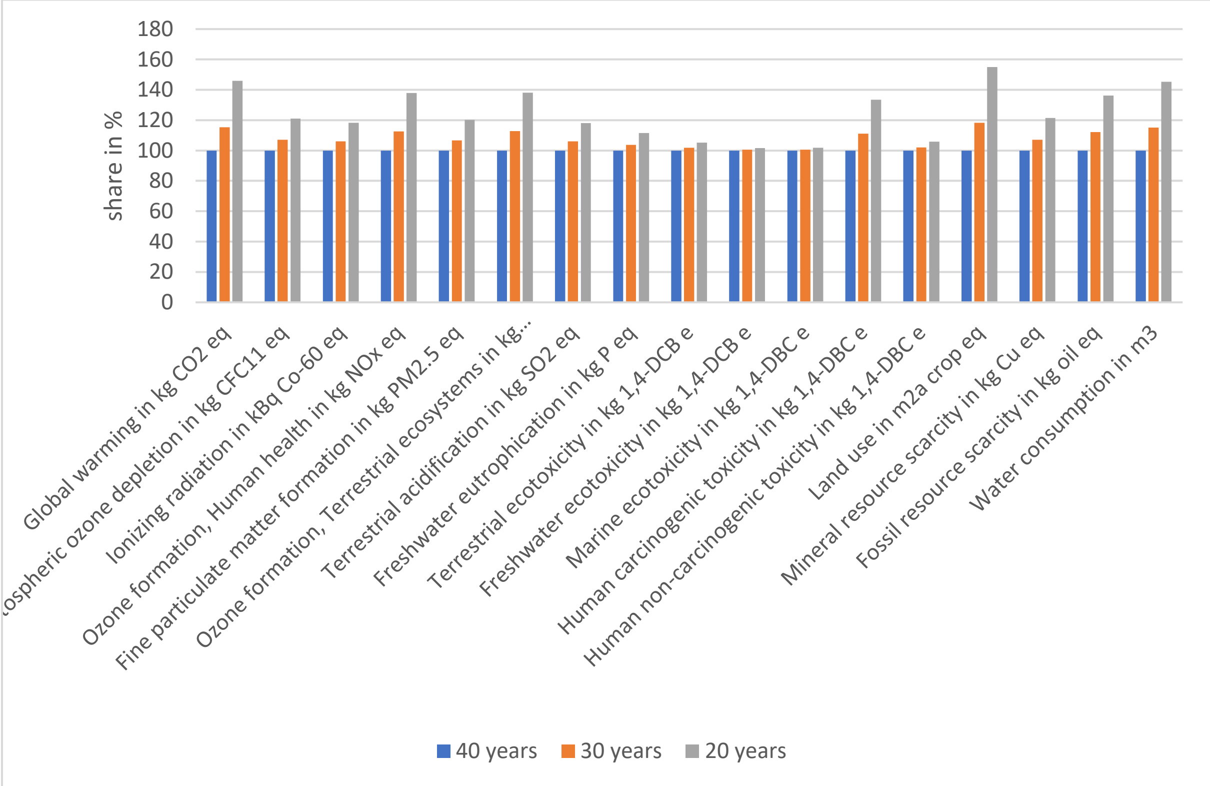

Figure 29: Different lifespans of the concrete hull, manufacturing of the concrete sphere storage system

6.2.2 Different lifespan of the machinery

The other component which had a big influence of the sphere's impact was the machinery which includes the pump turbine, the electric machine and the electronics. In the basic scenario a lifespan of 15 years was considered. As you can see in Figure 30 the 15 years scenario is represented by 100%. The variation of the impact is the highest for freshwater ecotoxicity and marine ecotoxicity with an impact decrease of about 22% and an impact increase of about 44% for both impact categories. The impact decrease for the other impact categories is about 15% to 8% for the 20 years scenario and the impact increase for the other impact categories is about 18% to 30% for the 10 years scenario.

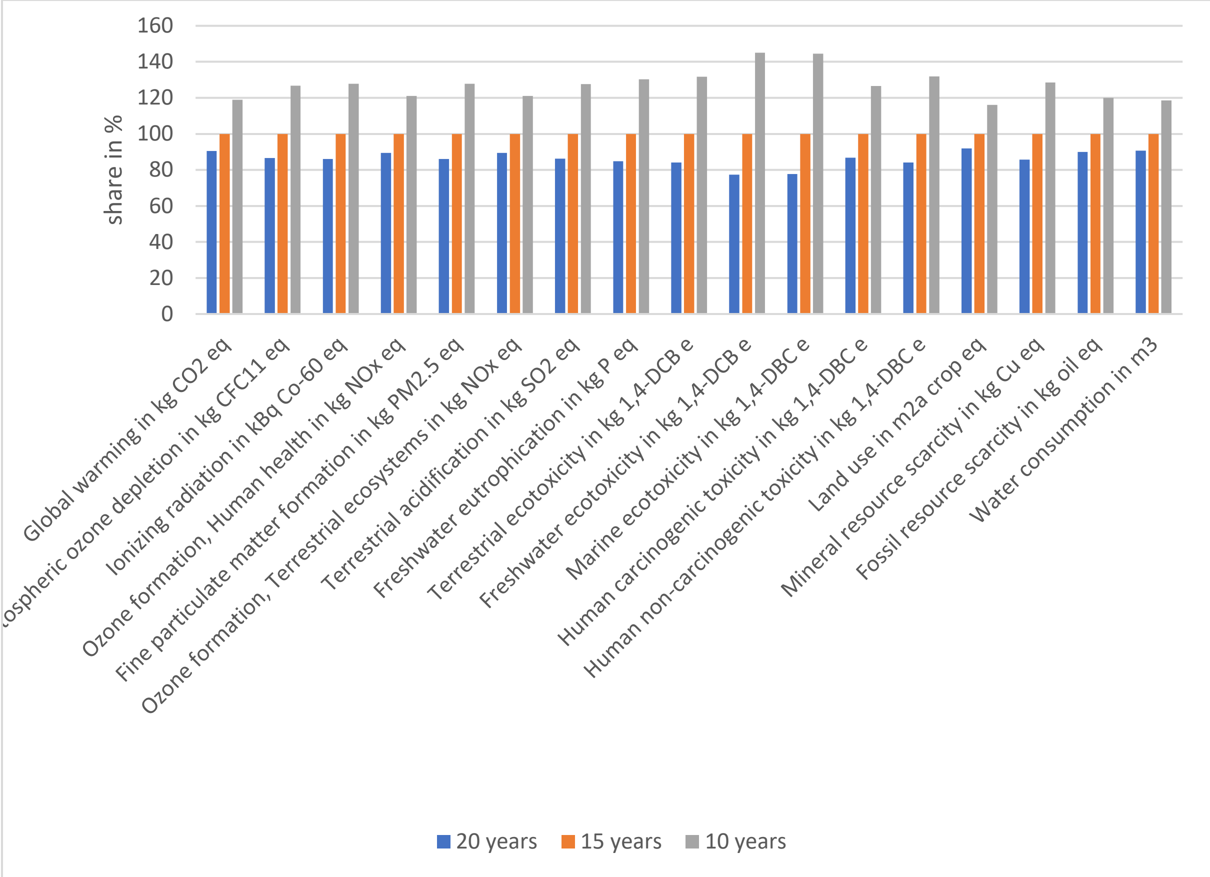

Figure 30: Different lifespans of the machinery, manufacturing of the concrete sphere storage system

6.3 Limitations

As is likely to be with life cycle assessments, the biggest limitation in this work is data quality. As the concrete sphere storage technology is still in development and no systems are available on the market, it is very difficult to estimate what kind of characteristics such a system will have in real operation.

Although there are some data from the StEnSea project of the Fraunhofer Institute, this system has been operating on a smaller scale. It is difficult to estimate how such systems behave in continuous operation, especially regarding to the lifespan of the system components.

In addition, it is quite possible that improvements will be made to such systems, as there has been only one model ever tested. Based on this test run, a further development is to be expected.

Moreover, no statement can be made about the costs of such a concrete sphere storage. Since this is not a series product, it can be expected that the costs for this can be considerably higher than for conventional and widespread batteries.

Furthermore, it was not taken into account how a possible grid expansion can affect the results. This would mean an enormous effort, but the lifespan of the electrical grid is significantly higher than the lifespan of the storage systems.

7 Conclusion

In this thesis, the existing onshore battery storage system of the MF Ampere was compared to the optional use of the new concrete sphere storage technology. For this purpose, a model has been created for both systems, which allows to visualize the storage values during a day.

In addition, it was examined whether the electric operation of further ferries on this ferry route is possible. This proved to be feasible, however, the expected additional effort in terms of storage size is enormous. For this reason, it wouldn't be reasonable to operate the additional ferry without improving the grid supply.

Based on this model, which takes the daily schedule of the ferries into account, the optional concrete sphere storage system has been dimensioned and the necessary system components were calculated considering the circumstances.

The resulting material and energy flows have been evaluated for both storage variants using SimaPro and compared to each other regarding to their environmental impact.

The examination proved, that the concrete sphere storage system causes a lower environmental impact in every impact category, compared to the onshore battery storage system. From the current point of view, therefore, it is reasonable to operate such a concrete sphere storage system in conjunction with an electric ferry in Norway considering the environmental impact. Nevertheless, the costs of a concrete sphere storage system must be considered to achieve a successful operation.

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Appendix

NA2XS2Y 6/10kV, 12/20kV, 18/30kV VPE-isoliert, Alu-Leiter, 1-adrig, geschirmt, PE-Mantel

Technische Daten
- VPE-isolierte Mittelspannungskabel nach DIN VDE 0276 Teil 620 bzw. HD 620 S2 und IEC 60502
- **Temperaturbereich**
  beim Verlegen bis -20°C
- **Betriebstemperatur**
  max. +90°C
- **Kurzschlusstemperatur**
  +250°C (Kurzschlussdauer max. 5 s)
- **Nennspannungen**
  U_0/U 6/10 kV, 12/20 kV, 18/30 kV
- **Betriebsspannungen**
  für 6/10 kV = max. 12 kV
  für 12/20 kV = max. 24 kV
  für 18/30 kV = max. 36 kV
- **Prüfspannungen**
  für 6/10 kV = 15 kV
  für 12/20 kV = 30 kV
  für 18/30 kV = 45 kV
- **Mindestbiegeradius**
  15x Kabel Ø
- **Strombelastbarkeit**
  siehe Tabelle Technische Informationen

Aufbau
- Aluminium-Leiter, nach DIN VDE 0295 Kl.2, mehrdrähtig, BS 6360 cl.2, IEC 60228 cl.2
- innere Leitschicht
- Aderisolation aus vernetztem Polyethylen (VPE), Mischungstyp DIX8 nach HD 620 S2
- äußere Leitschicht extrudiert und fest verschweißt mit Aderisolation
- leitfähige Bandierung
- Schirm: Umspinnung aus Cu-Drähten mit
- einer oder zwei Querleitwendeln
- Bandierung
- Außenmantel aus PE Mischungstyp DMP2 nach HD 620 S2
- Mantelfarbe schwarz

Eigenschaften
- Die verwendeten Materialien bei der Fertigung sind silicon- und cadmiumfrei und frei von lackbenetzungsstörenden Substanzen
- **Montagehinweis**
  Die extrudierte äußere Leitschicht mit der Isolierung ist dauerhaft fest verschweißt um ein Optimum an Betriebssicherheit zu gewährleisten. Deshalb empfehlen wir bei der Montage ein Schälwerkzeug.

Hinweise
- rm = runder Leiter, mehrdrähtig
- Roter Preis wird mit reduziertem Rabatt abgerechnet.
- Weitere Typen und Abmessungen auf Anfrage.

Verwendung
Verlegung in Innenräumen und in Kabelkanälen, im Freien, in Erde und im Wasser sowie auf Pritschen für Industrie- und Schaltanlagen und Kraftwerke. Der widerstandsfähige PE-Mantel kann bei der Verlegung und im Betrieb stark mechanisch beansprucht werden. Der PE-Mantel ist nicht flammwidrig nach DIN EN 60332-1-2. Durch die innere Leitschicht zwischen Leiter und VPE-Isolierung und der festhaftenden äußeren Leitschicht auf der VPE-Isolierung wird ein teilentladungsfreier Aufbau mit hoher Betriebssicherheit gewährleistet.

Art.-Nr.	Aderzahl x Nennquerschnitt mm²	Betriebsspannung max.	Nennspannung kV	Isolierwanddicke mm	Mantel-Wanddicke Nennwert mm	Außen-Ø min. - max. mm	Cu-Zahl kg / km	Alu-Zahl kg / km	Gewicht ca. kg / km	Hohlpreis EUR / 100m Cu 0,- / Alu 0,- Standardlänge	Hohlpreis EUR / 100m Cu 0,- / Alu 0,- Schnittlänge
32520	1 x 50 rm / 16	12	6 / 10	3,4	2,5	24,0 - 29,0	182,0	145,0	710,0	566,00	599,00
32521	1 x 70 rm / 16	12	6 / 10	3,4	2,5	26,0 - 31,0	182,0	203,0	790,0	585,00	620,00
32522	1 x 95 rm / 16	12	6 / 10	3,4	2,5	26,0 - 32,0	182,0	276,0	920,0	611,00	647,00
32523	1 x 120 rm / 16	12	6 / 10	3,4	2,5	28,0 - 34,0	182,0	348,0	990,0	653,00	692,00
32524	1 x 150 rm / 16	12	6 / 10	3,4	2,5	29,0 - 35,0	182,0	435,0	1110,0	673,00	713,00
32525	1 x 150 rm / 25	12	6 / 10	3,4	2,5	29,0 - 35,0	283,0	435,0	1220,0	695,00	736,00
32526	1 x 185 rm / 16	12	6 / 10	3,4	2,5	31,0 - 37,0	182,0	537,0	1260,0	757,00	802,00
32527	1 x 185 rm / 25	12	6 / 10	3,4	2,5	33,0 - 39,0	283,0	537,0	1370,0	778,00	824,00
32528	1 x 240 rm / 16	12	6 / 10	3,4	2,5	33,0 - 39,0	182,0	696,0	1480,0	830,00	879,00
32529	1 x 240 rm / 25	12	6 / 10	3,4	2,5	33,0 - 39,0	283,0	696,0	1530,0	873,00	925,00
32530	1 x 300 rm / 25	12	6 / 10	3,4	2,5	36,0 - 41,0	283,0	870,0	1820,0	1343,00	1423,00
32531	1 x 400 rm / 35	12	6 / 10	3,4	2,5	40,0 - 45,0	394,0	1160,0	2220,0	1626,00	1723,00
32532	1 x 500 rm / 35	12	6 / 10	3,4	2,5	43,0 - 48,0	394,0	1450,0	2570,0	1658,00	1757,00
32533	1 x 50 rm / 16	24	12 / 20	5,5	2,5	28,0 - 33,0	182,0	145,0	890,0	685,00	726,00
32534	1 x 70 rm / 16	24	12 / 20	5,5	2,5	30,0 - 35,0	182,0	203,0	970,0	712,00	754,00
32535	1 x 95 rm / 16	24	12 / 20	5,5	2,5	31,0 - 36,0	182,0	276,0	1120,0	750,00	795,00
32536	1 x 120 rm / 16	24	12 / 20	5,5	2,5	32,0 - 38,0	182,0	348,0	1210,0	803,00	851,00
32537	1 x 150 rm / 16	24	12 / 20	5,5	2,5	33,0 - 39,0	182,0	435,0	1370,0	860,00	933,00
32538	1 x 150 rm / 25	24	12 / 20	5,5	2,5	33,0 - 39,0	283,0	435,0	1420,0	881,00	911,00
32539	1 x 185 rm / 16	24	12 / 20	5,5	2,5	35,0 - 41,0	182,0	537,0	1530,0	945,00	1001,00
32540	1 x 185 rm / 25	24	12 / 20	5,5	2,5	35,0 - 41,0	283,0	537,0	1570,0	964,00	1021,00
32541	1 x 240 rm / 16	24	12 / 20	5,5	2,5	38,0 - 44,0	182,0	696,0	1720,0	1081,00	1145,00
32542	1 x 240 rm / 25	24	12 / 20	5,5	2,5	38,0 - 44,0	283,0	696,0	1830,0	1120,00	1187,00
32543	1 x 300 rm / 25	24	12 / 20	5,5	2,5	40,0 - 46,0	283,0	870,0	2070,0	1179,00	1249,00
32544	1 x 400 rm / 35	24	12 / 20	5,5	2,5	43,0 - 49,0	394,0	1160,0	2460,0	1777,00	1883,00
32545	1 x 500 rm / 35	24	12 / 20	5,5	2,5	46,0 - 52,0	394,0	1450,0	2890,0	2243,00	2377,00
33078	1 x 630 rm / 35	24	12 / 20	5,5	2,5	47,0 - 53,0	394,0	1827,0	3370,0	2546,00	2699,00
32546	1 x 50 rm / 16	36	18 / 30	8	2,5	32,0 - 38,0	182,0	145,0	1120,0	818,00	867,00

Fortsetzung ▸

Figure 31: Datasheet of the water cable

Figure 32: Datasheet of the wall panels 1

Äußere Deckschicht	Innere Deckschicht	Baubreite	Bezeichnung	Stahldeckschichten Außen / Innen[1]	Stahldeckschichten Standard Außen / Innen
gesickt (30 / 53 / 30; 1,5) 	gesickt (35 / 47/53 / 35; 3,5)	1000	1003B**	min. 0,50/0,40 max. 0,75/0,75	0,50/0,50 0,63/0,50
	eben		1003BF	min. 0,50/0,63 max. 0,75/0,75	
	liniert (41 / 84 / 41; 0,5)		1003BL*	min. 0,50/0,50 max. 0,75/0,75	
	gerillt (100; 1,2)		1003BR		
microprofiliert (12; 0,8) 	gesickt (35 / 47/53 / 35; 3,5)		1003BM**	min. 0,50/0,40 max. 0,75/0,75	
	eben		1003BMF	min. 0,50/0,63 max. 0,75/0,75	
	liniert (41 / 84 / 41; 0,5)		1003BML*	min. 0,50/0,50 max. 0,75/0,75	
	gerillt (100; 1,2)		1003BMR		
eben 	gesickt (35 / 47/53 / 35; 3,5)		1003BFG**	min. 0,75/0,40 max. 0,75/0,75	
	eben		1003BFF	min. 0,75/0,63 max. 0,75/0,75	
	liniert (41 / 84 / 41; 0,5)		1003BFL*	min. 0,75/0,50 max. 0,75/0,75	
	gerillt (100; 1,2)		1003BFR		

►► Alle Maßeinheiten in mm.

[1] Die Mindestnennblechdicken der Deckschalen sind gemäß Zulassung Außen 0,50 mm und Innen 0,40 mm.
Die angegebenen Mindestnennblechdicken sind unsere Empfehlung, um die gewünschte Ebenheit der Oberflächen zu gewährleisten.

Figure 33: Datasheet of the wall panels 2

Standardfarben							
Beschichtung Außen HAIRPLUS®	AM 1015	AM 5010	AM 7035	AM 9002	AM 9006	AM 9007	AM 9010
0,50 mm	×	×	–	×	×	×	×
0,63 mm	–	–	×	×	×	×	–
Beschichtung Innen INTERIEUR	A902						
0,40 mm/ 0,50 mm/ 0,63 mm	×						

▸▸ Die Verfügbarkeit unseres Farbsortimentes hängt von der Blechdicke, der Coilbreite sowie dem Beschichtungssystem der gewünschten Deckschalengeometrie ab. Spezielle Beschichtungssysteme fragen Sie bitte bei uns an.
Da sich die Lagerhaltung immer an der aktuellen Marktlage orientiert, behalten wir uns Änderungen unseres Angebotes vor.

▸ Informationen zu den **Sonderfarben** und **Beschichtungen** finden Sie hier:

Technische Eigenschaften							
Paneeldicke	mm	**50***	**60****	**80**	**100**	**120**	**160**⁴**
Schaumsystem	Typ	PIR					
Paneelgewicht (0,63 mm/ 0,50 mm)	kg/ m²	11,9	12,3	13,1	13,9	14,7	16,3
max. Anzahl je Paket	Stück	21	16	12**/ 13*	10	8	6
max. Paketgewicht	kg	2500			3000**/ 2500*		
max. Herstellungslänge (> auf Anfrage)[1]	m	14	21,5	21,5**/ 17,0*	21,5**/ 19,8*		
min. Herstellungslänge	m	0,2 (Paneele < 2,0 m müssen nachträglich gekürzt werden)					
Baubreite	mm	1000					
totale Paneelbreite	mm	1019					
Bemessungs-U-Werte[2], gemäß EN 14509 unter Berücksichtigung der Fugenverluste							
mit CE-Kennzeichnung[3]	W/ (m²K)	0,459	0,374	0,276	0,220	0,183	0,138
mit Zulassung und Ü-Zeichen	W/ (m²K)	0,517	0,421	0,300	0,240	0,200	0,150
Schalldämmung (DIN EN ISO 717-1)	Rw db	25					
Brandverhalten (DIN EN 13501-1)	Klasse	B-s1, d0[5]					
Brandwiderstand (DIN EN 13501-2)	EI	–			30[6]		

[1] min. 2 St. pro Paket bis Längen ≤ 16 m/ Dicken 40– 60 mm: min. 5 St. pro Paket bei Längen > 16 m/ Dicken 80– 140 mm: min. 3 St. pro Paket bei Längen > 16 m
[2] für Baubreite 1000 mm und ebene Deckschichten. Nähere Informationen entnehmen Sie bitte unserem Newsletter 2/ 2014
[3] Gemäß der technischen Baubestimmungen müssen die U-Werte der CE-Kennzeichnung um 20 % erhöht werden, wenn für die Dämmstoffe keine Allgemeine bauaufsichtliche Zulassung vorliegt. U-Werte nach EPAQ auf Anfrage
[4] ohne Allgemeine bauaufsichtliche Zulassung
[5] B-s2, d0 für Innendeckschicht t = 0,40 mm
[6] Nähere Informationen entnehmen Sie bitte den Klassifizierungsberichten

Figure 34: Datasheet of the wall panels 3

Durability of marine concrete structures – field investigations and modelling

Rob B. Polder
TNO Building and Construction Research, Delft, The Netherlands
Mario R. de Rooij
TNO Building and Construction Research, Delft, The Netherlands,
Delft University of Technology, Delft, The Netherlands

This article presents a series of investigations on six concrete structures along the North Sea coast in The Netherlands. They had ages between 18 and 41 years and most of them were made using Blast Furnace Slag cement. Visual inspections showed corrosion damage in only one structure, related to relatively low cover depths. All structures showed considerable chloride ingress with a large scatter within the relatively small tested areas. The interpretation was based on the DuraCrete model for chloride ingress. Curve fitting to chloride profiles produced chloride surface contents and apparent diffusion coefficients. Comparison was made to previously published data on chloride ingress and electrical resistivity of similar concretes. It was found that a single mean value and standard deviation applied to all concrete up to 7 m above mean sea level for the chloride surface content. Above 7 m, the local microclimate had a decisive influence, either increasing or reducing the chloride surface content. Apparent chloride diffusion coefficients did not depend on height above sea level. Their age dependency was expressed in a single value for the exponential aging coefficient. A simplified environmental factor was adopted from literature. A probabilistic model for corrosion initiation in Blast Furnace Slag Cement concrete in marine environment was proposed, the DuMaCon version of the DuraCrete model. Its application is explained for design of new structures and for assessment of existing structures. Issues for further research are the critical chloride content and the target failure probability for corrosion initiation, the effect of drying out on chloride transport in the marine splash zone and the nature and influence of spatial variation of chloride ingress.

Key words: Concrete, marine environment, chloride, blast furnace slag cement, reinforcement corrosion, service life, probabilistic model

1 Introduction

Durability of Concrete structures in marine environment has been an issue for many decades, due to the perception of sea water as aggressive to concrete and reinforcement and the long service life that is expected for marine infrastructure such as harbour and coastal defence structures. In particular in the 1970s, a lot of work has been done due to increasing construction for the oil and gas offshore industry, e.g., in Concrete in the Oceans [Leeming 1989]. In The

Figure 35: Durability of marine concrete structures

Kalkulation – Feinplanung: Massenermittlung

MASSENERMITTLUNG					
Bauteil	**Beton m³**	**Schalung m²**	**Bewehrung to**	**Schalungsgrad m²/m³**	**Bewehrungsgrad to/m³**
Fundamente					
Bodenplatte BA1	570,32	96,91	45,63	0,17	0,08
EG Bodenplatte	281,45	61,09	22,52	0,22	0,08
Gesamt	851,78	158,00	68,14	0,19	0,08
Einzelfundamente	5,07	15,60	0,41	3,08	0,08
Gesamt	5,07	15,60	0,41	3,08	0,08
Wände					
KG	205,78	1.441,88	20,58	7,01	0,10
EG	255,01	1.786,10	25,50	7,00	0,10
OG 1	176,85	1.263,75	17,69	7,15	0,10
OG 2	176,85	1.263,75	17,69	7,15	0,10
OG 3	176,85	1.263,75	17,69	7,15	0,10
OG 4	185,92	1.324,23	18,59	7,12	0,10
OG 5	175,03	1.251,58	17,50	7,15	0,10
Gesamt	1.352,29	9.595,04	135,23	7,10	0,10
Decken					
KG	256,26	826,90	25,63	3,23	0,10
EG	374,96	1.214,12	37,50	3,24	0,10
OG 1	374,96	1.214,12	37,50	3,24	0,10
OG 2	374,96	1.214,12	37,50	3,24	0,10
OG 3	374,96	1.214,12	37,50	3,24	0,10
OG 4	439,23	1.408,74	43,92	3,21	0,10
OG 5	469,24	1.510,43	46,92	3,22	0,10
Gesamt	2.664,57	8.602,55	266,46	3,23	0,10
Stützen					
KG	5,76	67,20	0,86	11,67	0,15
EG	29,16	340,20	4,37	11,67	0,15
OG 1	17,86	221,13	2,68	12,38	0,15
OG 2	17,86	221,13	2,68	12,38	0,15
OG 3	17,86	221,13	2,68	12,38	0,15
OG 4	14,18	189,00	2,13	13,33	0,15
OG 5	14,74	196,56	2,21	13,33	0,15
Aussenstützen	13,39	89,28	2,01	6,67	0,15
	130,81	1.545,63	19,62	11,82	0,15
Unterzug					
Unterzug Achse V	13,73	52,04	2,06	3,79	0,15

Figure 36: Concrete reinforcement calculation

Declaration of Authorship

I hereby certify that this thesis has been composed by me and is based on my own work, unless stated otherwise. No other person's work has been used without due acknowledgement in this thesis. All references and verbatim extracts have been quoted, and all sources of information, including graphs and data sets, have been specifically acknowledged.

Date Signature